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Estimated ultraviolet exposure levels for a sufficient vitamin D status in North America

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ABSTRACT

Solar UV radiation is a major provider of vitamin D for humans. This study examines the distribution of solar UV radiation weighted according to the vitamin D action spectrum over the USA and Canada. Hourly and daily doses of spectrally integrated UV irradiance using the vitamin D action spectrum were estimated using a statistical relationship between UV irradiance and global solar irradiance, total ozone, and dew point temperature for 45 sites in Canada and 52 in the USA. Brewer spectrophotometer measurements at 12 sites in Canada and 21 sites in the USA were used to validate the obtained results. Different characteristics of the vitamin D action spectrum-weighted UV irradiance distribution over North America are presented in the form of monthly maps and as a data file. The time required to obtain standard vitamin D dose is also calculated for six types of skin.

1. Introduction

Solar ultraviolet (UV) radiation is the main natural source of vitamin D, which is essential for human well-being. It is important for bone and musculoskeletal health, and has more recently been suggested to possibly reduce the risk of a number of cancers and other medical conditions and to improve prognosis following a cancer diagnosis [1–5]. However, overexposure to solar radiation is responsible for the majority of cases of skin cancer [6], as well as other negative health effects such as sunburn, skin aging, immunosuppression, and some forms of eye cataracts [7]. Therefore, it is important to know if a given UV dose is sufficient to produce the required amount of vitamin D. Information about UV doses can be further used to estimate the amount of sun exposure that represents a balance between minimizing negative health effects and maintaining sufficient vitamin D production [8–12].

Vitamin D production in the human body depends on a number of factors. The first group of factors is related to geophysical parameters (solar zenith angle, total ozone amount, surface albedo, etc.) that determine the amount of ambient UV radiation. Other factors determine how the human body transforms UV radiation into vitamin D. These factors include the percentage of the body exposed to UV, time in the sun, skin type, age, weight, etc., as well as genetic factors. The parameters from the first group can be estimated rather accurately, while there is a large uncertainty in estimates of the other factors.

Vitamin D is produced as a result of multiple reactions, each with a different action spectrum, but all within the UV range of wavelengths [13]. The effect of UV on vitamin D production is expressed here in terms of a single action spectrum [14] that represents the production of vitamin D in human skin. If the amount of ambient UV radiation as a function of the wavelength and the vitamin D action spectrum are known, vitamin D action spectrum-weighted UV (we will refer to it as "vitamin D weighted UV") can be calculated and used for vitamin D production estimates. Based on long-term record of measurements (or estimates) of UV irradiance at a given location, mean daily and hourly doses of vitamin D weighted UV can be calculated for each day of the year at that location. We will refer to these mean doses as "climatological" UV doses by analogy with, for example, climatological temperatures and we will use the term "climatology" to refer to a distribution of climatological UV doses over a certain region. Furthermore, if the sufficient amount of vitamin D, referred to as standard vitamin D dose (SDD), is known, the time required to achieve 1 SDD can be calculated.

There are several ways to estimate a vitamin D action spectrum-weighted UV climatology. Firstly, it can be calculated from spectral UV measurements at the ground by spectrophotometers. (e.g., [15–18]), There were 12 Canadian and 21 US sites, equipped with Brewer spectrophotometers, with spectral UV irradiance measurement records of several years and longer. While these measurements are very valuable for validation of UV climatology,

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their number is not sufficient to produce such climatology for the entire territory of the US and Canada.

Secondly, UV climatology can be estimated from radiative transfer calculations that use climatology or actual measurements of ozone, clouds, and other characteristics of the atmosphere measured by satellites as input parameters (e.g., [19,20]). This approach has been used to estimate global vitamin D weighted UV climatology recently [21]. There are however two principal problems with these estimates. It has been found that the most commonly used UV estimates based on total ozone mapping spectrometer (TOMS) ozone and cloud reflectivity measurements produce systematically higher UV irradiance values (typically 10–15%, with extremes ranging from 0% to 60%) than are measured at the ground for snow-free conditions. These biases are likely due to absorption by aerosols in the boundary layer [22–25]. In addition, present satellite algorithms underestimate UV, in some cases by as much as 60%, in the presence of snow at the ground [26–28]. This is particularly important during the winter–spring at high latitudes when vitamin D synthesis from solar UV is low.

Thirdly, climatology of spectral UV-B irradiance can also be constructed from long-term records of other geophysical parameters, primarily total ozone and cloud cover. Ground-based and satellite total ozone measurements are the sources of ozone data. Global shortwave solar radiation measured by pyranometers can also be used as a parameter for estimating the UV attenuation not due to ozone, and UV irradiance can be derived from global solar radiation (i.e., radiation integrated over the entire solar spectrum from about 300 to 3000 nm) and total ozone data [29,30]. Solar radiation measurements have been used to reconstruct climatology and to estimate long-term changes in surface UV over Canada [31,32], New Zealand [33], and Europe [34,35]. The presence of aerosols with strong absorption in the UV part of the spectrum, as for example, from forest fires, causes overestimation in the UV derived from pyranometer data. However, cases of large loadings of these aerosols are relatively rare and are, in general, of short duration [36]. Under "typical" conditions, aerosol effects can be taken into account by establishing an empirical relationship between UV and global solar radiation measurements [36].

Fig. 1 gives examples of different estimates on daily doses (in J m^{-2}) of vitamin D weighted UV in April over the US and Canada. Fig. 1a shows mean daily doses of vitamin D weighted UV from spectral UV measurements in the 1990s and early 2000s by Brewer spectrophotometers located in the US and Canada. Recent satellite observation-based estimates [21] are shown in Fig. 1b. These estimates are based on Nimbus 7 TOMS data for the period 1979–2000. Fig. 1c demonstrates results of the third method where UV irradiance is estimated from global solar radiation, column ozone and other geophysical parameters and then integrated through a day to get a daily dose. While Fig. 1a and c shows similar latitudinal distribution of UV, there are considerable differences at high latitudes due to the UV enhancement by snow. Actual observations (1b) suggest that the satellite algorithm substantially underestimates UV there. For example, satellite-based estimates of daily doses for Churchill, Manitoba (Canada) (59°N), are about 800 J m^{-2}, while these actual measurements by the Brewer spectrophotometer located in Churchill give a value of about 2800 J m^{-2} there. The global solar radiation-based estimates agree well with the actual Brewer measurements.

In this study, we present a gridded dataset of hourly vitamin D action spectrum-weighted UV climatology for the US and Canada. It is based on UV irradiance derived from global solar radiation, total ozone, dew point temperature and snow cover (the third method, Fig. 1c). The approach used in the study was previously developed for erythemal UV [27,32], and modified here for vitamin D action spectrum UV. The dataset also includes estimates of time required to achieve 1 SDD for different types of human skin based on the UV climatology using methodology described in [11].

2. Methods

One of the most commonly used UV action spectra is that for UV-induced erythema (sunburn). It is also used in the UV index definition: the UV index is non-dimensional, obtained by dividing the erythemal action spectrum-weighted irradiance by 25 mW m^{-2}. While the erythemal and vitamin D action spectra are different, the approach previously developed for estimating the UV index climatology [27,32] was used here. First, UV-A irradiance at 324 nm (E_{324}) (where ozone absorption is negligible) was derived from global solar radiation, dew point temperature, and solar zenith angle at all pyranometer sites using a parameterization [36]. Then, spectrally-weighted UV irradiance was derived from calculated E_{324}, total ozone, and solar zenith angle using a second parameterization. Finally, UV enhancement caused by snow and latitude was accounted for by an additional correction.

The details of the method and the parameterizations used for erythemal UV have been described in [31,36]. The only difference

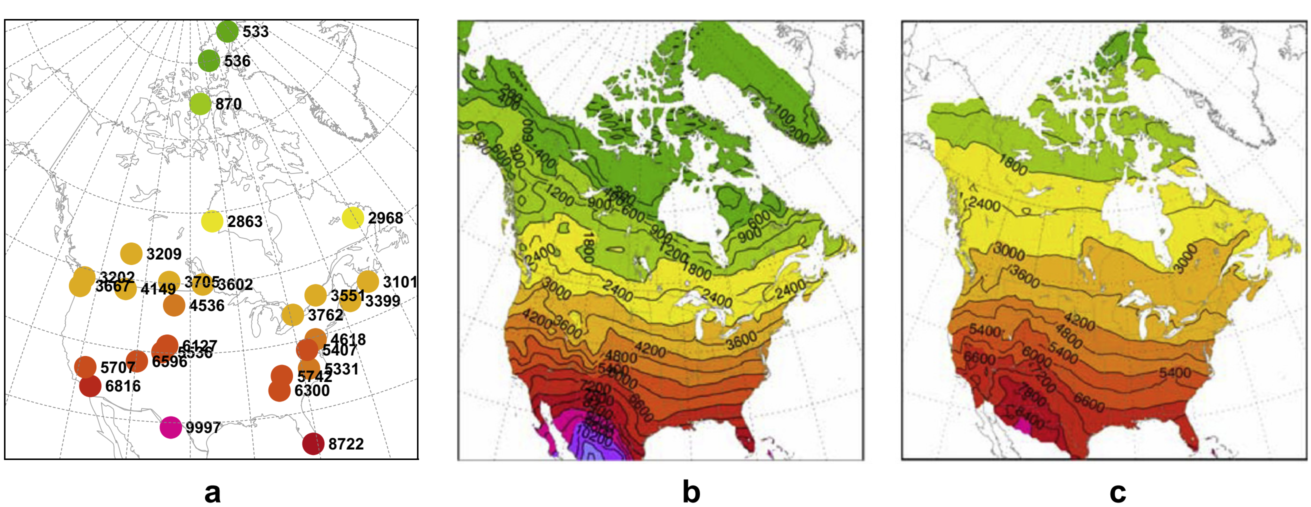

Fig. 1. Daily integrated doses of vitamin D weighted UV (in J m^{-2}) for April from (a) Brewer spectral UV measurements, (b) TOMS satellite estimates [21], and (c) global solar radiation and total ozone observations.

Table 1
General characteristics of skin types [40], Minimal Erythemal Dose (MED, J m^{-2}), and skin type-based adjustment factor (that represents 1 MED Relative to that for skin type II) for the time on the sun estimates for the skin type II (Figs. 7 and 8).

Skin type	Color	Reaction to sun	1 MED	Adjustment factor
I	Caucasian, blonde or red hair, freckles, fair skin, blue eyes	Always burns easily, never tans; very fair skin tone	200	0.8
II	Caucasian, blonde or red hair, freckles, fair skin, blue eyes or green eyes	Usually burns easily, tans with difficulty; fair skin tone	250	1.0
III	Darker Caucasian, light Asian	Burns moderately, tans gradually; fair to medium skin tone	300	1.2
IV	Mediterranean, Asian, Hispanic	Rarely burns, always tans well; medium skin tone	450	1.8
V	Middle Eastern, Latin, light-skinned black, Indian	Very rarely burns, tans very easily; olive or dark skin tone	600	2.4
VI	Dark-skinned black	Never burns, deeply pigmented; very dark skin tone	1000	4.0

between UV index estimates and vitamin D weighted UV estimates is in the parameterization for vitamin D used to calculate UV from UV-A (at 324 nm), column ozone and the solar zenith angle. Similarly to [32], the parameterization was established empirically using a large volume (about 2,000,000) of spectral UV measurements obtained from the US and Canadian Brewer networks be-

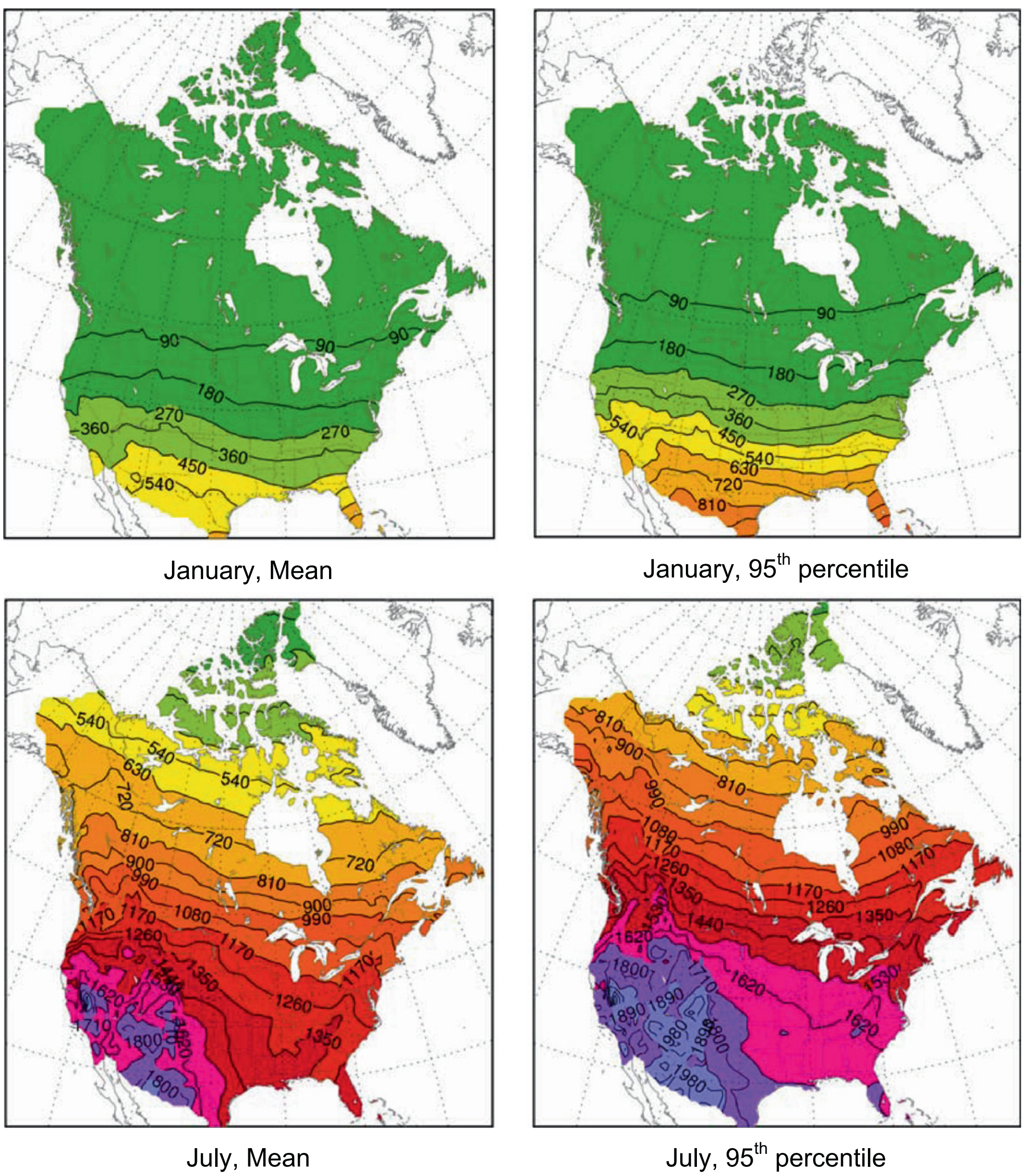

Fig. 2. Monthly mean (left) and 95th percentile (right) vitamin D action spectrum-weighted UV hourly doses for the 12:00–12:59 local solar time interval in J m^{-2}. Maps for January (top) and July (bottom) are shown.

tween 1990 and 2002. The network Brewer instruments performed several spectral measurements per hour for the entire day from sunrise to sunset throughout the year and therefore the available dataset covers a very wide range of atmospheric conditions.

The solar radiation data, which is available as hourly (solar time) integrated global solar radiation determines the temporal resolution of the derived UV data presented in this study. Hourly values of vitamin D weighted UV were calculated for 97 pyranometer sites and then interpolated to a 1° by 1° grid. A detailed description of the interpolation algorithm was given in [27,36].

The vitamin D action spectrum used in this study is the one published by the CIE [37]. The CIE action spectrum is based on [14], but extended from 315 nm to 330 nm using exponential decay function extrapolation and normalized to set its value at 300 nm to 1. As was shown by [17], such an extension (compared to the version where it was truncated at 315 nm) has a relatively small (∼5%) effect on vitamin D action spectrum-weighted UV doses.

If hourly doses of vitamin D weighted UV are known, the time required to obtain 1 SDD from UV on unprotected skin can be calculated as a function of the skin sensitivity to UV. Skin color is likely a result of human evolution that made it possible for people to produce sufficient vitamin D at higher latitudes [38]. While light skin reflects more light (i.e., absorbs less) than dark skin in the visible part of the spectrum, the situation is opposite in the UV-B part of the spectrum, where reflectivity of white skin is lower than that for the black skin [39]. Fitzpatrick [40] classified skin into six types based on sensitivity to erythemal UV radiation. These types are described in Table 1. Assuming that the effect of vitamin D weighted UV is attenuated to the same extent by skin type as that for erythemal UV, the time required to obtain 1 SDD can be estimated for different types of skin.

Following the approach used in [11], we defined SDD as a dose that corresponds to the UV equivalent of an oral dose of about 1000 IU vitamin D. The dose estimates in [11] are based on the original study by Holick [41,42], which recommends exposure to ¼ of personal minimal erythemal dose (MED) on ¼ skin area (hands, face and arms) to achieve 1 SDD. In order to estimate 1 SDD, we need to convert ¼ of MED into vitamin D weighted UV dose. As discussed in [18], the ratio between vitamin D and erythemal UV is

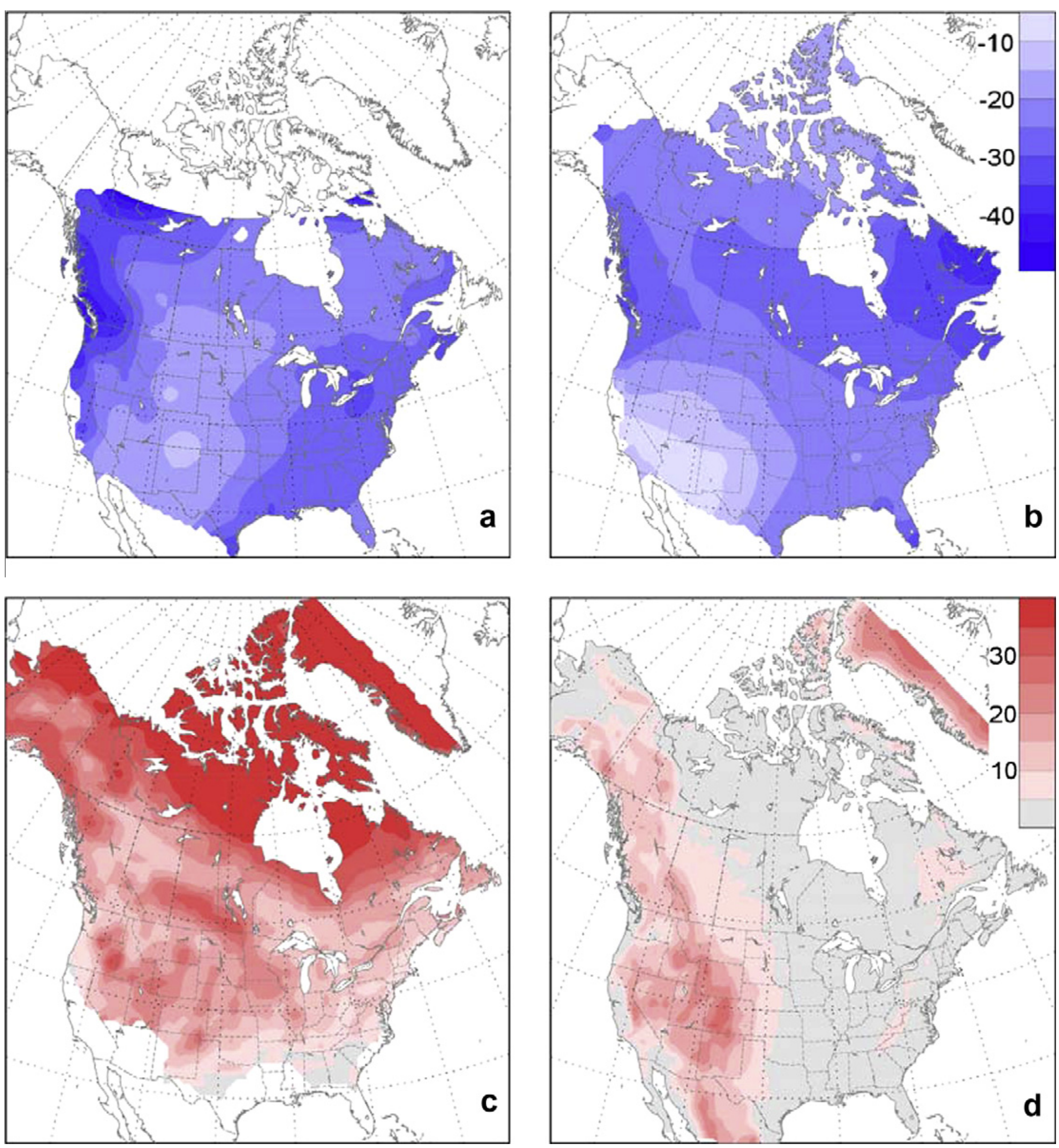

Fig. 3. The monthly mean UV reduction due to clouds in percent for January (a) and July (b). The cloud reduction estimates were done by comparing calculated UV hourly doses for the 12:00–12:59 local solar time to those calculated for clear sky conditions (see text for details). The UV enhancement due to snow albedo (c) and altitude (d) in percent.

between 1.5 and 2 (if CIE-recommended action spectra used) except for very low levels of erythemal UV (UV index less than 3). For the sake of consistency, we used the same reference conditions as in [11], i.e. mid-March in Boston, to convert MED into vitamin D UV dose. Based on our UV climatology estimates, the mean noon UV irradiance for Boston (42°N) in March is 110 mW m^{-2} for the vitamin D action spectrum and 65 mW m^{-2} for erythemal action spectrum [27] with the ratio between the two values of about 1.7. For type II skin, 1 MED = 250 J m^{-2}, i.e. it corresponds to 250 J m^{-2} × 1.7 = 423 J m^{-2} of vitamin D weighted UV, ¼ of this amount is 106 J m^{-2}.

The SDD value of 106 J m^{-2} for type II skin reported here is different from that used in [11]. While the study [11] used essentially the same action spectrum, the weighting coefficients for the vitamin D production action spectrum are on a different scale resulting in a different scale for vitamin D weighted UV. If the same scale were used in [11], the estimated SDD value would be about 106 J m^{-2} for type II skin (Ola Engelsen, personal communication, 2008).

Estimated vitamin D weighted UV hourly (solar time) doses were available at a 1° by 1° grid for the period 1980–1990. Then for every hour of a day and every grid cell, the monthly mean value was calculated by averaging all data for that hour and that month from all years. Similarly, the 95th percentile was calculated to demonstrate how high vitamin D values can be for 5% of all days. The results for 12:00–12:59 pm solar time are shown in Fig. 2 for January and July.

3. Results

The maps for vitamin D action spectrum-weighted UV exhibit the same features as was previously reported for the UV index climatology maps [27]. While latitude is one of the key factors affect-

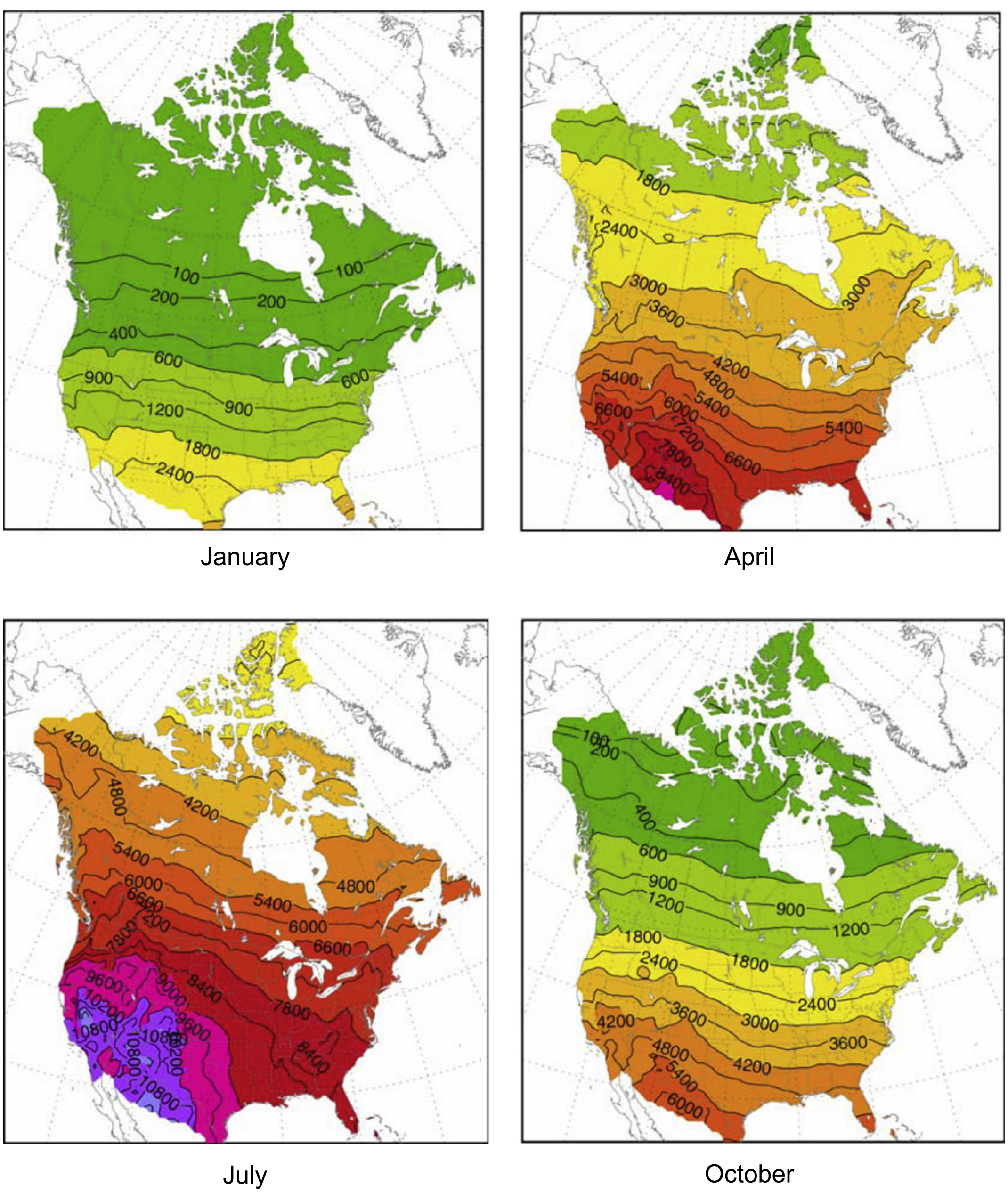

Fig. 4. Mean daily integrated UV (vitamin D action spectrum) in J m^{-2}. Maps for January, April, July, and October are shown.

ing the UV distribution, it is not the only one. Summertime vitamin D weighted UV over the US has longitudinal differences related to the cloud cover and elevation that are as large as latitudinal differences. In July, UV values over Arizona and New Mexico are about 25% higher than values over Georgia located at the same latitudes and Georgia UV values are close to those over Oregon or Idaho. There are no large longitudinal differences in winter. For Canada, there is also some difference between the eastern and western regions due to the difference in the cloud cover.

The effect of clouds on UV is further illustrated by Fig. 3 that shows the UV reduction by the clouds (compared to the clear sky condition) for monthly mean UV doses for January (a) and July (b). The UV reduction by the clouds was calculated by comparing the estimated UV-A irradiance at 324 nm values (see Section 2) with the values calculated by a radiative transfer model for clear sky, no aerosol conditions [23]. The impact of snow and altitude, on UV is also illustrated in Fig. 3. The maps of UV enhancement by snow and altitude are adapted from [27] and repeated here for readers' convenience. While these maps were produced for erythemal UV, the maps for vitamin D weighted UV should be nearly the same. Although vitamin D and erythemal action spectra are different, factors responsible for UV enhancement by snow and altitude have a weak dependence on the wavelength (e.g., [43]). Only the UV increase caused by the reduction of the ozone column with altitude has a strong wavelength dependence, but even that effect is relatively small ([43], their Fig. 7) since only a small fraction of total ozone is located in the troposphere.

Daily doses of vitamin D UV were then calculated by integrating hourly values over the entire day. The maps of mean daily values for various months are shown in Fig. 4. The main features of daily doses are similar to those for the noon values. They also show substantial longitudinal differences in summer and nearly zonal struc-

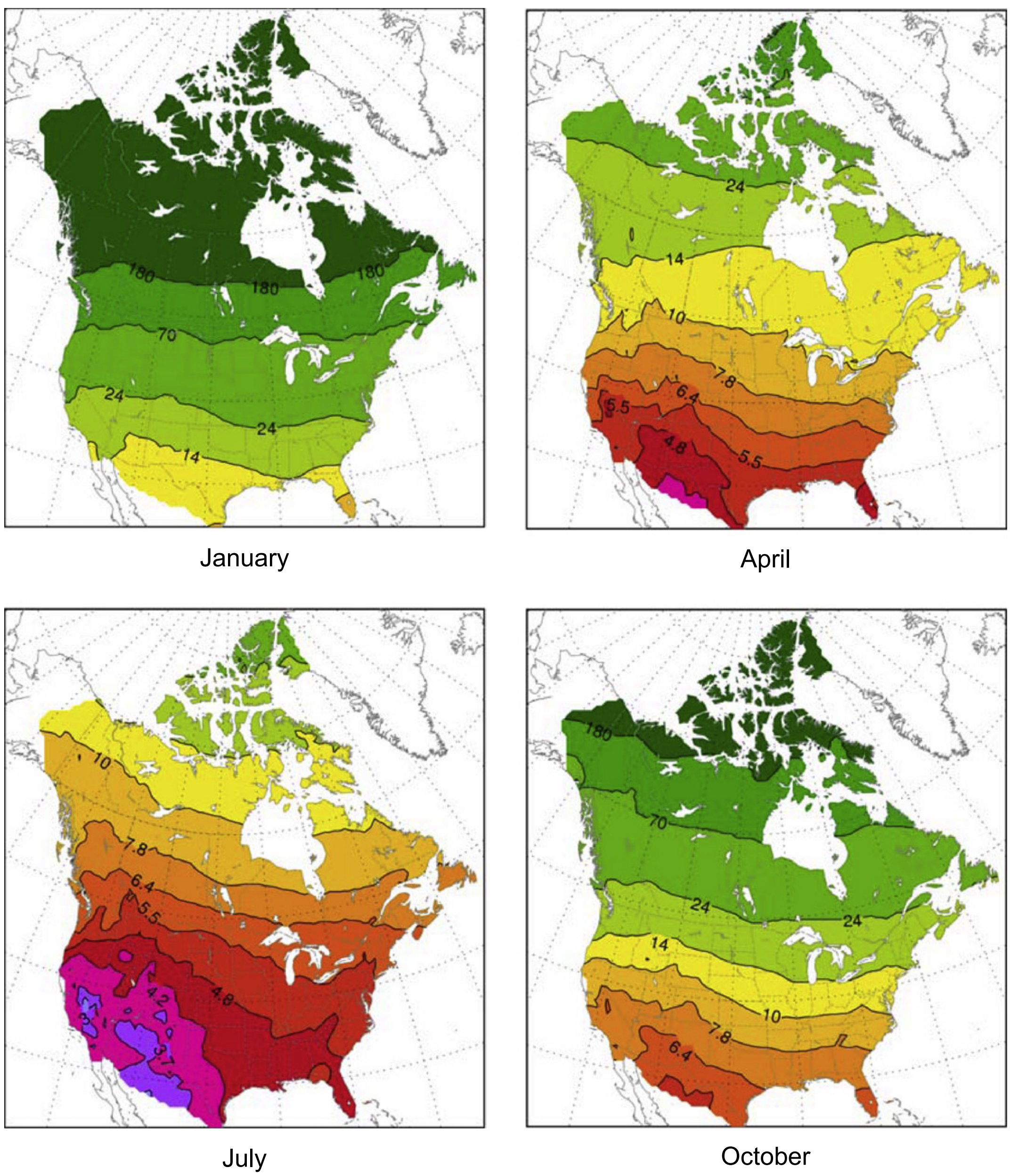

Fig. 5. The mean time (in minutes) required to obtain a dose of 106 J m^{-2} of vitamin D weighted UV (1 SDD for skin type II) for the 12:00–12:59 local solar time interval assuming that ¼ of skin is exposed to the sun. Maps of mean values for January, April, July, and October are shown.

ture in winter. There are also large annual variations in vitamin D UV doses with the highest doses occurring in January in the southern US, which are similar to July values over the Canadian Arctic.

Figs. 5 and 6 show the mean number of minutes required to achieve 1 SDD for type II skin (106 J m^{-2}) in different months near noon and at 9:00–9:59 respectively assuming that ¼ of skin is exposed to the sun. The number of minutes is calculated by multiplying 60 min by the ratio of the 1 SDD threshold level (106 J m^{-2}) to the mean hourly vitamin D UV dose shown in Fig. 2 (left).

Based on these estimates, it takes as little as 3.3 min to get 1 SDD in Arizona or New Mexico at noon in July and less than 10 min elsewhere except for the Arctic. In winter however, even a 1 h long exposure near noon is not enough to produce 1 SDD north of ~45°N. Fig. 7 shows the borders of the areas where 1 SDD can be obtained within 1 h near noon for six different types of skin. Maps are shown for January, March, September, and November. In summer, 1 SDD level is reachable in 1 h for all types of skin at all latitudes (except for the high Arctic).

The estimates of UV doses presented in Fig. 7 are based on assumptions such as exposure of ¼ of skin area exposure time of 1 h near noon, etc., that are rather arbitrary. Nevertheless, Fig. 7 demonstrates that in winter a person with type 1 skin can obtain the same amount of vitamin D weighted UV at 40–45°N as a person with type VI skin at 25–30°N. This can be further illustrated by Fig. 8 (top), where hourly UV dose is plotted as a function of latitude for 94°W. Note the logarithmic scale of the vertical axis. For latitudes between 30° and 50°N, the plot appears as a collection of nearly straight lines suggesting an exponential decline of UV doses as a function of latitude.

Fig. 8 (top) also shows that the slope of the lines is changing with the season. The steepest decline can be seen in December and January when the UV dose declines five times (the difference in adjustment factor between types I and VI skin according to Table 1) for a 20° latitude increment. By spring (March) the same decline occurs for a 35° difference. Results shown in Fig. 8 (top) are UV doses near noon. Results for other hours of the day are similar:

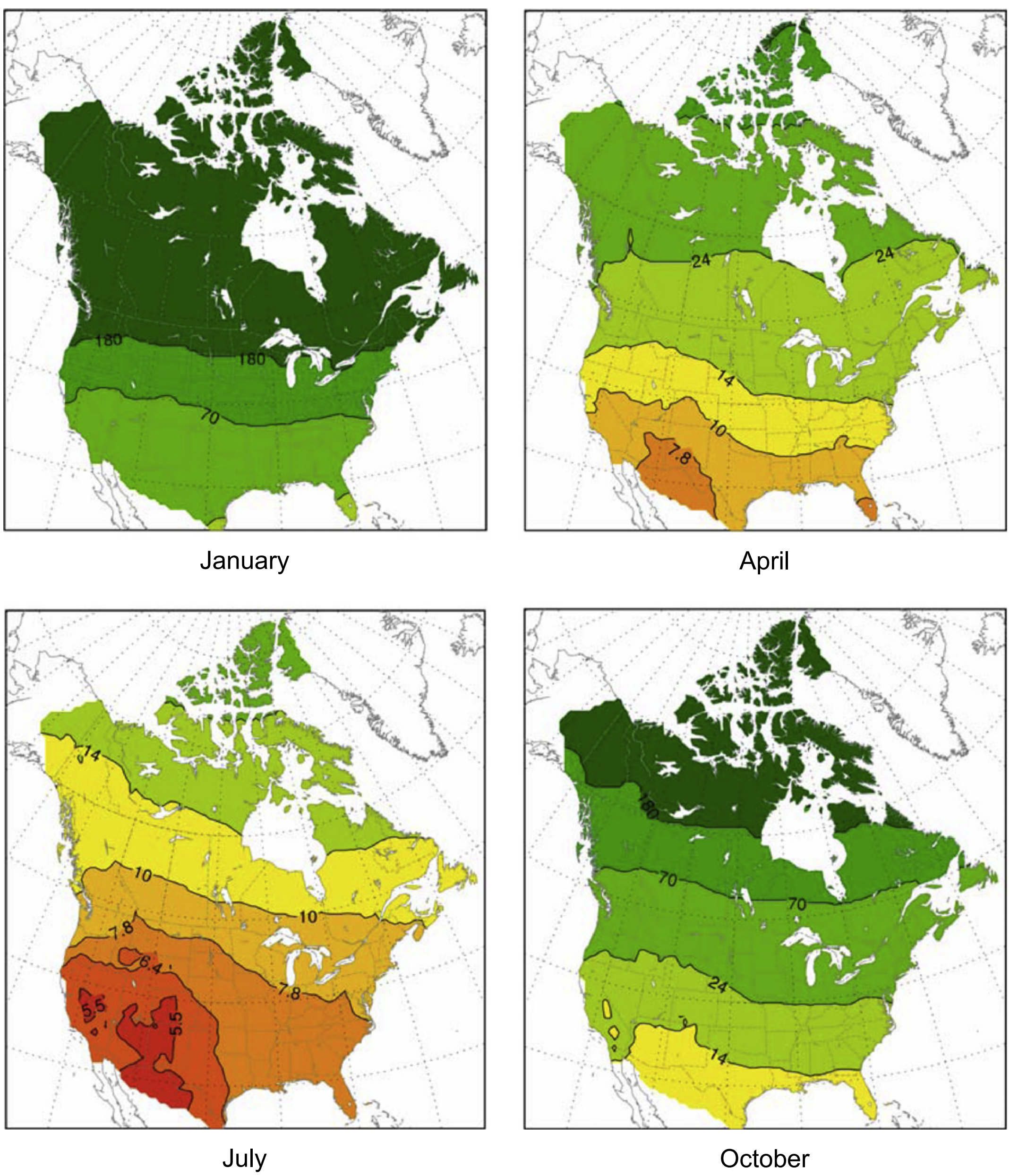

Fig. 6. The same as Fig. 5, but for the 9:00–9:59 local solar time interval.

the slope on the log scale is nearly the same as at noon meaning the same five times decline for a 20° latitude increment in winter (Fig. 8 bottom).

Various factors affecting UV can be also illustrated by Fig. 8 (top). Lines for months with approximately the same solar elevation are shown by the same color and should overlap if all other factors are identical. The ozone layer is thicker in spring than in autumn over midlatitudes and UV values are lower in April than in September up to about 45°N. At high latitudes, however, UV enhancement due to snow reflection and difference in cloud cover make springtime values greater than those for autumn. The springtime values can be almost twice as high as autumn values for nearly the same sun elevation. This suggests that simple UV estimates based on total ozone and sun elevation should be used with caution.

Comparison of the mean daily UV dose maps (Fig. 4) with monthly mean doses calculated from measurements by Brewer spectrophotometers shows an agreement within ±8% for summer months at most of the sites. The exceptions are Arctic sites where UV levels are low and are affected by variable snow/ice conditions. Also, the presented maps underestimate UV (by 10–15%) for a few sites located in a very clean environment (e.g., in some national parks). It is because the empirical parameterizations were established for using data from urban sites with "typical" aerosol loading, as mentioned in the Introduction.

4. Discussion and conclusion

This study introduces a dataset of vitamin D action spectrum-weighted UV climatology for the US and Canada. The climatology is for UV on a horizontal surface. It is derived from ground-based measurements of global solar radiation, satellite total ozone observations and on empirical relationships between UV irradiance and these measurements. In addition to vitamin D weighted UV does, estimates of time required to obtain 1 SDD are also provided based on the assumption that exposure to ¼ MED on ¼ skin area (hands,

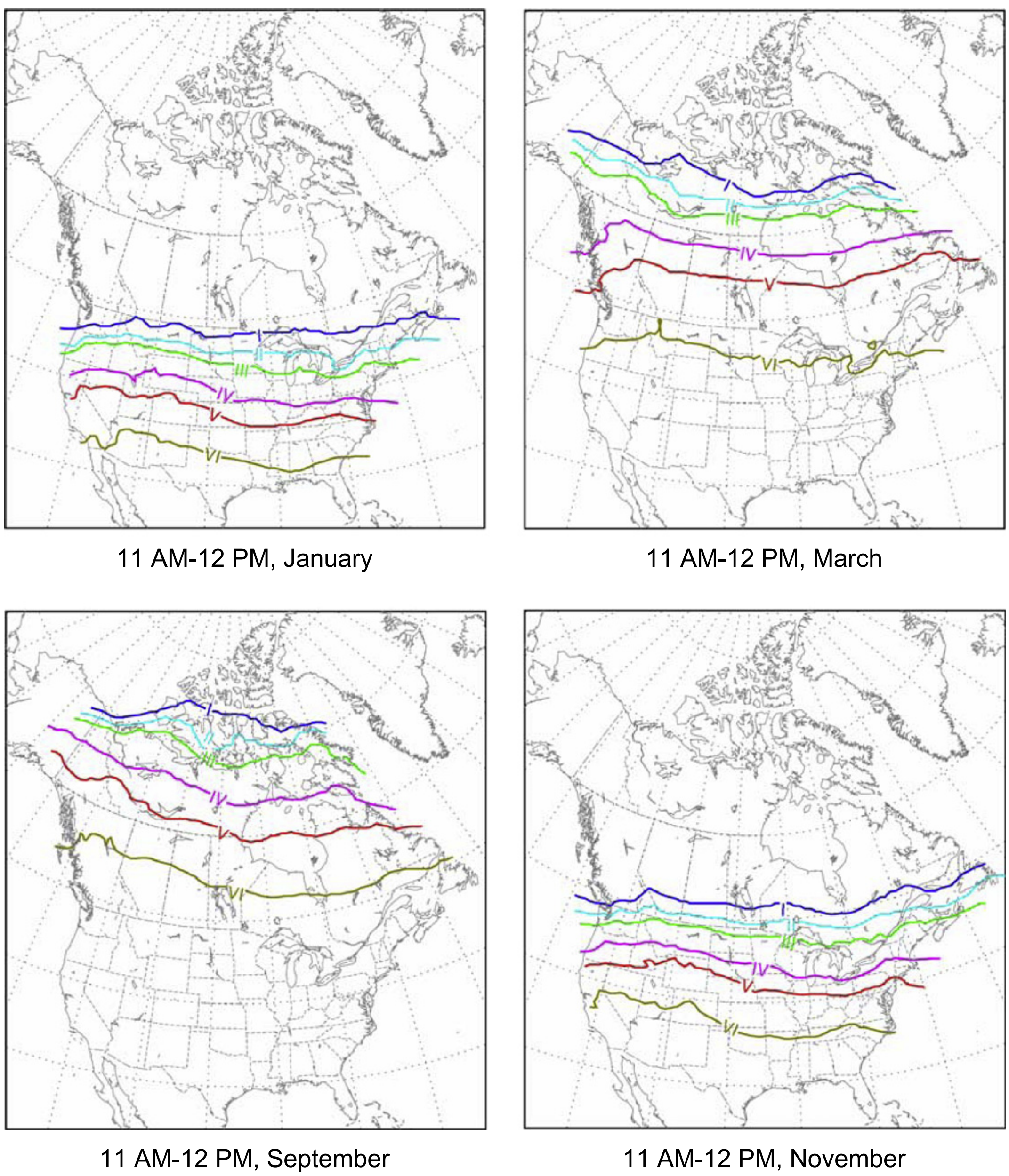

Fig. 7. The borders of the areas where 1 SDD can be obtained within 1 h near noon. The borders are shown for six different types of skin (I–VI).

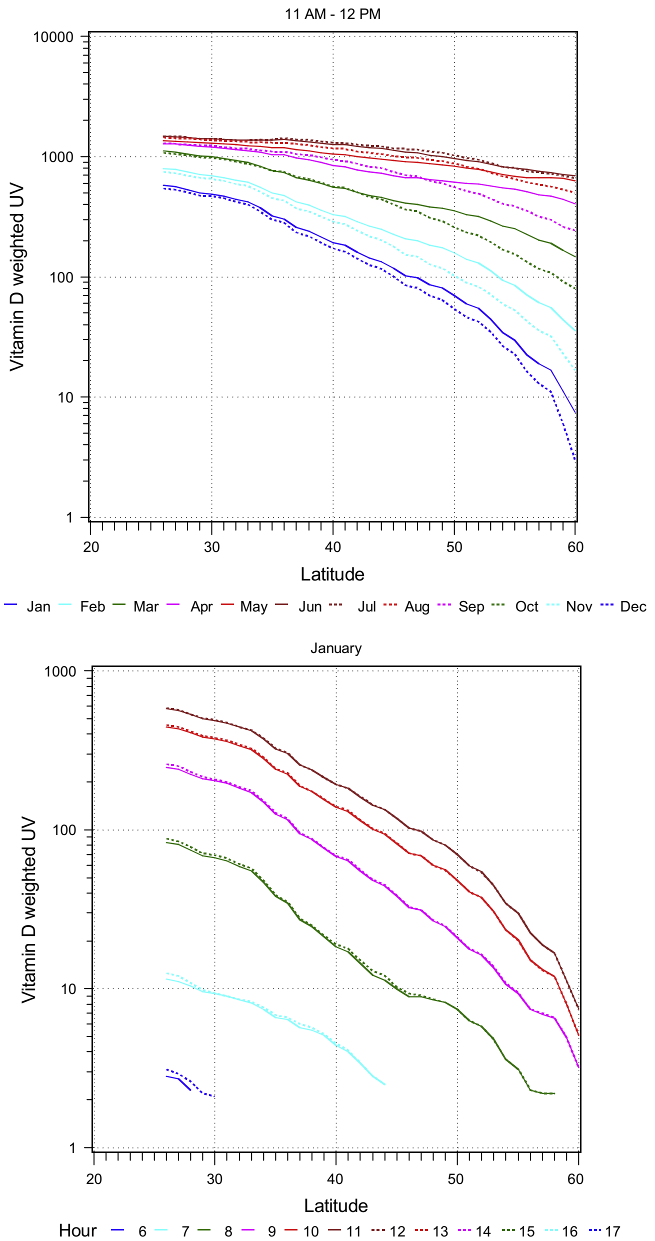

Fig. 8. (Top) Monthly mean values of vitamin D weighted UV doses (in J m^{-2}) for 11 am–12 pm local solar time as a function of latitude at 94°W. (Bottom) Monthly mean values of hourly vitamin D weighted UV doses (in J m^{-2}) for January. The beginning of the hour is shown in the legend (i.e., 6 means from 6 am to 7 am).

face and arms) to produce the UV equivalent of an oral dose of 1000 IU vitamin D at 42°N in March. It should be reminded that this assumption is based on a study by Holick [41,42], This assumption yields a 1 SDD dose of 106 J m^{-2} for type II skin. We should emphasize that the doses presented in this study are calculated using the CIE vitamin D action spectrum [37] that is based on [14], but extended from 315 nm to 330 nm using exponential decay function extrapolation and normalized to set its value at 300 nm to 1. If the extension or normalization is done differently, the obtained doses will also differ from those presented here, although they will be proportional (or nearly proportional, depending on the extension procedure) to the values from this study.

In January the 106 J m^{-2} threshold for 1 SDD for type II skin can be reached with all day exposure near 54°N (latitude of Edmonton) and even farther north over northern Quebec and Ontario. This seems to contradict findings by Webb et al. [44] who found no vitamin D production at these latitudes at that time. This contradiction was previously reported by McKenzie et al. [17], who raised the question on whether the action spectrum for vitamin D production is correct. It should be noted that our estimate is a dose integrated over the entire day for ¼ of the body exposed. It is rather unrealistic for cold winter conditions at these latitudes. It also assumes that the relationship between UV irradiance and vitamin D production is a linear function. In addition, the study by Webb et al. [44] was based on in vitro experimentation, while Holick [41,42] was based on in vivo experimentation.

Estimates of UV on a horizontal surface presented in this study do not reflect the real situation when various parts of human bodies are tilted over different angles (although the latter can be modeled [45]). In addition, the link between UV exposure and vitamin D production may be non-linear [46]. Therefore, the absolute values of the "time in the sun" estimates should be used with some caution. Perhaps it is even better to use the estimated time as a relative scale rather than as absolute values. For example, it can be used to estimate how Ultraviolet exposure levels for a sufficient vitamin D status depend on latitude for different skin types. If vitamin D production doses for different types of skin follow the same proportion as erythemal UV doses presented in Table 1, a person with type 1 skin can produce the same amount of vitamin D in winter at 40–45°N as a person with type VI skin at 25–30°N.

Vitamin D weighted UV climatology described in the study was developed for "typical" urban conditions. UV values are expected to be higher (by as much as 15%) for "clean" environments and they can be lower in heavily polluted areas [27]. It is expected that climatology can be improved as more information about absorbing aerosols over the US and Canada become available.

The 1° latitude by 1° longitude gridded dataset of UV estimates presented in this study is available for download from ftp://es-ee.tor.ec.gc.ca/pub/vitamind/. The data file includes the mean and 95th percentile values for hourly doses of vitamin D weighted UV for each month of the year, as well as the mean and 95th percentile values for the time in the sun required to get 1 SDD for six types of skin. The hourly mean and 95th percentile values of UV index (or erythemal UV) are also included in the file.

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