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Relationship between UVB and erythemally weighted radiation †

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We discuss the move from reporting damaging UV radiation in terms of UVB to the now widely accepted erythemally weighted UV radiation (UV_{Ery}) and the UV Index (UVI). The relationship between these quantities is given: to a good approximation, it is found that $UVB_{280–315\ nm} = 7.55 \times UV_{Ery}$. In terms of the UV Index, the estimated $UVB_{280–315\ nm}$ in units of W m^{-2} is 18.9 times the UVI. These approximations generally hold to within ~10% for all solar zenith angles (sza) less than 70°. For most practical purposes, this is a sufficient range, since for larger sza, the intensity of UVB is less than 10% of that for overhead sun conditions. The simple relationship above is verified using spectral measurements. However, tables are provided to enable calculation of the conversion with greater accuracy under such conditions. Similar model calculations are provided to estimate $UVB_{280–320\ nm}$. Correction tables to convert erythemally weighted UV to other biological weightings are also presented.

Introduction

Historically, biologically damaging UV data have often been quoted in terms of the integral between 280–315 nm ($UVB_{280–315\ nm}$) or in terms of the integral between 280 and 320 nm ($UVB_{280–320\ nm}$). The problems with these definitions are twofold. Firstly, there can be confusion as to which definition is used. UV radiation increases markedly over the range 300 to 320 nm due, primarily, to the decreasing absorption of ozone, so that the integral to 320 nm is typically about twice as large as the integral to 315 nm. The second issue is that with either definition, the very steep slope of the spectrum over the UVB range means that it is impossible to manufacture a simple broadband sensor to measure the quantity accurately over a wide range of solar zenith angles (sza) and ozone amounts. Thus, there is always an implicit error in any broadband instrument that claims to measure UVB.

With increased public awareness of the health consequences of decreasing stratospheric ozone, there has been international agreement to report UV using the 'sunburning', or erythemally weighted, radiation (UV_{Ery}), rather than in terms of UVB. The erythemally weighted UV is

$$UV_{Ery} = \int I(\lambda) w(\lambda)\, d\lambda$$

where λ is the wavelength in nm, $I(\lambda)$ is the irradiance in W m^{-2} and $w(\lambda)$ is the erythemal weighting function, defined[1] as

$$w(\lambda) = 1.0 \text{ for } 250 < \lambda \le 298 \text{ nm}$$
$$w(\lambda) = 10^{0.094(298 - \lambda)} \text{ for } 298 < \lambda \le 328 \text{ nm}$$
$$w(\lambda) = 10^{0.015(139 - \lambda)} \text{ for } 328 < \lambda \le 400 \text{ nm}$$
$$w(\lambda) = 0 \text{ for } \lambda > 400 \text{ nm}$$

The erythemal weighting function and its relationship to solar UV received at the surface is shown in Fig. 1. The weighting function is unity at wavelengths of 298 nm and less. As the wavelength increases above 298 nm, it decreases throughout the UVB and UVA range. Although the weighting function includes an arbitrary normalisation, erythemally weighted UV is given in terms of SI units such as W m^{-2} (or derived units such as μW cm^{-2}). Unlike other weighting functions in common use, the erythemal weighting function is defined mathematically, so there is no ambiguity in its use. Furthermore, although the function was designed to represent skin damage, it follows a similar form to other damage processes (Fig. 2).

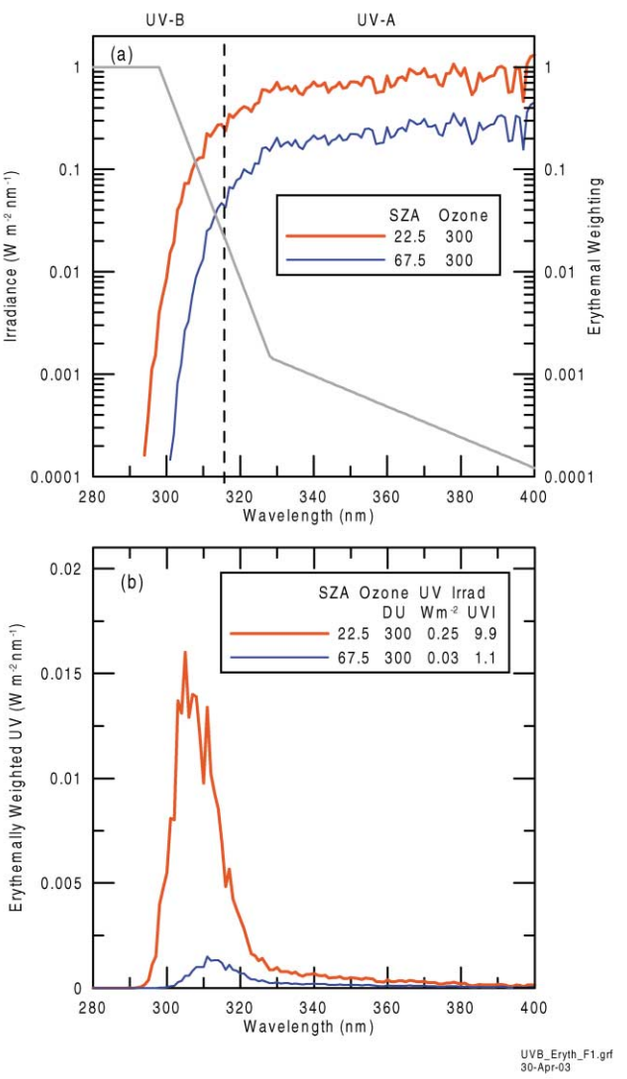

Fig. 1 (a) Calculated spectra (1 nm resolution) and the erythemal weighting function plotted using a logarithmic *y*-axis. (b) Erythemally weighted UV for two sza and two ozone amounts.

† Electronic supplementary information (ESI) available: Appendices 1 and 2. See http://www.rsc.org/suppdata/pp/b3/b312985c/

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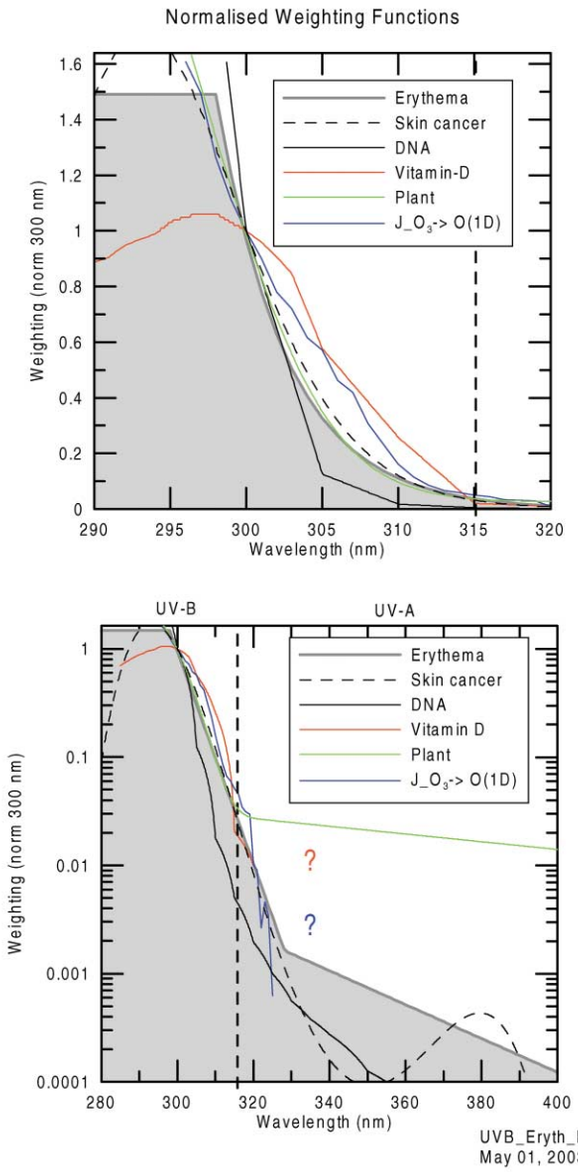

Fig. 2 Erythemal response function[1] compared with other weighting functions, all normalised at 300 nm: skin cancer;[2] Vitamin D = photosynthesis of previtamin D3;[3] plant damage;[4] $J_{O_3} \longrightarrow O(1D)$ = ozone photolysis;[5] DNA = damage to bare DNA.[6] Data are plotted on a linear *y*-axis in the upper panel and a logarithmic *y*-axis in the lower panel.

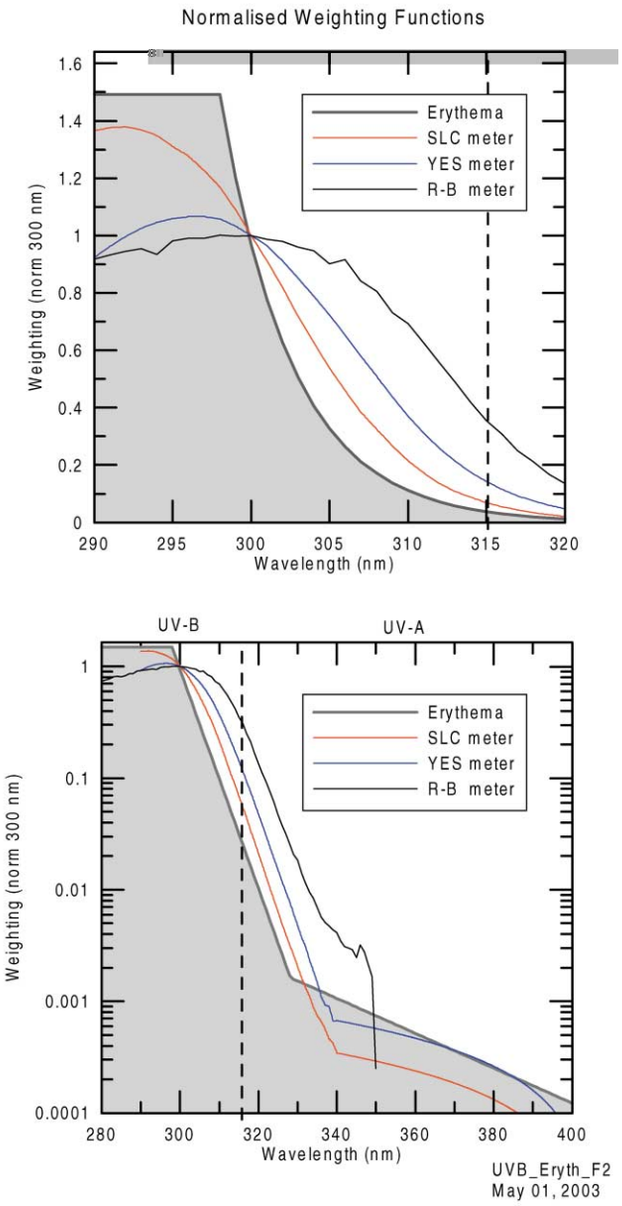

Fig. 3 Erythemal response compared with weighting functions from instruments, as measured by Industrial Research Ltd., New Zealand, all normalised at 300 nm: SLC = Solar Light Company biometer; YES = Yankee Environmental Systems UVB-1 sensor; R-B = Robertson–Berger meter. Plot axes are as in Fig. 2.

The UV Index (UVI), which is based on this weighting function, is now a standardised way of reporting UV information to the public.

$$\mathrm{UVI} = 0.4 \times \mathrm{UV_{Ery}}\ (\text{for } \mathrm{UV_{Ery}} \text{ in } \mathrm{Wm^{-2}})$$
$$\mathrm{UVI} = 40 \times \mathrm{UV_{Ery}}\ (\text{for } \mathrm{UV_{Ery}} \text{ in } \mu\mathrm{Wcm^{-2}})$$

UVI values of 10 or more are considered 'extreme'. This threshold corresponds to 0.25 W m^{-2} (or 25 μW cm^{-2}) of erythemally weighted UV radiation.

In recent years, there has been a rapid growth in the deployment of instruments that measure 'sunburning', or erythemally weighted, radiation. Although the bandpasses of these instruments are designed to match the erythemal weighting function, in practice, some differences remain (Fig. 3). The effects of these differences may be removed using a radiative transfer model. Typically, these corrections are functions of sza and ozone amount, and can exceed ~10% even for the best sensors available. Similarly, if the angular response of the instrument has been characterised, then a model-derived correction can be applied to remove the effects of deviations from the ideal cosine response. By 2002, there were over 1100 such sensors deployed worldwide[7], and the availability and reliability of data from them probably exceed those of data from traditional 'UVB' meters. Here, the relationship between these quantities is investigated. It is demonstrated that there is a simple relationship between erythemally weighted UV and $\mathrm{UVB_{280–315\ nm}}$ over a wide range of ozone amounts and solar zenith angles. However, for most other weightings, no such relationship exists.

Calculated relationship between UVB and erythema

Because the solar spectrum is so steep in the UVB region, there is no simple conversion factor to convert erythemally weighted UV to UVB. The precise correction factor depends on solar zenith angle and ozone amount. However, if the sza and ozone amount are known, then it is possible to calculate a correction using a radiative transfer model.

Here, we used the 'tuv' radiative transfer model developed at NCAR (version 4.1, using the discrete-ordinate pseudo-

spherical option) to calculate erythemally weighted UV and UVB over a range of ozone amounts and sza. Samples of the ratio $UVB_{280–315\ nm}/UV_{Ery}$ are shown in Fig. 4, and tabulated ratios over a wider range of ozone values are shown in Appendix 1 (ESI †).

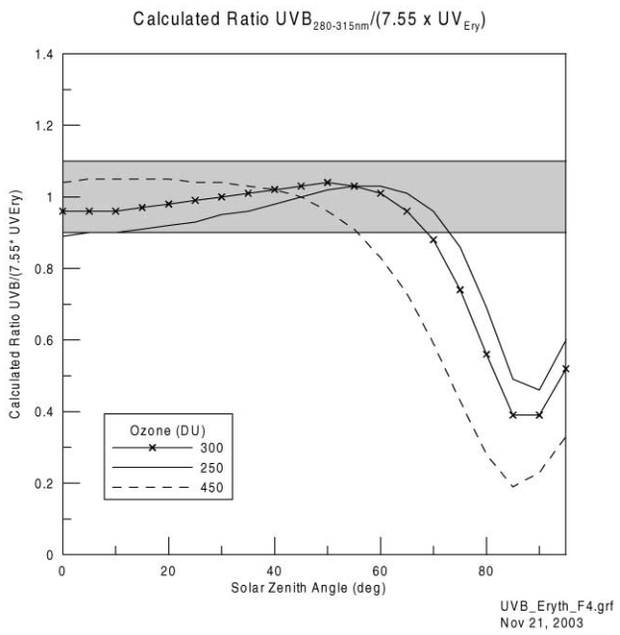

Fig. 4 Calculated $UVB_{280–315\ nm}/UV_{Ery}$ ratios for three ozone amounts. The shading represents the region where the conversion factor of 7.55 can be used with an error of less than ±10%.

These tables may be used to calculate UVB irradiances from erythemal UV irradiances (or *vice versa*). For example, at sza = 30°, toz = 300 DU, $UVB_{280–315\ nm}$ is 7.55 times greater than erythema. For ozone amounts in the range 250 to 400 DU, this conversion factor can be used with an error of less than 10% up to sza = 60°. Therefore, over a usefully wide range of solar zenith angle and ozone amounts, the relationship

$$UVB_{280–315\ nm} = 7.55 \times UV_{Ery}$$

can be used with a loss of accuracy of less than 10%. Combining this with the definition of UVI, we have, to a similar level of accuracy,

$$UVB_{280–315\ nm}\ (W\ m^{-2}) = 18.9 \times UVI$$

The shaded areas in the tables in Appendix 1 (ESI †) show the region where a simple conversion may be made with a loss of accuracy of less than 10%.

No such simple relationships exist for $UVB_{280–320\ nm}$, which is relatively insensitive to changes in ozone amounts. For example, at sza = 30°, toz = 300 DU, $UVB_{280–320\ nm}$ is 14.38 times greater than erythema, but the corresponding error in using this factor over the range of conditions above increases from 10 to 30%. For ozone amounts close to the global mean value of 300 DU, and for noon conditions at mid latitudes, $UVB_{280–320\ nm}$ is about twice as large as $UVB_{280–315\ nm}$.

Relationship between other weightings and erythema

Correction tables to convert erythemally weighted UV to other weightings are given in Appendix 2 (ESI †). Samples of the ratios are shown in Fig. 5. For the most part, these are restricted to biological weightings of UV, which have approximately similar sensitivities to changes in ozone amount. Clearly, if the sensitivity to changes in ozone amount is different from that for erythemally weighted UV, then a compact relationship cannot be expected. These sensitivities are sometimes expressed as "radiative amplification factors" (RAFs), defined as the percentage increase in weighted UV per 1% reduction in ozone.[8] The RAFs listed in Table 1 are as calculated for summer conditions at 30° N. In some cases, the weighting functions were not provided to wavelengths long enough for accurate determination of correction tables. In these cases, they were extrapolated as shown in Table 1. The resulting RAFs are also strongly dependent on the method of extrapolation, as has been discussed previously.[9] In the case of vitamin D production, which could be a beneficial effect of UV radiation, the resulting conversion factors depend strongly on the method of extrapolation (see Fig. 6). Thus, there is clearly a need for more accurate measurements of this quantity.

Table 1 Details of the biological weightings considered, as calculated with the tuv discrete-ordinate eight-stream pseudo-spherical model (sza = 30°, toz = 305 DU, ground albedo = 0.02, aerosol optical depth = 0.38 at 340 nm, with a λ^{-1} dependence)

Weighting	RAF
Erythema [1]	1.2
$UVB_{280–315\ nm}$	1.0
$UVB_{280–320\ nm}$	0.7
DNA damage [6]	2.1
USC skin cancer [2]	1.4
Plant damage [4]	0.2
General plant [10] (ends 313 nm)	1.6
Vitamin D [3] (ends 320 nm)	1.4
Vitamin D, logarithmic extrapolation to 10^{-5} at 400 nm	1.2
Vitamin D, logarithmic extrapolation to 10^{-4} at 400 nm	1.1
Vitamin D, linear extrapolation to 10^{-5} at 400 nm	0.9

For most of these weightings, there is no simple conversion factor from erythemally weighted UV. As expected, the largest range of correction factors occurs for weightings where the RAF differs markedly from erythema; namely, DNA damage, where the sensitivity is much greater, and Flint's plant damage weighting, which has a much lower sensitivity.

Weightings with RAFs closest to that of erythema (*i.e.* near 1.2) have the tightest grouping (*e.g.* $UVB_{280–315\ nm}$, vitamin D with logarithmic extrapolation to 400 nm).

Measured relationship between UVB and erythema

Using spectral measurements, both $UVB_{280–315\ nm}$ and erythemally weighted UV can be derived. Spectral data measured at Lauder, New Zealand (45° S, 170° E, altitude 370 m), during January 2003 were used to experimentally derive the relationship calculated using the radiative transfer model. During this period, ozone was in the range 260 to 320 DU.

A regression between the two UV quantities is shown in Fig. 7. The slope of a regression line though the origin is 7.50, which is in good agreement with the calculated value. The maximum erythemally weighted UV during this period was ~30 μW cm^{-2}, corresponding to a UV Index of 12.

Similarly, regression statistics can be derived for daily doses of UV rather than instantaneous measurements of irradiances. The regression statistics for monthly mean doses of UV taken at Lauder over several years are shown in Fig. 8. The range of ozone values included in this plot is from 220 to 420 DU. The regression slope in this case is 7.66, which is slightly larger than implied previously. However, the differences are small and are within the range of uncertainty (±3%) expected from the measurement accuracy. In passing, we note that the standard erythemal dose as defined by the International Commission on Illumination (100 J m^{-2} of erythemally weighted UV radiation) [11] is exceeded by more than a factor of 50 by the summertime daily doses at Lauder. More detailed statistics in the form of linear and quadratic fits are also shown in the plots.

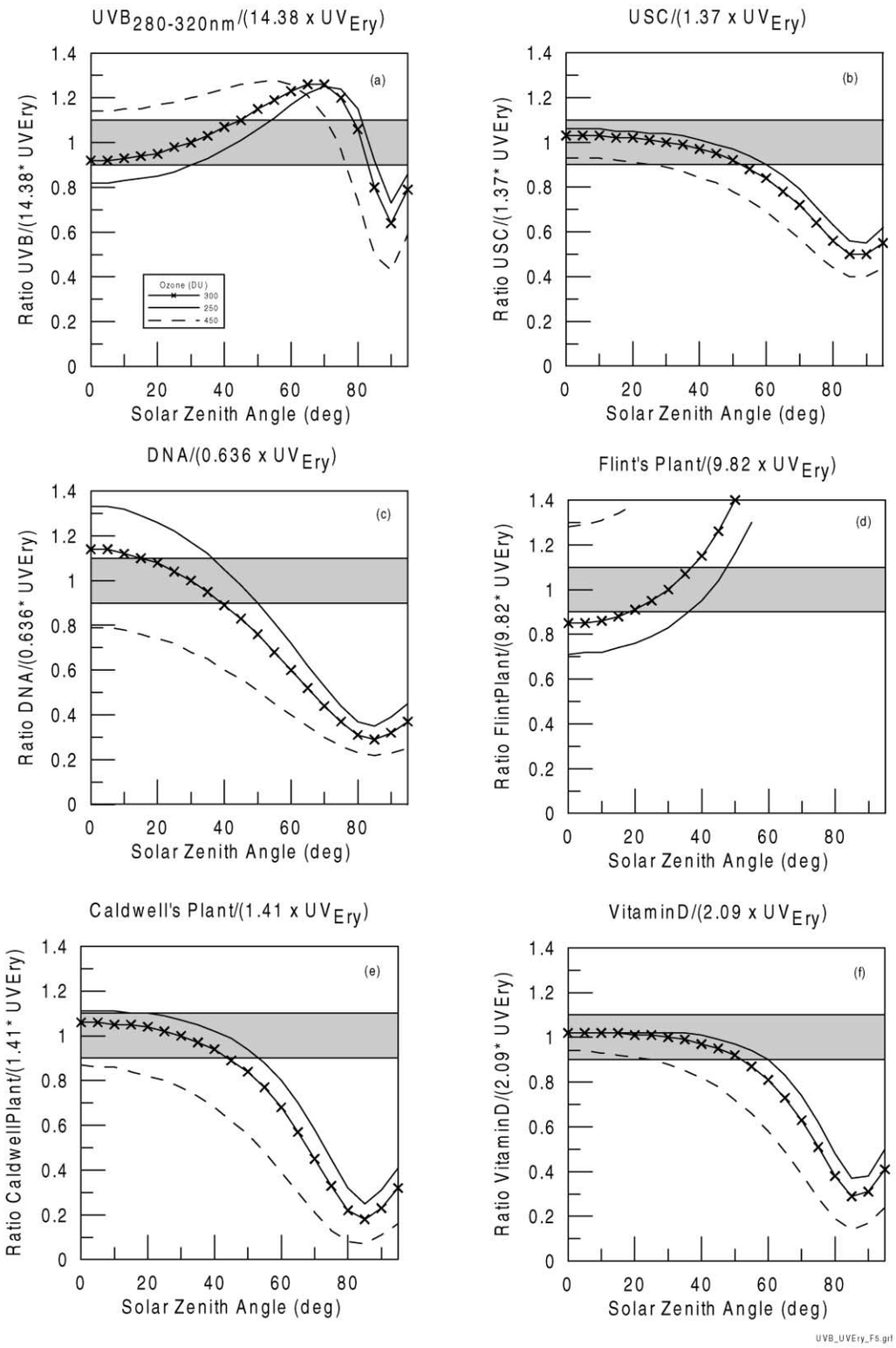

Fig. 5 Calculated ratios of various weightings to UV_{Ery} for three ozone amounts: (a) $UVB_{280–320\ nm}$; (b) USC skin cancer; (c) DNA-weighted; (d) Flint's plant damage; (e) Caldwell's plant damage; (f) previtamin D production (see Table 1).

Conclusions

Model calculations have been used to derive a relationship between erythemally weighted UV and UVB radiation. In the case of $UVB_{280–315\ nm}$, there is a compact relationship that can be approximated by a linear or quadratic regression. Over a wide range of sza and ozone amounts, the UVB irradiance can be predicted with a loss of accuracy of less than 10% using the simple relationship $UVB_{280–315\ nm} = 7.55 \times UV_{Ery}$. This calculated relationship is confirmed by measurement. For greater accuracy, the look-up table supplied (ESI†) can be used.

For $UVB_{280–320\ nm}$, no such compact relationship exists. To estimate this quantity from erythemally weighted UV, knowledge of ozone and sza is required. In this case, $UVB_{280–320\ nm}$ values can be obtained from the look-up table supplied (ESI†). Tables are also provided for other weightings of UV radiation (as shown in Fig. 2). Compact relationships exist only for weightings where the sensitivity to ozone (*i.e.* the RAF) is close to that for erythema.

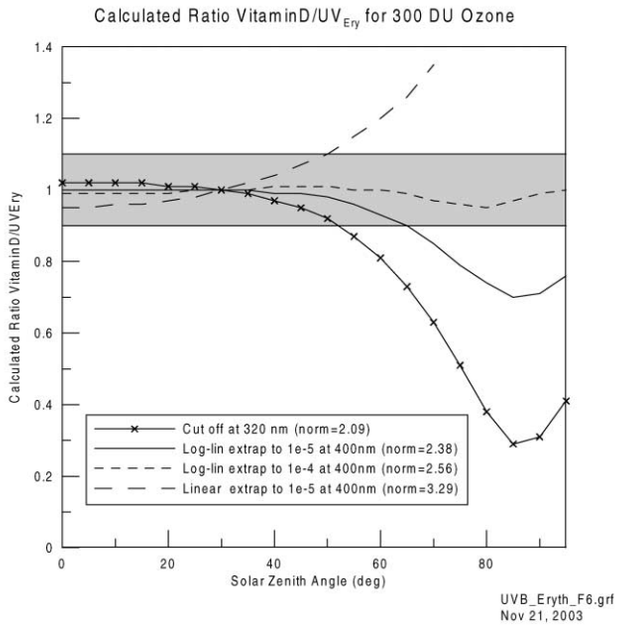

Fig. 6 Sensitivity of the ratio UV_{VitD}/UV_{Ery} to the extrapolation method used in the vitamin D action spectrum, all for 300 DU ozone.

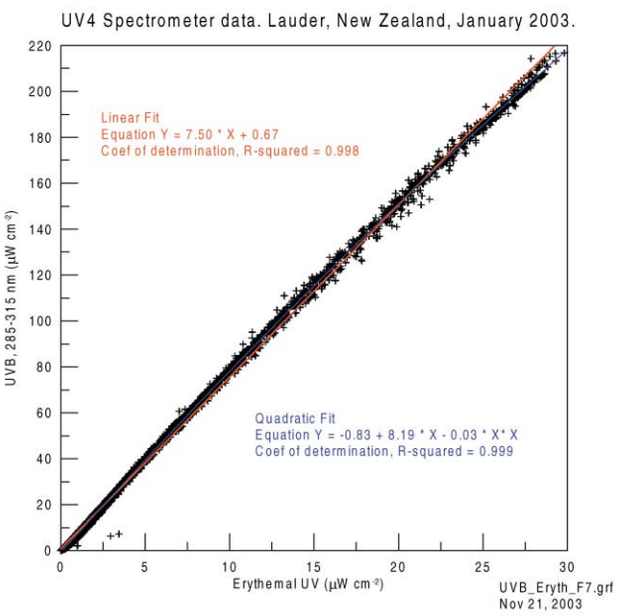

Fig. 7 Regression between UVB and erythemally weighted UV. The data include 2935 individual measurements. Outliers correspond to times when cloud effects were changing during the scan.

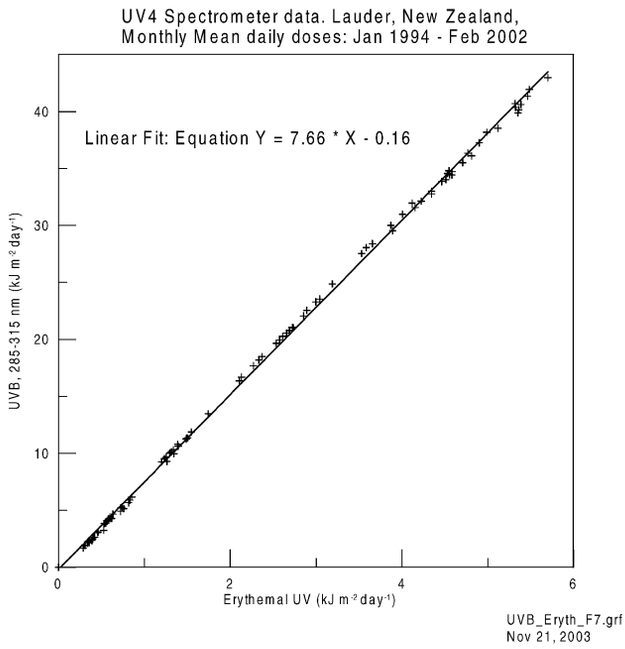

Fig. 8 Regression between daily doses of UVB and erythemally weighted UV. The plot uses measurements at Lauder, New Zealand, over the period Jan 1994 through Feb 2002.

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