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Transport of Solar Radiation through the Atmosphere: Aspects Relevant for Health

Knut Stamnes[1] and Jakob J. Stamnes[2]

[1]Stevens Institute of Technology, Hoboken, USA
[2]University of Bergen, Norway.

Correspondence: Jakob J. Stamnes, Department of Physics and Technology,
University of Bergen, Norway.
E-mail: jakobj.stamnes@ift.uib.no Telephone: +47 9577 00 66 Fax: +47 55 589440

Abstract

The spectral distribution of the solar radiation reaching the Earth's surface depends on the irradiance emitted by the Sun, the Earth-Sun distance, and the transmission properties of the atmosphere. The changing Earth-Sun distance due to an eccentric orbit implies that the irradiance received at the top of the atmosphere varies with an annual cycle, being 6.9% above and below the yearly mean. The bulk of the Earth's atmosphere (99% by mass) consists of molecular nitrogen and oxygen, which are radiatively inactive homo-nuclear, diatomic molecules. Trace amounts of polyatomic molecules including ozone are responsible for atmospheric absorption of solar radiation. In recent years ozone loss has been tied to the release of man-made trace gases, mainly chlorofluorocarbons used in the refrigeration industry and as propellants in spray cans. Since ozone provides an effective shield against harmful ultraviolet (UV) solar radiation, a thinning of the ozone layer could have serious biological ramifications. This paper provides an overview of how UV radiation affects human health, how UV radiation is measured, and how the penetration of UV radiation is affected by the ozone layer as well as by molecules and suspended particles (aerosols and clouds) in the atmosphere.

Introduction

Since the Earth moves around the Sun in an elliptical orbit, the Earth-Sun distance varies throughout the year by about 3.4% from its minimum value on about January 3 to its maximum value on about July 3. Since the irradiance is inversely proportional to the square of the distance, the variation in the Earth-Sun distance of about 3.4% causes a variation in the extraterrestrial solar irradiance of about 6.9% This implies that the UV exposure is almost 7% larger in the Southern hemisphere in January, than at the same latitude in the Northern hemisphere in July (1-3).

The amount of solar radiation incident upon the Earth's surface depends on the *solar zenith angle*, which is the angle between the local vertical and the direction of the center of the solar disk. The complementary angle between the local horizon and the Sun is the called the *solar elevation angle*. The solar zenith angle depends on the time of the day, the time of the year, and the geographic location. Thus, the solar radiation incident upon the Earth at the top of the atmosphere varies on diurnal and seasonal time scales as well as on the 11-year solar cycle time scale. The radiation exposure of an object (human being) at the Earth's surface depends in addition on the condition of the atmosphere, the reflection of the surface and the orientation of the object. Atmospheric transmission of UV radiation is determined largely by the amount of ozone, the total amount of molecules (proportional to atmospheric pressure), and the amount of suspended cloud and aerosol particles. Figure 1 illustrates the significant difference in UV radiation exposure between summer and winter.

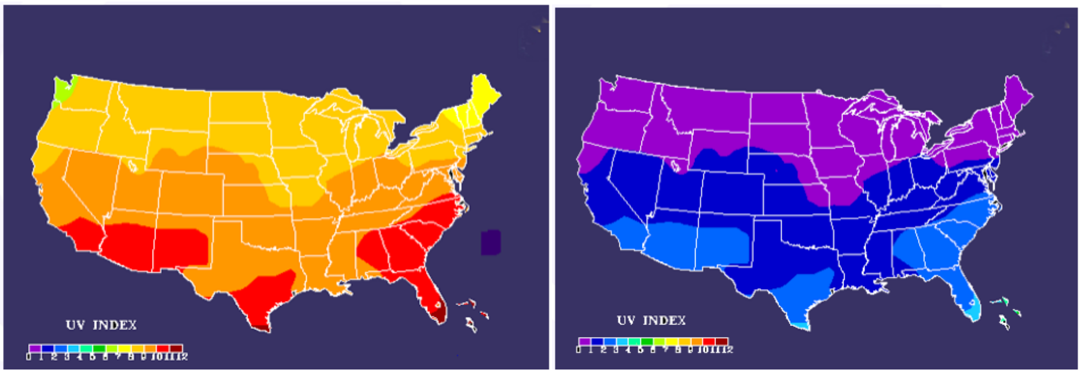
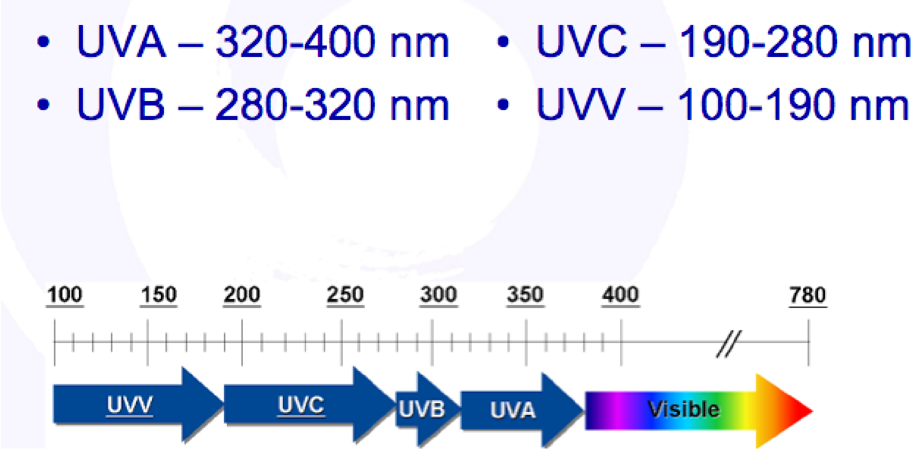


Figure 1. *UV radiation exposure for summer (left) and winter (right) conditions.*

Exposure to too much solar radiation can have a negative effect on vision. Specifically, it is the invisible component of the solar radiation (called the UV radiation) that may pose an actual risk to the health and function of the eye. Figure 2 shows how UV radiation is divided into 4 parts: UVA, UVB, UVC, and UVV. Both UVV radiation and UVC radiation are filtered by the protective ozone layer in the stratosphere, and UVC radiation is also absorbed by oxygen. Therefore, UVB radiation and UVA radiation have been the primary concerns of the medical community from the viewpoint of eye and skin exposure. Note that ozone absorbs very little UVA radiation, whereas it absorbs UVB radiation quite strongly.

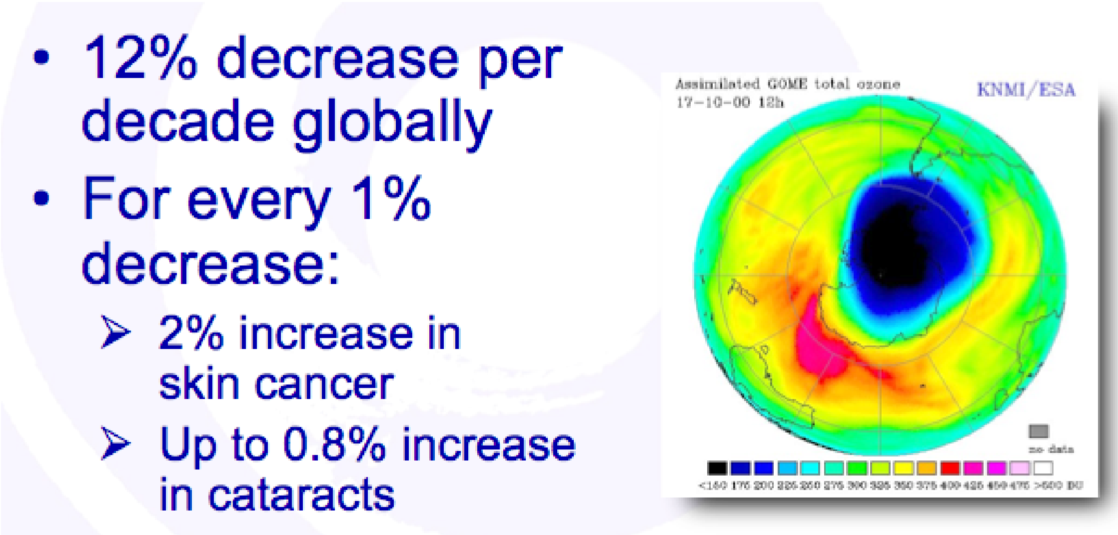


- UVA – 320-400 nm
- UVB – 280-320 nm
- UVC – 190-280 nm
- UVV – 100-190 nm

Figure 2. *Illustration of the various parts of the UV radiation spectrum.*

UV radiation and ozone depletion

Profound alterations in the Earth’s protective ozone layer have served to increase the risk of UV radiation related ocular and skin diseases. Ongoing ozone depletion increases the risk of danger from exposure to UVB radiation and UVA radiation. Despite worldwide efforts to halt the ozone-depletion trend, it is still progressing at an estimated rate of 12% per decade globally (3% in the Northern hemisphere) as illustrated in Figure 3. For every 1% decrease in the ozone layer, there will be an associated 2% increase in skin cancer (4) and a 0.6 to 0.8% increase in cataracts. The image in Figure 3 is made from assimilated data from the Global Ozone Monitoring Experiment (GOME), which shows the dramatic hole in the ozone layer over the Antarctic.



- 12% decrease per decade globally
- For every 1% decrease:
  - 2% increase in skin cancer
  - Up to 0.8% increase in cataracts

Figure 3. *UV radiation and ozone depletion.*

UV radiation and human health issues

UV radiation and visible light affect different parts of the eye

Most of the UVB radiation is absorbed by the cornea and lens of the eye. It can cause damage to these tissues, but normally does not reach deep enough to damage the retina. UVA radiation has lower energy, but penetrates much deeper into the eye and may also cause injury.

Figure 4 demonstrates how different wavelengths of UV radiation penetrate into different parts of the eye. Although only small amounts of UVA radiation and UVB radiation reach the inner eye, the high sensitivity of ocular tissues to the damaging effects of UV radiation and the cumulative effect of UV radiation exposure make these amounts clinically significant.

The parts of the eye primarily at risk from UV radiation exposure are the eyelid skin, the conjunctiva, the cornea, the crystalline lens, and the retina. Acute or chronic exposure may produce acute or chronic disease. The developing crystalline lens in children allows UV radiation to penetrate the eye and the retina. Therefore, UV radiation exposure is especially significant for children because their crystalline lenses are not yet fully developed to adequately filter UV radiation. Consequently, a child's retina may be damaged from exposure to UV radiation even on cloudy days.

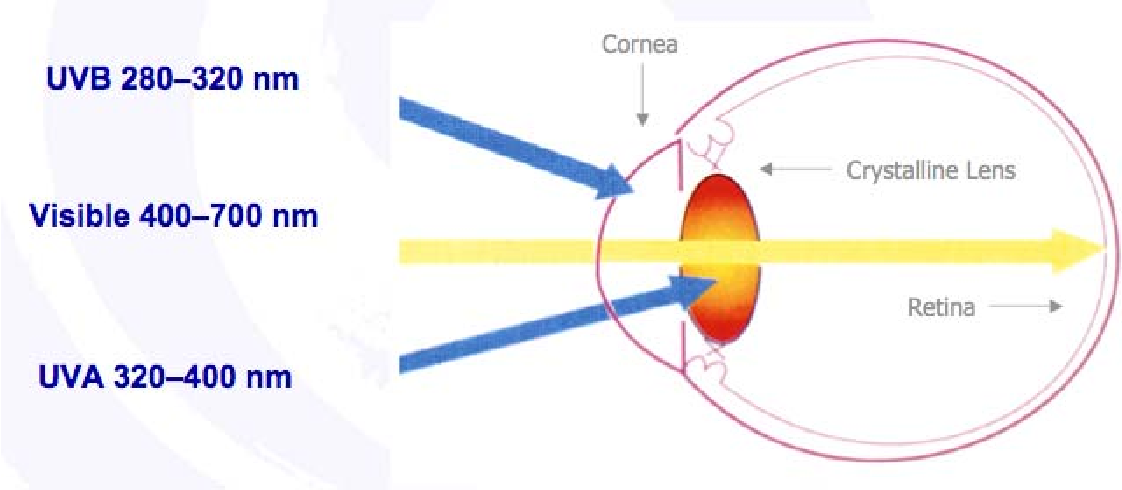


Figure 4. *Penetration of solar radiation into the eye.*

UV radiation and ocular disease

Probably the most common acute ocular manifestation of UV radiation overexposure is sunburn that affects the eyelid skin, which can manifest in cutaneous swelling and erythema, and in severe cases it is followed by blistering and exfoliation. Photokeratitis, another manifestation, is characterized by pain, foreign body sensation, photophobia, and blurred vision. Other ocular diseases attributed to chronic UV radiation exposure are cutaneous neoplasms of the eyelid (benign and malignant skin cancer), pinguecula (swelling in the corner of the eye near the nose), and pterygium (benign, progressive growth over the eye surface), see Figure 5.

Figure 5. *UV radiation and ocular disease.*

UV radiation exposure and risk of melanoma skin cancer

Skin cancer occurs at a higher rate of incidence in the Southern and Western parts compared to the Northeastern part of the USA. The incidence of melanoma skin cancer in the USA has increased by about 3% per year since 1981, to a current rate of about 14 per 100,000 (American Cancer Society, 2001). Exposure to solar UV radiation is now known to be one of the most important risk factors for melanoma and other skin cancers, and stratospheric ozone, which filters most of the solar UV radiation, has been decreasing by about 5% per decade over much of the USA (5). Melanoma cancer, considered the most serious form of skin cancer, was expected to be responsible for nearly 8,000 deaths in the USA during 2001.

Growing evidence for inverse correlation between UV radiation and internal cancers

Statistical analyses have shown that cancer rates of all types, except skin cancer, are significantly higher in the Northeastern part of the USA than elsewhere in the contiguous USA. A similar north-south gradient is observed for breast cancer in the U.S.S.R. (6). These analyses as well as recent epidemiological and laboratory evidence suggest that extreme underexposure to UV radiation can increase the incidence of more common forms of cancer, such as breast, ovarian, colon, and prostate cancer (7-9).

The inverse correlation between UV exposure and incidence of these cancers is related to vitamin D, a fat-soluble vitamin that occurs naturally in fish and fish liver oils. Vitamin D is used to fortify some milk and cereal products in USA, Canada, and Europe, but vitamin D deficiency remains a general problem, with the average dietary intake of 80 IU being far below the Recommended Daily Allowance of 200 IU in the USA (10). It is estimated that up to 90% of our vitamin D uptake originates from exposure to solar UVB radiation (wavelengths between 280-320 nm). Additional information concerning UV radiation, vitamin D, skin cancer, and other types of cancer, can be found in (11-14).

The human and economic toll

The economic cost associated with UV radiation related health problems is staggering. For example, some research indicates that a modest exposure to solar UV radiation may actually provide a beneficial reduction in the risk of developing serious internal cancers. The National Institutes of Health estimates the cost of cancers to be about USD 180 billion per year (USD 60 billion for direct medical costs, USD 15 billion for lost productivity due to illness, and USD 105 billion for lost productivity due to premature death). Every year about 54,000 women die from breast and ovarian cancer in the USA, and about the same number of men die from colon and prostate cancer. On the other hand, excessive exposure to UV radiation is known to be associated with an increasing risk for skin cancer and eye damage.

Measurements of UV radiation

A variety of instruments are available for measuring UV radiation, including:

- Spectrometers (Dobson, Brewer, Optronics)
- Multi-band filter instruments
- Broadband dosimeters
- Standard ozone instruments:
    - Dobson spectrophotometer (ozone only)
    - Brewer (ozone, sulfur dioxide, UV radiation spectra).

The Dobson spectrophotometer was developed in the 1920's to measure the total column amount of ozone in the atmosphere. A worldwide network of such instruments is still in operation, and serves as a benchmark for ozone measurements. The Brewer instrument may be considered a modern version of the Dobson spectrophotometer, which has the capability of measuring sulfur dioxide, and UV radiation spectra in addition to ozone amounts.

Scanning radiometers

Scanning radiometers designed for UV radiation measurements have the following characteristics:

- Wavelength resolution: 1 nm (typical)
- Wavelength range: 280 - 450 nm
- 4-6 scans per hour
- Frequent laboratory calibration needed
- Expensive (manpower, maintenance, etc.).

As indicated above, these instruments require considerable human attention, but if properly calibrated and maintained, they can provide a wealth of information. Figure 6 shows typical deployments of UV radiation instruments.

Multi-band filter instruments

The right-hand picture in Figure 6 shows two multi-band UV radiation instruments deployed side-by-side. These instruments have the following characteristics:

- Center wavelengths approximately at 305, 313, 320, 340, 380 nm
- Bandwidths 5-10 nm
- Temperature stabilized at 40 ^{o}C
- 1-minute time resolution.

Advantages of such multi-band UV radiation instruments are that they (i) can be deployed unattended for long periods of time, (ii) provide data with high time-resolution, and (iii) can provide a lot of data at low cost.

Figure 6. *UV radiation instruments deployed in Oslo, Norway (left), and Fairbanks, Alaska (right). (Courtesy of A. Dahlback and R. Storvold.)*

Information retrieved from multi-band data

Another advantage of the multi-band UV radiation instruments is that they can be used to provide very valuable information including (15-18):

- Total ozone amount
- Cloud and surface albedo effects
- Discrimination between cloud and ozone effects
- UV dose rates for a variety of different action spectra (biological response).

Environmental effects on solar radiation transport

The cloud- and pollution-free blue sky: Effects of molecular scattering and ozone absorption

Figure 7 illustrates the impact of ozone absorption on the UV radiation spectrum. The black curve is the spectrum measured at the top of the atmosphere, while the red curve shows the computed spectrum at the surface if there were no ozone in the atmosphere, implying that the attenuation would be due entirely to molecular scattering. The blue curve shows that the absorption of UV radiation by ozone becomes progressively stronger as the wavelength decreases into the UV part of the spectrum. In the absence of cloud and aerosol particles in the atmosphere, we note that:

- The bulk of the atmospheric molecules mainly scatter UV radiation (Rayleigh scattering). Thus, molecular scattering is stronger the shorter the wavelength of the radiation, which explains why the sky is blue. Rayleigh scattering of UV radiation plays a significant role because of the large number of molecules in the atmosphere.
- The most important gaseous absorber of UV radiation is ozone (see Figure 7), which absorbs UVB radiation quite strongly, but absorbs very little UVA radiation.

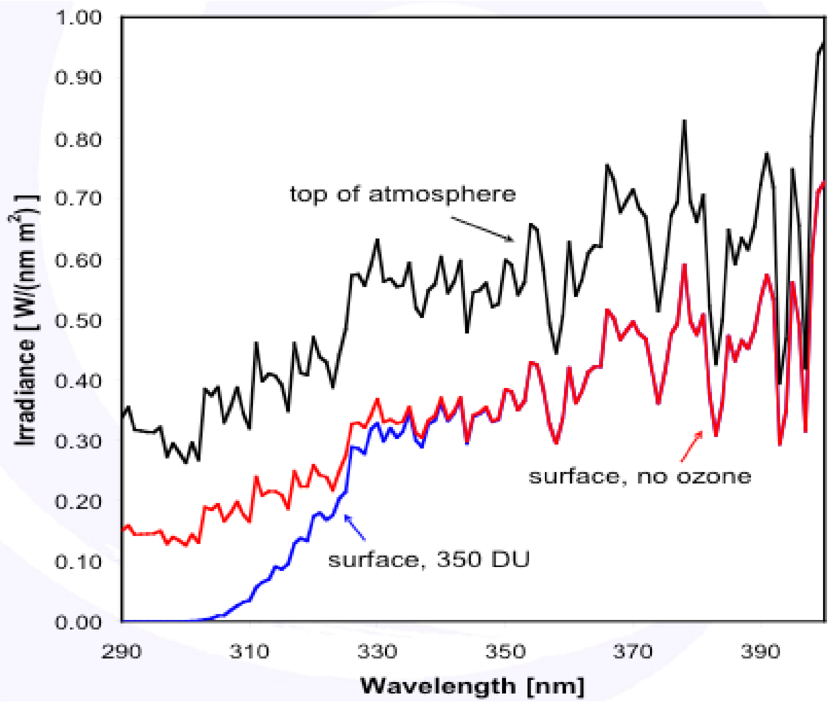


Figure 7. *The effect of ozone absorption. (Courtesy of A. Dahlback.)*

Effects of clouds and aerosols

The effects of clouds and aerosols on solar radiation transport may be summarized as follows:

- Clouds consist of either (spherical) water droplets or non-spherical ice particles.
- Aerosol particles are non-spherical and consist of dust, sulfur, soot, and other compounds.
- Cloud and aerosol particles both scatter and absorb UV radiation - the effect is large, but weakly dependent on wavelength.

The role of particle size

Radiation interaction with particles depends on the particle size compared to the radiation wavelength:

- Small particles (like molecules) are Rayleigh scatterers, and have a small effect per particle.
- Particles of size comparable to the wavelength have a strong interaction.

Spherical particles - Mie theory

In 1908 Gustaf Mie developed a theoretical description for scattering of electromagnetic radiation by spherical particles, and in recent years efficient computer codes have been developed.

- By the use of such codes it has been shown (19) that the scattering and absorption by spherical water droplets depend primarily on the mean droplet size and the refractive index of water relative to the surrounding air.
- A very efficient method has been developed to compute the scattering and absorption coefficients for a collection of spherical water droplets (19). Thus, we can easily quantify the effects of cloud droplets on the solar radiation transport.

Non-spherical particles

Scattering of solar radiation by non-spherical particles is an active area of research and considerable progress has been made in recent years (20-24). Here we would like to note that:

- Most atmospheric particles are non-spherical (ice and aerosol particles):
  - Computer codes for scattering by non-spherical particles are still under development.
  - The effect of departure from spherical shape is considerable but not yet well established.

An illustration of the variety of shapes assumed by ice particles in clouds is provided in Figure 8.

Why study transport of solar radiation in the environment?

The absorption and multiple scattering of solar radiation determine the amount of radiation available at various levels in the atmosphere, at the surface, and at various depths in the ocean. Knowledge of the spectral distribution of the radiation field is important because it drives:

- The photobiology and photochemistry of natural Systems
- The dynamics of the atmosphere and ocean.

Furthermore, a better understanding of the solar radiation transport in the environment is required for:

- Improved understanding of radiative energy disposition and climate evolution
- Improved capability to detect environmental changes from space.

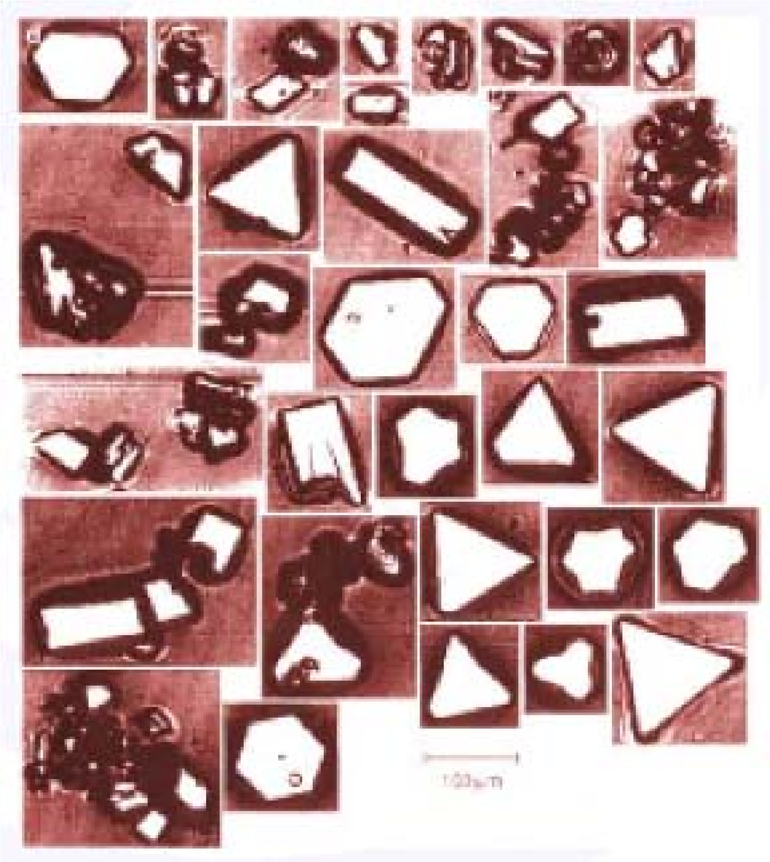


Figure 8. *Examples of ice particle shapes observed in clouds.*

Solar radiation is driving the weather and the general circulation

It is important to realize that:

- Without the radiative energy from the Sun our planet would be a dead block of ice. A stable climate requires that the Earth radiate the same amount of energy to space as it receives from the Sun.
- Climate is influenced by reflection of solar radiation by air molecules, clouds and aerosols, and the surface.

Albedo impact on UV radiation

The albedo of a surface is the fraction of the incoming radiative energy reflected from it. Examples of *high albedo* surfaces are snow, clouds, white clothing, and examples of *low albedo* surfaces are dirt, man-made constructions, dark clothing.

As an example, a warmer climate could lead to increased evaporation and more clouds, which could increase the albedo of the Earth and thus result in more solar radiation reflected back to space. Thus, a warmer climate could reduce the levels of solar UV radiation received by the biosphere including people, but unlike ozone, clouds screen UVA radiation and UVB radiation by equal amounts.

Concluding Remarks

The discussion in this paper may be summarized as follows:

- Changes in UV radiation exposure can be quantified and monitored, but not yet well predicted.
- Ozone and clouds affect the UV radiation penetration, and the cloud effect is most uncertain.
- It is important to determine what level of UV radiation exposure is sufficient, and what constitutes a harmful overexposure.
- Also, it is important to determine how much UV radiation is needed for vitamin-D production, but is yet harmless.
- Finally, the challenge is to make such assessments on global, regional, and local scales.

In closing we offer the following remarks. The photochemistry of vitamin D synthesis in the skin is reasonably well understood, as is the transformation of previtamin D3 to active forms that have the capacity to regulate cell differentiation and growth. It is this link between UVB radiation exposure, cutaneous production of vitamin D, and suppression of malignant growth, which may explain observed patterns of cancer incidence. Unfortunately, further progress in this research area is impeded by the lack of high accuracy measurements of surface-level UV radiation exposure and other atmospheric parameters specifically targeted for correlation with the incidence of cancer.

There are additional considerations related to the exposure of UVA radiation (320-400 nm wavelengths). Skin damage can occur also through excessive exposure to UVA radiation, although the sensitivity is much less than for UVB radiation, so that longer durations of exposure are required. Vitamin D synthesis is essentially zero for UVA radiation. Since common sunscreens block UVB radiation but provide little protection against UVA radiation, there is the possibility that the use of sunscreens may shift the proportion of cancer risk factors associated with exposure to solar radiation. In addition, the danger signals associated with sunburns are reduced, implying that high exposures of UVA radiation and increased risk of skin cancer may unknowingly be received by people involved in recreational outdoor activities, while none of the vitamin D benefits are redeemed.

References

1. Stamnes K. Ultraviolet Radiation. *Encyclopedia of Atmospheric Sciences* 2003; **6**: 2467-2473.
2. Moan J. Effects of UV radiation and visible light. In: Radiation at home, outdoors and in the workplace. Editors: D. Brune, R. Hellborg, B. R. R. Persson and R. Pääkkönen. Scandinavian Science Publisher, Oslo, pp. 474–491, 2001.
3. Moan J. Visible light and UV radiation. In: Radiation at home, outdoors and in the workplace. Editors: D. Brune, R. Hellborg B. R. R. Persson and R. Pääkkönen, Scandinavian Science Publisher, Oslo, pp. 69–85, 2001.
4. Moan J, Dahlback A, Henriksen T, Magnus K. Biological Amplification Factor for Sunlight-induced Nonmelanoma Skin Cancer at High Latitudes. *Cancer Research* 1989; **49:** 5207-5212.
5. McPeters RM et al. Long term ozone trends derived from the 16-year combined Nimbus 7 Meteor 3 TOMS Version 7 record. *Geophys Res Lett* 1996; **23**: 3699-3702.
6. Gorham ED, Garland FC, Garland CF. Sunlight and breast cancer incidence in the USSR. *Int J Epidemiol* 1990; **19**: 820-824.
7. Garland FC, Garland CF, Gorham ED, Young JF. Geographic variation in breast cancer mortality in the United States: A hypothesis involving exposure to solar radiation. *Prev Med* 1990; **19**: 614-622.
8. Lefkowitz ES, Garland CF. Sunlight, vitamin D, and ovarian cancer mortality rates in US women. *Int J Epidemiol* 1994; **23**: 1133-1136.
9. Hanchette C, Schwartz GG. Geographic patterns of prostate cancer mortality. *Cancer* 1992; **70**: 2861-2869.
10. Hollick MF. Sunlight and vitamin D: the bone and cancer connections. *Rad Prot Dosim* 2000; **91**: 65-71.
11. Moan J, Henriksen EK, Dahlback A. Effects of increased UV-radiation on human health. In: Chemical climatology and geomedical problems. Editor: J. Låg. The Norwegian Academy of Science and Letters, pp. 57-72, 1992.

12. Moan J, Dahlback A. Ultraviolet Radiation and Skin Cancer: Epidemoiological Data from Scandinavia. In "Environmental UV Photobiology". Editors: A.R. Young, L.O. Bjørn, J. Moan and W. Nultsch. Plenum Press, New York and London, pp. 255-293, 1993.
13. Moan J, Porojnicu AC, Dahlback A. Epidemiology of cutaneous malignant melanoma. In: Skin cancer prevention. Editors: U. Ringborg, Y. Brandberg, E.W. Breitbart and R. Greinert. ISBN 0849398894. Informa Healthcare, NY, USA, pp. 179-201, 2007.
14. Moan J, Porojnicu AC, Dahlback A, Setlow RB. Addressing the health benefits and risks, involving vitamin D or skin cancer, of increased sun exposure. *PNAS* 2008; **105**: 668-673.
15. Dahlback A. Measurements of biologically effective UV-doses, total ozone abundance and cloud effects with multi-channel moderate bandwidth filter instruments. *Appl Opt* 1996; **35**: 6514-6521.
16. Høiskar BA, Haugen R, Danielsen T, Kylling A, Edvardsen K, Dahlback A, Johnsen B, Blumthaler M, Schreder J. Multichannel moderate-bandwidth filter instrument for measurement of the ozone-column amount, cloud transmittance, and ultraviolet dose rates. *Appl Opt* 2003; **42**: 3472-3479.
17. Lakkala K. et al. Quality assurance of the solar UV network in the Antarctic. *J Geophys Res* 2005; **110**, D15101, doi:10.1029/2004JD005584.
18. Dahlback A, Gelsor N, Stamnes JJ, Gjessing Y. UV measurements in the 3000-5000 m altitude region in Tibet. *J Geophys Res* 2007; **112**, D09308, doi:10.1029/2006JD007700.
19. Hu Y-X, Stamnes K. An accurate parameterization of the radiative properties of water clouds suitable for use in climate models. *J Climate* 1993; **6**: 728-742.
20. Schulz FM, Stamnes K, Stamnes JJ. Shape dependence of the optical properties in size-shape distributions of randomly oriented prolate spheroids, including highly elongated shapes. *J Geophys Res* 1999; **104**: 9413-9421.
21. Kahnert FM, Stamnes JJ, Stamnes K. Can simple particle shapes be used to model scalar optical properties of an ensemble of wavelength-sized particles with complex shapes? *J Opt Soc Am* 2002; **A 19**: 521-531.
22. Kahnert FM, Stamnes JJ, Stamnes K. Using simple particle shapes to model the Stokes scattering matrix of ensembles of wavelength-sized particles with complex shapes: Possibilities and limitations. *J Quant Spectr Radiat Transfer* 2002; **74**: 167-182.
23. Sandvik A, Biryulina M, Kvamstø NG, Stamnes JJ, Stamnes K. Observed and simulated microphysical composition of arctic clouds: Data properties and model validation. *J Geophys Res Atmosph* 2007; **112**: D05205, doi:10.1029/2006JD007351.

24. Kahnert FM, Sandvik A, Biryulina M, Stamnes JJ, Stamnes K. Impact of ice particle shape on short wave radiative forcing: A case study for an arctic ice cloud. *J Quant Spec Rad Transfer* 2007 (accepted).

Suggestions for Further Reading

1. American Cancer Society, Cancer Facts and Figures, pp. 10-17, 2001.
2. Stamnes K, Thomas GE. Atmospheric Radiation. *Encyclopedia of Science and Technology, Third Edition* 2002; **13**, 511-522.
3. Thomas GE, Stamnes K. Radiative Transfer in the Atmosphere and Ocean, Cambridge University Press, 1999.