Biometeorology

Why is it so hard to gain enough Vitamin D by solar exposure in the European winter?

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Abstract

UV exposure, which is the main source for a sufficient level of vitamin D in the human body, is found to be up to a factor of 7 lower in Northern Germany (52° N) in the winter months compared to UV levels in the central region of New Zealand's South Island (45° S). When corrected for the influence of solar zenith angle, the vitamin D-weighted exposure is still a factor of 2 higher in the southern hemisphere at the corresponding latitude. The major part of the difference can be attributed to differences in cloudiness, and a minor part to total ozone and aerosols. Data from several stations in Europe show a high variability due to cloudiness differences between the stations and between different years, but they also show that the differences are not restricted to individual sites and may characterize a northern versus southern hemisphere contrast. Wintertime erythemally-weighted irradiance is also found to be much higher in New Zealand than in Europe. Whereas on a monthly average clouds weaken the UV irradiation by up to 25 % for most locations in New Zealand, the reduction is usually up to 50 % in central Europe in winter.

Keywords: Vitamin D, Erythema, Hemispherical UV Differences, Exposure model

1 Introduction

Ultraviolet radiation (UV) from the sun (Seckmeyer et al., 2012; Lucas et al., 2015) causes a considerable global disease burden, including acute and chronic health effects on the skin, eye and immune system. On the other hand, UV is essential for vitamin D3 production in humans (Seckmeyer et al., 2012; IARC, 2008). Emerging evidence suggests that vitamin D levels are an indicator of health risk (IARC, 2008) relating to some cancers, multiple sclerosis, and other autoimmune disorders, along with the established link with musculoskeletal health. However, the causal relationship between numerous diseases and vitamin D3 insufficiency is still under debate (Wacker and Holick, 2013; Burns et al., 2015). In the following, vitamin D is used as a general term whereas we use the expression vitamin D3 to describe the complex UV-induced process in the human skin (Holick, 2004) in which vitamin D3 is synthesized.

Vitamin D3 synthesis in the human skin due to solar UV-B (280–315 nm) radiation is the main source of vitamin D for humans, whereas dietary intake generally contributes only a small percentage (∼ 10 %) to the necessary supply (Biesalski et al., 2002), at least according to current knowledge. Although vitamin D3 can be effectively produced by UV-B radiation, there are large seasonal differences in its production at middle to high latitudes (Seckmeyer et al., 2008a; Webb et al., 2010). As a result, more than 50 % of the German population has an insufficient vitamin D supply (25 to 49.9 nmol/L of circulating 25(OH)D concentrations), especially during wintertime (Zittermann, 2010). This finding has been recently reconfirmed in a large group of patients (Kramer et al., 2014).

The irradiance incident on a horizontal surface, as used in most studies to date, does not take into account the complex geometry of the radiation field of the sky for different meteorological conditions. To address this concern a new way to calculate the vitamin D3-weighted exposure of a human, represented by a 3D voxel model (Seckmeyer et al., 2013), has been developed. The model uses the information on both the human geometry and spatial distribution of spectral sky radiance. In future, sky radiance may also be measured sufficiently rapidly by a newly-developed multi-

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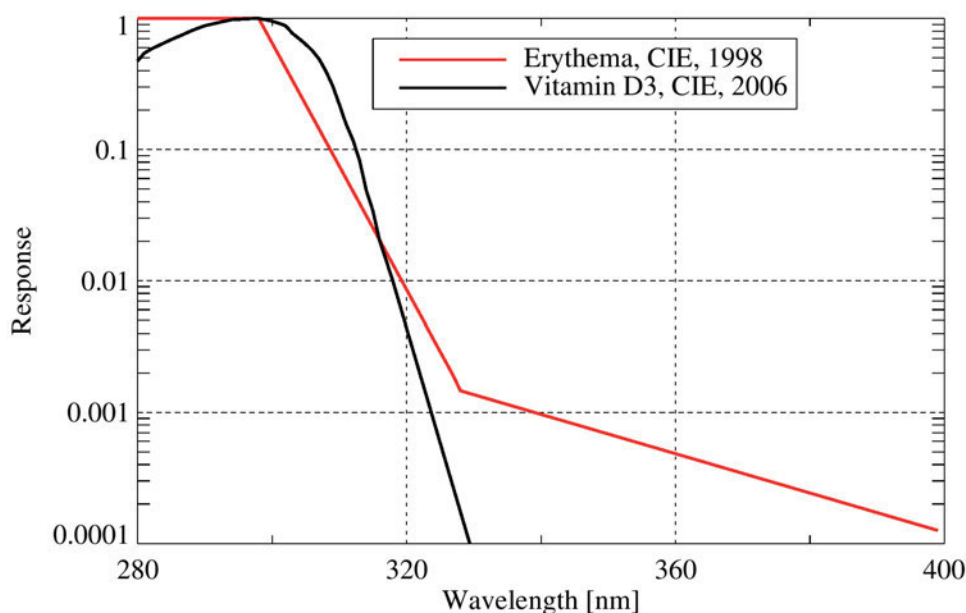
Figure 1: Biological action spectra for erythema and vitamin D3 production.

directional spectroradiometer (MUDIS) (RIECHELMANN et al., 2013) but this is not yet in operational use. So far this instrument has been used only for short campaigns. New calibration methods still have to be developed prior to its operational use.

Solar UV radiation reaching the Earth's surface shows a high degree of temporal and spatial variability. In addition to its dominant solar zenith angle (SZA) dependence, it is also strongly affected by the total ozone column, the aerosol optical depth (AOD) and clouds. Recent comparisons of instantaneous values of cloud cover derivations from satellite images versus ground based derivations (WERKMEISTER et al., 2015) showed limited agreement, especially for broken clouds. Therefore the assessment of differences of cloud cover derived by satellites should be treated with great caution. Because of their more relevant viewing geometry, derivations of cloud cover with ground-based all-sky images are likely to be more reliable at those sites.

For human health it is important to investigate how much UV radiation is available for Vitamin-D3-production and how this varies seasonally and geographically. Here we investigate wintertime differences between two sites with comparable latitudes: Hannover, in northern Germany, and Lauder in southern New Zealand. Former investigations by SECKMEYER et al. (2008b), SECKMEYER and MCKENZIE (1992) and MCKENZIE et al. (2006) focused on hemispheric UV differences in summer. It was found that irradiation (irradiance integrated over time) in the UV wavelength range is up to 50 % higher in the New Zealand summer compared to sites with comparable latitudes in Europe and the US. These differences were mainly attributed to the differences in total ozone, cloudiness, aerosol loading and Sun-Earth separation between the stations. However, un-

til now none of the studies has investigated the winter differences because the focus has been on the negative aspects of UV exposure rather than on the positive aspects, for which winter exposures are more relevant.

2   Data and evaluation method

In this study, differences in solar UV radiation between New Zealand and Germany in winter were analyzed based on quality-controlled spectral irradiance measurements from Hannover (52.39° N, 9.70° E, 52 m.a.s.l.) in Germany and from Lauder (45.04° S, 169.68° E, 370 m.a.s.l.) in New Zealand. A further aim of this work was to quantify the causes of UV differences between these sites in winter. The two stations: Hannover located in the plains of northern Germany and Lauder in the east of the New Zealand Alps, operate spectroradiometers complying with the Network for the Detection of Atmospheric Composition Change (NDACC) standards (MCKENZIE et al., 1997). The meteorological conditions in Hannover are characteristic of a mid-latitude oceanic climate with a relatively high cloud cover during the winter. On the other hand the Lauder site is relatively cloud-free, and pristine. The aerosol optical depth in Lauder is one of the lowest measured worldwide (LILEY and FORGAN, 2009).

Data from the winter (May to September) 2010, 2013, and 2014 in Lauder and the winter (November to March) 2010/11 and 2014/15 in Hannover have been used. Biologically weighted irradiances (erythemal and vitamin D3) were calculated based on the spectral irradiance measurements. The action spectra used to calculate the biologically weighted irradiances are shown in Fig. 1. In addition,clear-sky estimates of vitamin D3-weighted exposure of a human have been calculated us-
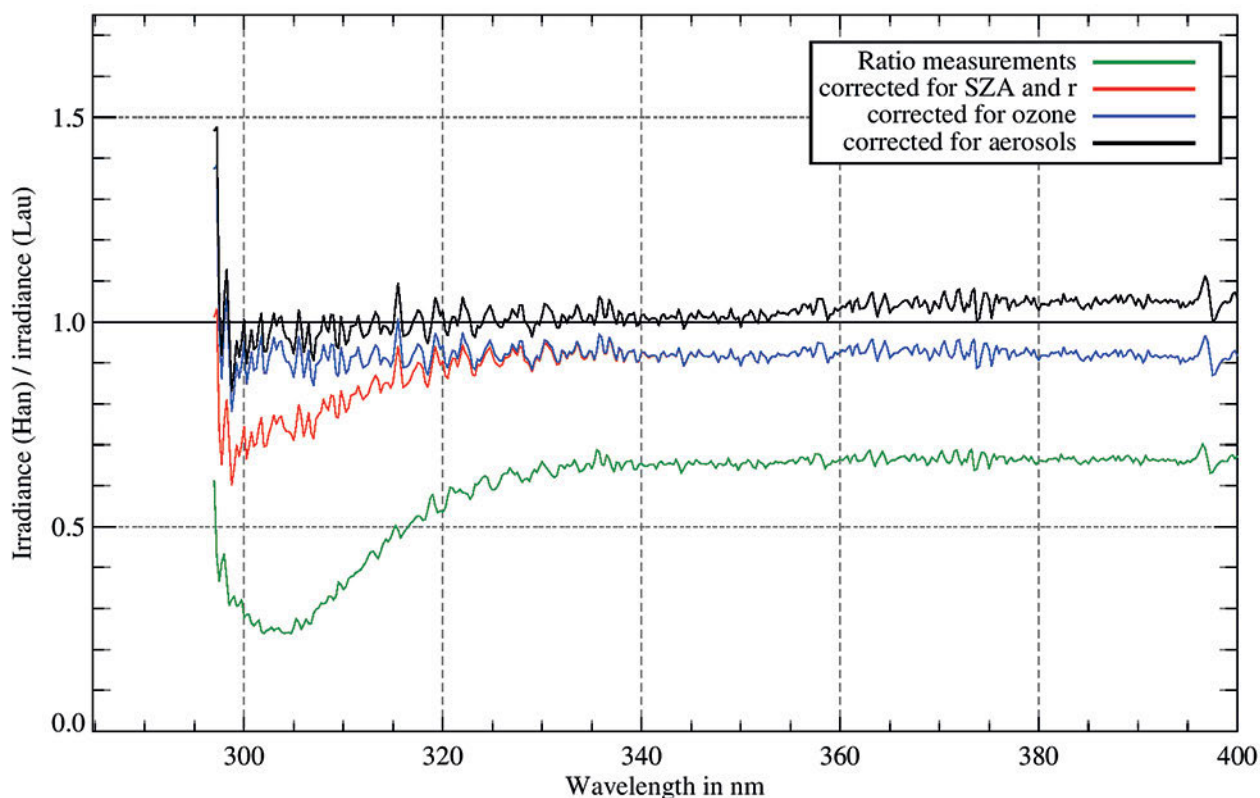
Figure 2: Ratio of clear sky spectral irradiance at 1100 local time (LT) 07 December 2014 in Hannover to 02 June 2014 in Lauder 1113 LT, initially and after different corrections. The difference in latitude is 7°, the difference in total ozone has been 15 DU with 325 DU in Hannover and 310 DU in Lauder. Green: ratio without corrections. Red: corrected for latitude and parameters r (pressure, altitude and difference in Sun-Earth separation). Blue: additionally corrected for ozone. Black: additionally corrected for aerosols. Almost all differences can be explained by these factors.

ing weighted radiance distributions of the sky and the direct beam by means of a 3D human model. The radiance distribution was simulated with the UVSPEC model of the libRadtran package (MAYER and KYLLING, 2005). The geometry of the human form was taken into account by using projected areas (projections) of the 3D-Model of the human. For the exposure calculation in wintertime, the human model cladding covers 93 % of the human body with only face and hands exposed. The weighted exposure is calculated by multiplying the weighted radiance distribution with the projections of the human and by integrating over the upper hemisphere only, as for snow-free condition, any contribution from the lower hemisphere is small. The method is described in detail in SECKMEYER et al. (2013).

To quantify the causes of the differences between the UV spectral irradiance at each station, further calculations with the model UVSPEC (part of the libRadtran package) were performed. The deviation between measurement and UVSPEC model calculation for clear-sky spectra was slightly wavelength dependent, but was in the range of ±10 % for both stations strongly depending on the aerosol parameterization. Clear-sky conditions were chosen for the comparison with a radiative transfer model because of the difficulty of an adequate cloud parameterization in the model. Based on the model cal-

culations, correction functions accounting for the differences in the influencing parameters (SZA, altitude, Sun-Earth separation, total ozone column and aerosols) between the two stations were calculated and applied to the measurements. This method has also been used in SECKMEYER et al. (2008b).

For all simulations, the Atlas-plus-Modtran extraterrestrial spectrum was used (BERNHARD et al., 2004; MAYER and KYLLING, 2005), which is corrected for the Sun-Earth separation by specifying the day of the year. Ozone column amounts for both stations were extracted from the NIWA/BS assimilated total column ozone data base (BODEKER et al., 2001). For the aerosol parametrization at Hannover the default settings by SHETTLE (1989) were slightly modified with the visibility set to 20 km. As an exception, the clear sky spectrum in Fig. 2 was calculated with a visibility of 40 km. Due to the weak influence of aerosols at Lauder, further settings were changed for their parametrization: the visibility was set to 120 km, the type of aerosols was set to maritime and the vertical profile was changed to fall/winter. The single-scattering albedo was set to 0.90, the asymmetry factor to 0.9 and for the Angstrom turbidity parameters alpha and beta, 1.2 and 0.01 were used, respectively. The albedo for the simulations was set to 0.05 for both stations.
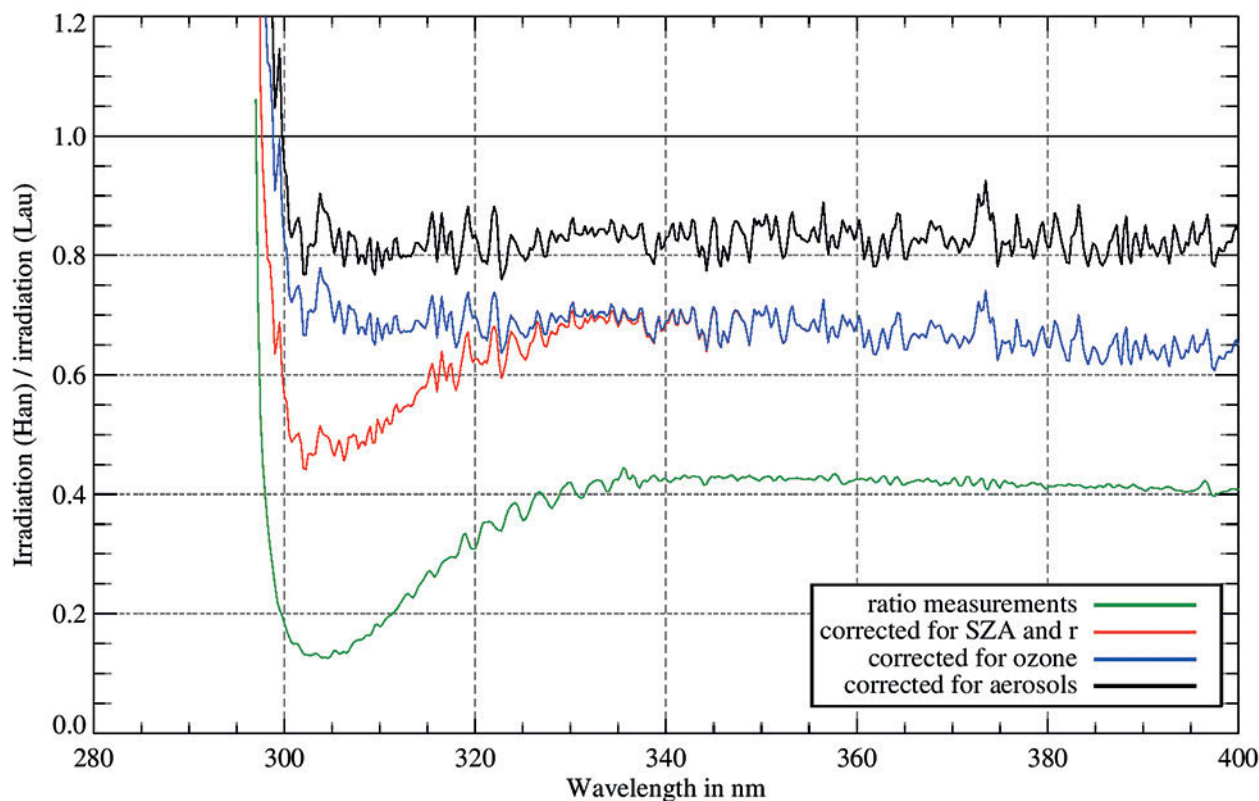
Figure 3: Ratio of the monthly mean daily spectral irradiation – including cloudy conditions – of January 2015 in Hannover and July 2014 in Lauder initially and after different corrections. Green: ratio without corrections. Red: corrected for latitude, pressure, altitude and difference in Sun-Earth separation. Blue: additionally corrected for ozone. Black: additionally corrected for aerosols The black curve is reasonably flat, showing that nearly all spectrally dependent features are well represented; there is, however, a strong gap to unity, which can only be explained by cloud differences.

Potentially snow cover within the vicinity of 50 km has a significant impact on the horizontal UV irradiance (DeGünther et al., 1998) though the effective albedo is lowered significantly by streets, houses and trees (Schwander et al., 1999). However in both Hannover and Lauder there is usually no snow cover and therefore a low albedo. For these sites any snow has little impact on the irradiance for monthly averages. At other sites, for example alpine sites, the situation may be quite different in winter. The impact of snow on the exposure at these sites can be quite significant (Schrempf et al., 2016). However, for Hannover and Lauder snow effects are neglected in this study.

3 Analysis

3.1 Differences of irradiance between Hannover and Lauder

Differences are displayed as ratios between Hannover and Lauder values for clear sky conditions (Fig. 2), and for all sky conditions (Fig. 3).

Practically all of the clear sky differences can be explained by a correction factor containing Sun-Earth separation, latitude, total ozone and differences in aerosols.

This good agreement gives confidence in the conclusion that all relevant parameters are understood to explain all relevant differences for clear skies.

The vitamin D3-weighted monthly mean daily irradiation measured during the winter 2014 in Lauder and 2014/15 in Hannover is shown in Table 1. Large differences between both stations were also found for the monthly mean daily erythemally weighted irradiation (not reported in Table 1), and also after correction for differences in latitude. In winter 2014 the measured daily erythemally weighted irradiation ranges from 300 to 750 Jm^{-2} in Lauder and from 80 to 320 Jm^{-2} in Hannover. The combination of SZA, Sun-Earth separation, and altitude contributes up to 44 % of the difference; ozone contributes up to 6 %; the influence of aerosols is estimated between 0 and 20 %. The contribution from differences in clouds is up to 24 %.

Fig. 4 illustrates that differences in vitamin D3-weighted irradiance between the two stations cannot exclusively be explained by differences in latitude. The figure contains histograms of vitamin D3-weighted irradiance for the same SZA (75°) in Hannover and Lauder with irradiances rounded off to whole numbers. Despite the same solar elevation, there is a distinct deviation between the two sites.

Table 1: Monthly mean of the vitamin D_3-weighted daily radiation doses for Hannover and Lauder. A significant difference between the two sites can be recognized. This large difference can only partly be explained by the difference in solar zenith angle. If all data from Hannover are corrected for the latitudinal difference in SZA the irradiation is still significantly higher in Lauder – an effect of the difference in cloudiness and ozone.

| Monthly means of vitamin D_3 weighted daily irradiation in J/m^2					
	May / Nov	**Jun / Dec**	**Jul / Jan**	**Aug / Feb**	**Sep / Mar**
Lauder 2014	607	281	337	844	1884
Lauder (Mean over 2010, 13, 14)	613	282	358	799	1937
Hannover 2010	166	31	72	298	–
Hannover* 2010	440	107	236	675	–
Hannover 2014	223	48	61	275	920
Hannover* 2014	594	168	197	617	1529
Hannover (Mean)	194	39	66	286	–
Hannover* (Mean)	517	138	216	646	–

*corrected for differences in latitude
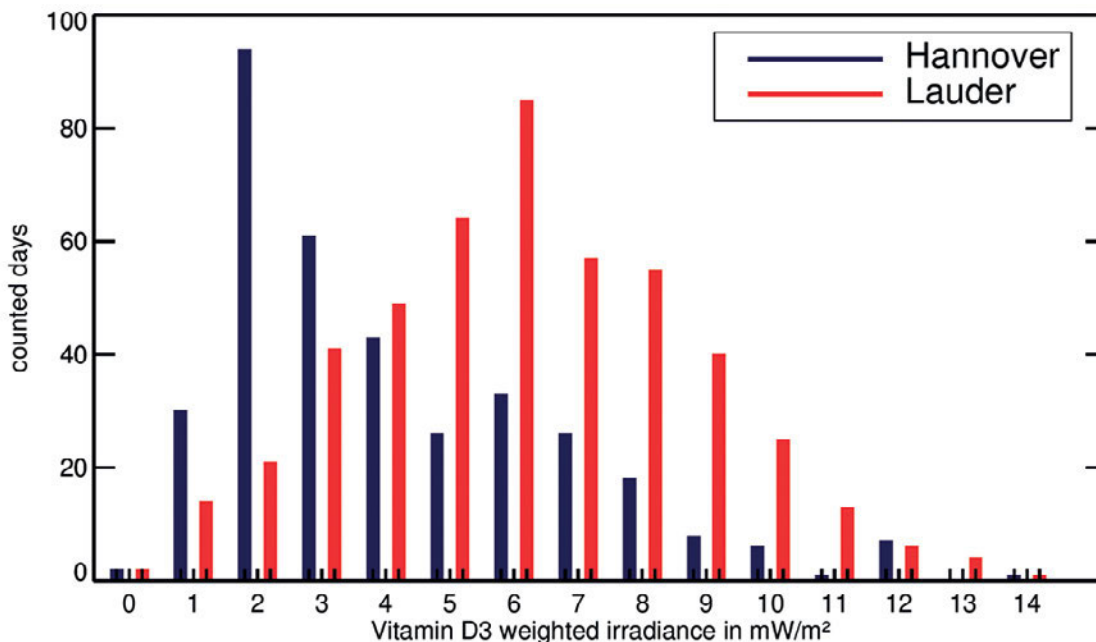
Figure 4: Histogram of vitamin D_3 weighted irradiances measured during the winters 2010/11 and 2014/15 in Hannover (blue) and during winters 2010 and 2014 in Lauder (red) in mW m^{-2}. Only measurements while the SZA was 75±0.5° are represented.

No model, or correction for latitude, is required to recognize that there is a substantial difference – attributed to clouds and possibly aerosols – between the two sites. Ozone differences are relatively unimportant here, since mean ozone amounts were quite similar: 336 DU and 321 DU at Hannover and Lauder, respectively. Assuming a radiation amplification factor (RAF) for vitamin D3-weighted UV of 1.8 (BAIS et al., 2015) only 8 % of the difference in vitamin D3-weighted UV can be attributed to differences in ozone.

3.2 Differences in cloudiness between Hannover and Lauder

Because earlier studies have shown that the differences in UV between Hannover and Lauder are in large part caused by the different cloud amount, cloud modification factors (CMFs) were calculated as the ratio between measurements and clear-sky model calculations with UVSPEC. If the measurements were performed under cloudless sky (and if aerosol and albedos were prop-

Table 2: Cloud modification factors of the vitamin D$_3$-weighted irradiation in Hannover and Lauder. CMFs are calculated by dividing the measured monthly average daily dose by the calculated daily dose for clear skies. While the CMF in May/November and March/September are nearly identical for both stations, in June/December there is a strong difference. Erythemally weighted CMFs are found to be within 0.01 of these values.

CMFs of the vitamin D$_3$-weighted irradiation					
S.H. / N.H.	**May / Nov**	**Jun / Dec**	**Jul / Jan**	**Aug / Feb**	**Sep / Mar**
Lauder 2014	0.74	0.70	0.79	0.80	0.80
Hannover 2014/15	0.77	0.51	0.64	0.73	0.74
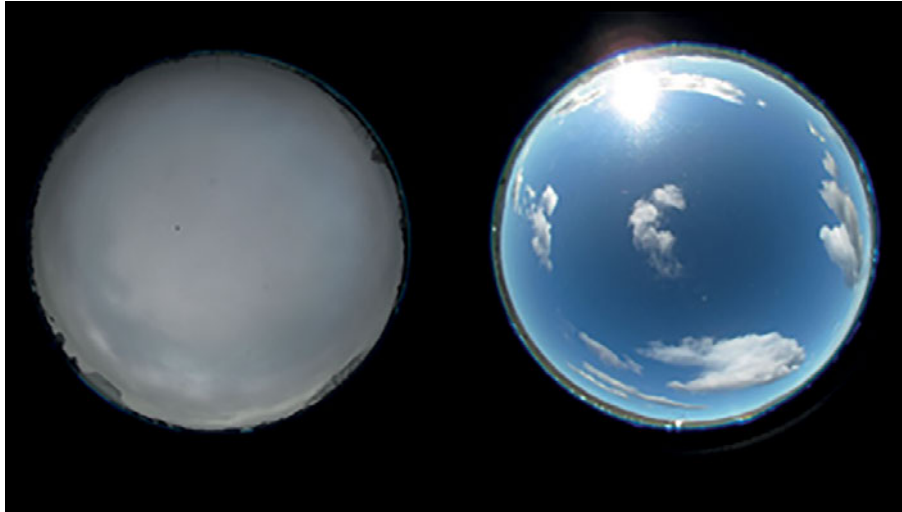
Figure 5: Left panel: Cloud image taken with HSI at 1304 LT on 25 January 2015 in Hannover, Germany. Right panel: Cloud image with identical HSI taken at 1204 LT on 2 July 2015 in Lauder, New Zealand. The CMFs calculated for the situations shown here are about 0.84 for Lauder and 0.69 for Hannover and therefore close to the mean biologically weighted CMFs for July and January, respectively. While the blue sky is visible in New Zealand, the grey sky is typical for central and northern Europe in winter.

erly characterized in the model) then the CMF should be unity. Table 2 shows the CMFs of vitamin D3-weighted irradiation for both stations. It is obvious that the biologically weighted irradiation (dose) are more strongly attenuated by clouds in Hannover than in Lauder. Large differences in the attenuation exist for June/December and July/January, resulting in strong deviations in the measured irradiation of the stations for these months. Moreover, a stronger variation of the CMFs throughout the winter months is apparent at Hannover. The CMFs at Lauder are, with minimum 0.7, similar to the CMFs that were calculated for the summer months by Seckmeyer et al. (2008b). The cloud-induced attenuation in Hannover is up to 50 % with a minimum CMF of 0.5.

The difference in cloudiness between Lauder, and Hannover, is quite striking, especially in winter. Two typical examples are shown in Fig. 5. In each case, the CMF is close to the mean for each site (actually 0.05 greater than the mean). We consider these samples typical because nearly clear skies often occur at Lauder in winter, e.g. in 2015 between May and August on 45 days out of 119 days (4 days the Hemispherical Sky Imager (HSI) was not working) it was cloudless sky at noon and on many other days cloud covered only a small fraction of the sky. In Hannover, there were only 3 days with nearly cloudless sky in winter 2014/15.

3.3 Differences in vitamin D3-weighted exposure between Hannover and Lauder

Since there are no measurements of the radiance available in winter for either Hannover or Lauder, typical radiance spectra were simulated with the UVSPEC model to calculate the vitamin D3-weighted exposure. The direct irradiance is assumed to be negligible compared to the diffuse irradiance (as justified in Seckmeyer et al. (2013) and it is assumed that alto- and stratocumulus clouds are a sufficient description of the actual clouds during the measurements in December in Hannover. We multiplied the radiance of each direction with the ratio of the measured irradiance and the integrated radiance over the upper hemisphere. In the absence of operational radiance measurements, the spatial distribution (spectral radiance) is assumed to be equal at both sites. This assumption does not fully reflect reality, e.g. because the direct beam component is more prevalent in Lauder than in Hannover. However, as noted above, in winter the direct beam may be neglected. In Seckmeyer et al. (2013) it has been shown that the direct beam contributes only 20 % to the exposure under high sun elevation, and is much smaller for lower sun. The proportion of direct beam are larger at Lauder, reaching 50 % of
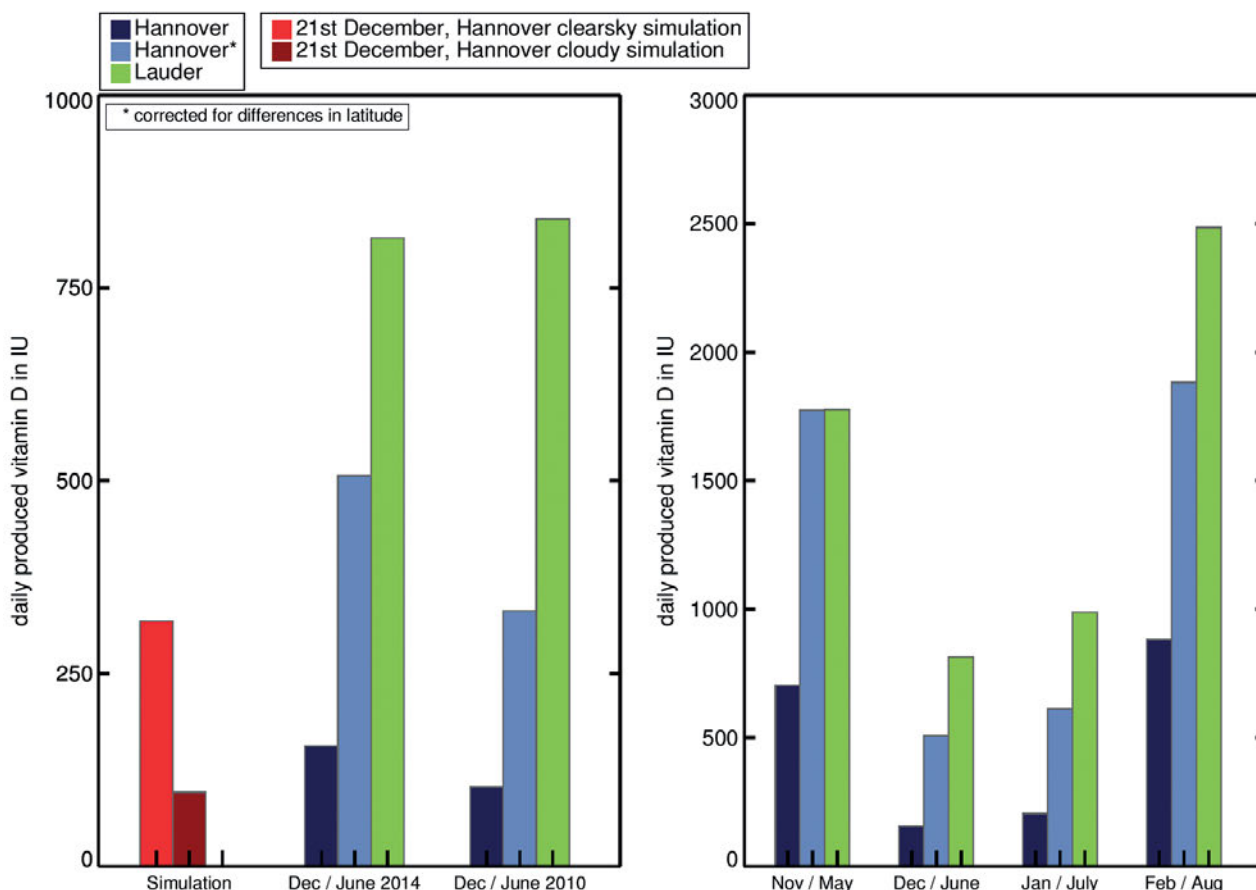
Figure 6: Monthly means of simulated daily vitamin D_3-weighted exposure in International Units for a human wearing winter clothing for December in Hannover and June in Lauder (left Figure) and for all four winter months in the winter 2014 in Lauder and 2014/15 in Hannover (right Figure). Values for Hannover (dark blue), Hannover shifted to 45° S (light blue) and Lauder (green) are shown in the Figure. Additionally, simulations of the daily exposure for the 21st December, the shortest day, in Hannover are shown for a clear-sky case (red) and a typical cloudy condition (dark red).

the irradiance for high sun, but is still relatively small in winter.

With these assumptions the exposure for a human in vertical posture with winter clothing, which covers 93 % of the human body, and exposes only the face and hands to the sun is found to be up to a factor of 7 lower in Hannover, Germany (52° N) in the winter months compared to vitamin D3-weighted UV levels in the winter in Lauder, New Zealand (45° S). When corrected for the influence of solar zenith angle the vitamin D3 weighted exposure is a factor of 2 higher in the southern hemisphere at the same corresponding latitude. The major difference can be attributed to differences in cloudiness and to a lesser extent (about 2 %) to total ozone. An unclothed human would receive about a factor of 18 more vitamin D3-weighted exposure than for this assumed clothing, but the relative proportions, as shown in Fig. 6, remain the same for the winter case.

For Hannover the monthly mean of produced vitamin D stays below the threshold of the suggested 1000 IU for all available winter months while for Lauder this is only the case in the months June and July.

3.4 Spatial and temporal representativeness

For both stations the representativeness of UV irradiance for other years and the representativeness of the stations for larger areas have been analyzed, to determine whether the observed differences in UV between the two stations indicate that they can be regarded as typical for differences between Central Europe and New Zealand in winter.

Mean monthly CMFs for different stations in New Zealand and Europe are presented in Fig. 7, which shows the mean over the months May to August and November to February for New Zealand stations and European stations, respectively, and over all available years since 2000. The CMFs of the New Zealand sites are extracted from the NIWA UV Atlas (BODEKER and MCKENZIE, 1996; BODEKER et al., 2006). While Lauder is one of the driest places in New Zealand, Fig. 7 shows that the cloud impact on solar UV irradiance in Lauder in winter can be regarded as representative for New Zealand.
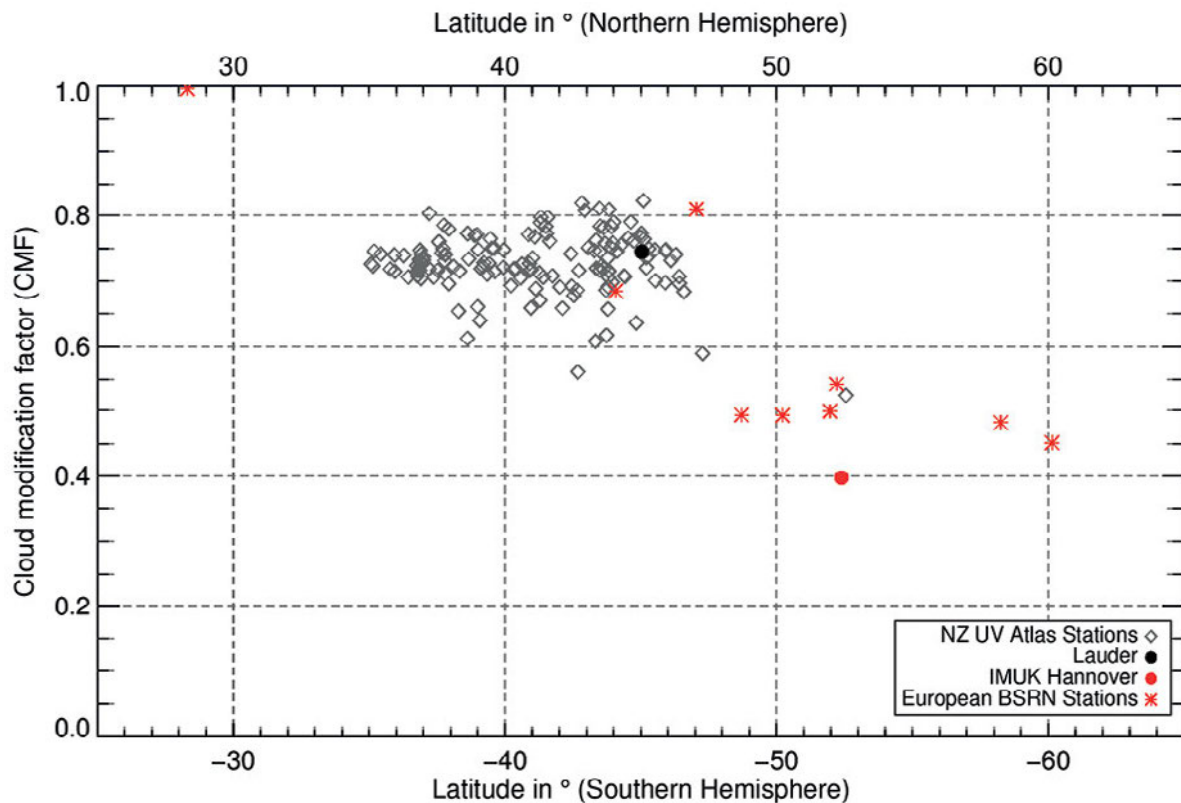
Figure 7: Mean cloud modification factors for all stations of the NIWA UV Atlas (Grey) and for all European sites from the BSRN (red). Displayed is the mean over all winter months (May to August and November to February for New Zealand and Europe, respectively) over all available years since 2000. The data for Hannover (denoted by a red circle) is extracted from the pyranometer at the IMUK in Hannover. Lauder (denoted by a black circle) is representative for New Zealand while the CMF in Hannover is lower than that of the other European stations.

The monthly mean CMFs for the European stations were calculated from pyranometer measurements extracted from the Baseline Surface Radiation Network (BSRN) archive at the World Radiation Monitoring Center (WRMC) (Behrens et al., 2017), and from simulations of the global irradiance. For the calculations of clear-sky irradiance a modified equation from Bourges (1979) was used, verified for CMF calculations using BSRN data in Hofmann et al. (2014). The extraterrestrial spectrum was calculated with the approach of Duffie and Beckman (2013).

Fig. 8 shows the monthly mean CMFs in Hannover from the winters 2003/04 to 2014/15. They were calculated in the same manner as the European CMFs in Fig. 7 using pyranometer measurements from IMUK in Hannover. The mean CMF over the years 2003–2015 is also shown in Table 3. While the CMFs of the winter 2010 are within the standard deviation of the calculated mean, the CMFs for December 2014 and February 2015 are lower and higher than the mean, respectively.

In order to investigate the representativeness of Hannover for other stations in Europe the measurements were compared with data from different stations of the European Database for UV Climatology and Evaluation (EDUCE).

A comparison between Hannover and the selected stations concerning the vitamin D3-weighted irradiation is presented in Fig. 9. The data have been corrected for differences in latitude. The values for each station were chosen to be representative for other years. Because of a higher cloud amount, Hannover shows a stronger attenuation of UV radiation compared to the majority of the other European stations. The UV levels of December and January are at the lower end compared to these stations. Nevertheless, further investigations have shown that they are typical for other years in Hannover. These results are in good agreement with former analysis of EDUCE data. Kazantzidis et al. (2009) have shown that for Bilthoven, the daily dose of vitamin D effective irradiance from November to February is not high enough to produce the daily requirement for vitamin D sufficiency.

4   Summary and conclusions

Differences of vitamin D3-weighted irradiation and vitamin D3-weighted exposure in winter were analyzed based on measurements of solar spectral UV irradiance for two winters in Hannover and for several years
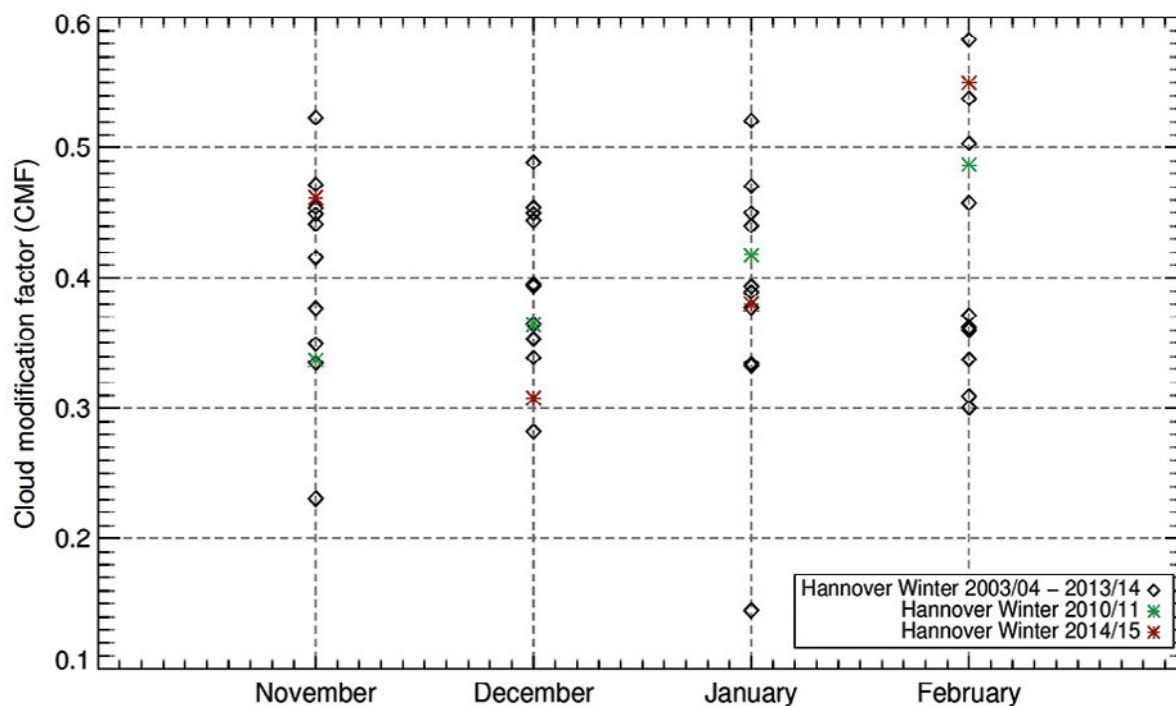
Figure 8: Monthly mean CMF derived from pyranometer measurements at Hannover from the winters 2003/04 to 2014/15. While the CMF in the winter 2010/11 (marked in green) can be regarded normal, the CMF in December 2014 (marked in red) is one of the most cloudy and the February 2015 one of the least cloudy months. The data were measured with the CMP11 pyranometer at the IMUK in Hannover.

Table 3: Mean CMF for Hannover over the winters of the years 2003–2015 is shown with the resulting standard deviation. Together with the mean value the CMFs for the winters 2010/11 and 2014/15 are shown.

Mean CMF for Hannover over the years 2003–2015				
	November	**December**	**January**	**February**
Mean CMF	0.404 (±0.08)	0.386 (±0.06)	0.388 (±0.09)	0.43 (±0.1)
Hannover 2010/11	0.337	0.364	0.418	0.487
Hannover 2014/15	0.462	0.308	0.38	0.55

in Lauder. The comparison between stations showed large differences that could not be explained by the solar zenith angle differences only. While the exact value of the difference remains uncertain due to the limited data available to date, it is evident that the large differences between stations can mainly be attributed to a higher cloud impact in Hannover, especially in December and January with cloud-induced attenuation of average UV by up to 50 % compared to 25 % in Lauder. The CMFs calculated from spectral measurements are in accordance with cloud cover derived from hemispherical sky imager observations at both stations as well as with long-term pyranometric measurements of total irradiance. Other influencing parameters are the differences in total ozone column and atmospheric aerosols with Lauder having one of the lowest mean aerosol optical depths worldwide.

An analysis of the representativeness of the stations for larger areas and the considered winters for other years illustrated that Lauder is adequately representative for New Zealand. The UV levels in Hannover are at the lower end compared to other European stations after the correction for differences in latitude.

The findings suggest somewhat different advice for the people in winter in New Zealand than in Europe. While at both sites there is ample UV radiation available in summer a for vitamin D sufficiency, in practical terms there is insufficient UV at both sites, but most particularly the winter in Northern Germany does not provide enough UV radiation being able to produce sufficient vitamin D. One major factor is the presence of clouds, the other is the low sun as a result of the higher latitudes of Europe. In New Zealand and probably in southern Europe the opportunity to gain enough Vitamin D in winter are much better due to its proximity to the equator and due to the lack of overcast or cloudy skies. However, with typical winter clothing even the much higher UV at 45° S does not provide enough vitamin D at winter solstice, even if the exposure is extended to all daylight hours and no shading of trees or buildings occurs.
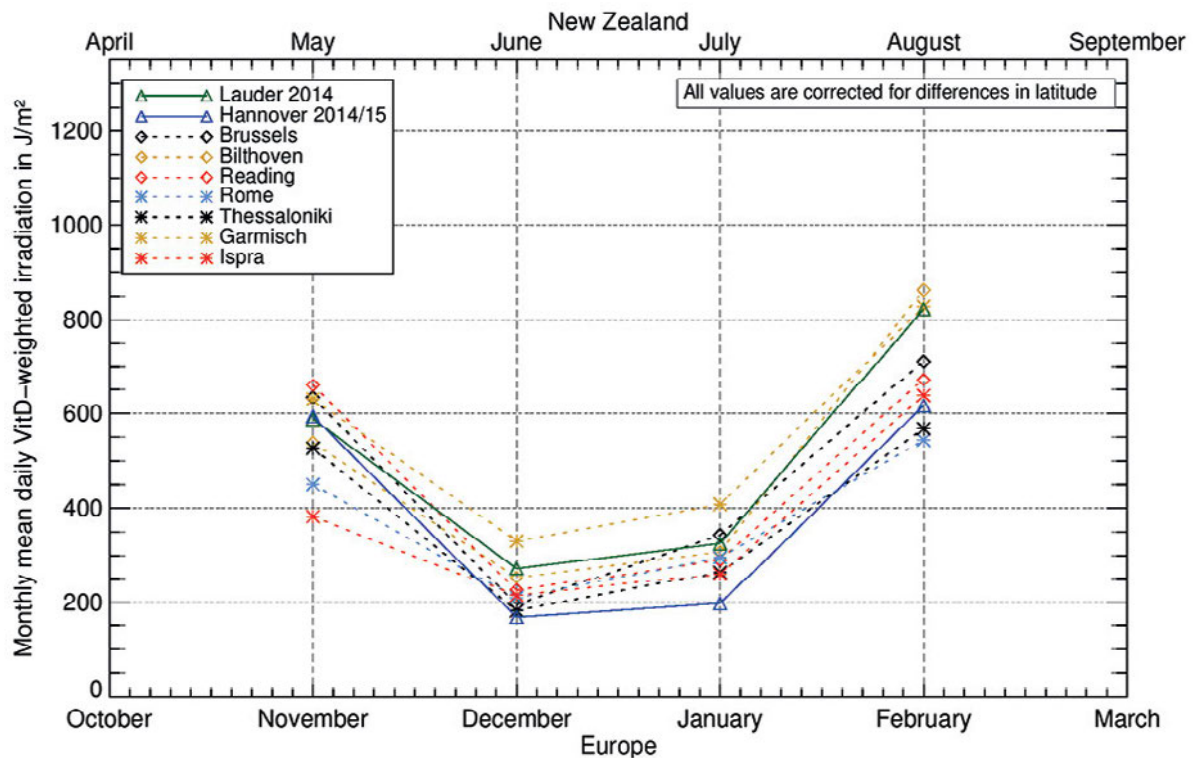
Figure 9: Monthly mean daily vitamin D$_3$-weighted irradiation for different stations in Europe and Lauder corrected for differences in latitude. The values for each station were chosen to be representative for other years. Hannover shows a stronger attenuation of solar UV radiation compared to the majority of the other stations in Europe, which can be attributed to a higher cloud amount. The UV levels of December and January in Hannover are at the lower end compared to stations in Europe.

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