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# Projected changes in erythemal and the vitamin D effective irradiance over northern-hemisphere high latitudes

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## Abstract

Simulations of monthly mean noon UV Index and the effective dose for the production of vitamin D in the human skin have been performed for local noon for the latitude band 55° N- 85°N using a radiative transfer model. The magnitude and spatial distribution of changes estimated for the two quantities between the past (1955-1965 mean), the present (2010-2020 mean) and the future (2085-2095 mean) are discussed and the main drives for these changes are identified. The irradiance simulations are based on simulations and projections of total ozone, surface reflectivity and aerosol optical depth from models that participated in the fifth phase of the Coupled Model Intercomparison Project (CMIP-5). The cloud modification factor is also derived from the CMIP-5 models and used to account for the effects of cloudiness. Simulations have been derived for two socioeconomic scenarios: the moderate RCP 4.5 and the extreme RCP 8.5. In the future, the two quantities are projected to be generally lower than in the past and the present, mainly due to the projected super-recovery of stratospheric ozone and reduced surface reflectivity. Although the greatest changes are projected over the Arctic Ocean and do not directly affect humans, the changes over land are also important. Over land, the greatest changes are found in northern Asia, Greenland and the north-east shores of Canada and Alaska. The greatest reductions over land are projected for April under all skies, locally reaching ~30% for the noon UV Index and ~50% for the noon effective UV dose for the production of vitamin D.

## 1. Introduction

Exposure to UV radiation can be beneficial or harmful for both, human populations [1] and ecosystems [2-4]. Due to interactions between humans and the natural environment, any change in the function of the ecosystems, will also affect humans [5-8]. The direct effects of the solar ultraviolet (UV) radiation on human health are diverse and of vital importance [1, 9]. UV can cause DNA damage and is the main environmental risk factor for melanoma and non-melanoma skin cancers [10]. It is also related to induction of erythema [11], suppression of the immune response [12], as well as to eye diseases [13-15], such as cataract which was the leading cause of blindness world-wide in 2010 [16]. Harmful effects may also result from the interaction between UV radiation and specific environmental contaminants [17, 18]. Contrary to its detrimental effects, the solar UV radiation is also beneficial for the human health. The main source of vitamin D for humans is the formation of pre-vitamin $D_3$ in skin when it is exposed to UV-B (280-315 nm) radiation [9, 19]. Several studies have indicated that vitamin D enhances the immune function [20] and protects humans from infections [21-23], autoimmune diseases [24], mental disorders [25, 26] and cancer [27-29]. According to Jablonski and Chaplin [30, 31] the production of vitamin D in the human skin is the main evolutionary force that caused the white skin development when humans migrated from central Africa to higher latitudes.

People living at latitudes outside the tropics do not get sufficient sunlight to induce cutaneous pre-vitamin $D_3$ synthesis during the winter months [32], while at latitudes higher than 70°N vitamin D production is impossible between October and March [33]. Although for most people living at northern mid-latitudes (near 55°N), a normal lifestyle with relatively short, regular exposures to summer sunlight increases the vitamin D at the end of the summer enough to maintain sufficiency levels throughout the winter [34, 35], at higher latitudes humans need supplementation of vitamin D in order to balance the insufficiency [36, 37]. At latitudes near 70°N, several hours of exposure to solar UV radiation during the summer months may lead to the synthesis of adequate vitamin $D_3$ [38]; though sun protection is needed when the UV Index (UVI) is higher than 3 [1] since extended exposure may be hazardous. For latitudes between 55°N and 75°N, the noon UVI during the summer months typically ranges between 3 and 5 [39-41], while for latitudes above 80°N, the UVI may exceed 3 only in extreme cases [39, 42].

Practically, only the UV-B part of the spectrum contributes to the formation of pre-vitamin $D_3$ in the human skin while for erythema there is appreciable contribution of UV-A (315-400 nm) [43]. Instead of contributing to the formation of pre-vitamin $D_3$, excessive exposure to UV-A has been found to lead to its degradation [44]. The levels of surface UV-A and UV-B irradiance in the Arctic are strongly affected by several factors [45, 46]. During the last decades, important changes in surface UV radiation levels have been induced from changes in total ozone column (TOC), surface reflectivity, tropospheric air quality and cloudiness. In the future, the same factors are expected to undergo major changes, with important influences on the surface UV irradiance [47-50]. Model projections indicate that the magnitude of the differences between present, past, and future UV levels will vary locally and temporally due to the large spatial and temporal changes of these factors, leading to a corresponding high variability of impacts on the local populations and the ecosystems [1-4, 7, 51].

For high latitudes, reliable ground based measurements are limited [39, 42] and available only for the past two decades [52, 53], while satellite measurements are associated with high uncertainties [54]. Thus, estimations of differences between the UV levels in the past (before 1970) and the present are mainly based on reconstructions of UV irradiance from ground based and satellite proxy data [55] and on projections from climate models [56]. Projections of future changes in surface erythemal irradiance over the Arctic have been recently reported in several studies [41, 57-59]. The clear-sky annual mean UVI is projected to be ~7% lower at the end of the century compared to levels before 1980, solely due to the super-recovery of TOC [58]. The corresponding decrease in UVI relative to the mean levels for the period 1996-2005 is estimated to about 15% [59]. Increased cloudiness over that period is projected to further decrease the annual mean UVI. The overall decrease in the UVI by the end of the 21$^{st}$ century relative to the 1960-1969 mean due to ozone recovery and increased cloudiness is projected to 11% [57]. In Fountoulakis et al [41], the estimated changes in the all-sky monthly mean noon UVI between 2095 and 1955 range from -40% to +15% over the ocean, depending on emissions scenario, season and location. These changes were attributed to changes of surface reflectivity, clouds and TOC.

Although the changes of the effective UV dose for the production of vitamin D (vitamin-D weighted irradiance, hereafter denoted as VID) over the high latitudes of the northern hemisphere are of great importance, only a few studies have reported quantitative estimates. Kazantzidis et al [60] estimated that changes in tropospheric ozone between 2075 and 2005 would lead to reduction of the mean VID for spring, of ~17% and ~25% for the latitude bands 50°N-70°N and 70°N-90°N respectively. Correa et al [61] reported changes in VID over Europe, taking into account the future changes in TOC and aerosol optical depth (AOD) for four different representative concentration pathways (RCPs) [62]. In the latitude band 55°N - 75°N, the mean daily VID levels in 2051-2100 were projected between 5% and 25% lower compared to the period 1995 – 2005. Recently, Fioletov et al. [63] developed an empirical formula to calculate vitamin D weighted UV from UVI which is valid for UVI greater than 5.5. The results from this formula are highly uncertain for latitudes higher than 55°N where the UVI is usually lower than the suggested threshold.

The present study is an extension of Fountoulakis et al [41] over land and aims at providing estimations of the past and the future changes in the noon UVI and VID, under clear-sky and all-sky conditions, over latitudes between 55°N and 85°N, based on projections of TOC, AOD, surface reflectivity and cloudiness. The calculated changes in UVI and VID for local noon can be safely considered as representative of the changes in the corresponding daily doses because values around noon contribute most to the daily integral of irradiance, assuming that ozone, clouds and aerosols remain constant during the day. Although the population in the Arctic would be mainly affected by the changes in UVI and VID over land, changes over the ocean are also discussed since they are indicative for the changes in other quantities (e.g. the DNA damage-weighted irradiance [60]) which are important not only for humans. Additionally, changes over the ocean may be helpful for the identification of the main drivers of changes over land. Generally, UV irradiance over land and ocean is influenced differently by the factors considered here. For example, the changes in surface reflectivity due to changes in sea-ice affect primarily the solar radiation reaching the ocean and not the radiation over land, since one dimensional modeling has been used. Moreover, the radiation on land depends also on altitude and topography, although 3-dimentional effects of the latter are not considered in this study.

## 2. Data, methodology and uncertainties

The past (1955-1965 mean), the present (2010-2020 mean) and the future (2085-2095 mean) levels of the monthly mean noon UVI and VID were estimated from model simulations and percentage differences between the past and the present and between the future and the present were calculated. Simulations of spectral surface UV irradiance were performed with the radiative transfer model UVSPEC, which is included in version 1.7 of the libRadtran package [64], for a standard 5°x5° grid and for latitudes between 55°N and 85°N. For each grid point, the mean surface elevation from CESM1-WACCM model [65] was used in the calculations. The model-derived spectra are in the range of 280–400nm, in steps and resolution of 0.5nm. The erythemal irradiance and the VID were calculated by integrating the global irradiance spectra, weighted with the Commission Internationale de l'Éclairage (CIE) action spectrum [32] and the pre-vitamin $D_3$ action spectrum [66], respectively. The UVI is calculated by multiplying the erythemal irradiance (in $W/m^2$) by 40. The model inputs were taken partly from climatological data and partly from the Earth System Models (ESMs), which participated in the fifth phase of the Climate Model Intercomparison Project (CMIP5) [67], particularly for the socioeconomic scenarios RCP 4.5 [68] and RCP 8.5 [69]. The RCPs are a set of four different pathways developed for the climate modeling community as a basis for long-term and short-term modeling experiments. Each RCP provides a comprehensive, high resolution data set for land use and emissions of air pollutants and greenhouse gases for the period 2005-2100. The different RCPs (2.6, 4.5, 6.0 and 8.5) are named according to the projected radiative forcing level for 2100 [62]. Thus RCP 4.5 corresponds to moderate global emissions of greenhouse gasses and air pollutants, for which the radiative forcing due to the emissions and the changes in land use–land cover will reach 4.5 $W/m^2$ until 2100 without ever exceeding that value. For the extreme scenario RCP 8.5, the emissions increase over time, leading to a radiative forcing of 8.5 $W/m^2$ at the end of the 21st century.

The input data were monthly mean values and the model simulations were performed for the local noon of the 15th of each month.

The TOC was obtained from the chemistry coupled Earth System Model CESM1-WACCM [65]. The TOC (and its past and future evolution) from the particular model is generally in good agreement with the observations and with the CMIP-5 model-mean [70]. Using a multi model mean TOC instead of TOC from a single model would not change significantly the results. In contrast with TOC, for which most of the climate models are in good agreement with each other, the multi-model spread of surface reflectivity [71], cloudiness [72] and AOD [73] is large. A multi model mean was calculated from all the CMIP5 models that provide these parameters. The used models are presented in Table 1. To avoid artificial biases due to the different number of ensemble members that are available for each model, first the ensemble mean for each individual model was calculated and then the average of all the ensemble means was used as input in the radiative transfer model. In order to assess the effect of clouds, the Cloud Modification Factor (CMF) in the UV (UV_CMF) [74, 75] was used. For each day, the CMF is calculated as the ratio between the irradiance under all skies and the irradiance for cloud-free conditions. The CMF is then converted to UV_CMF with the empirical relations suggested by den Outer et al. [74]. Subsequently the mean UV_CMF is calculated for each month and each model and the multi-model average is derived and used in the projections. The aerosol optical properties, such as single scattering albedo, asymmetry factor and Ångstrom exponent, were assumed to be invariant between 1950 and 2100 and were taken from the Max-Planck-Institute Aerosol Climatology version 1 (MAC-v1) [76].

**Table 1.** The CMIP 5 models used in this study. The parameters provided by each model are marked with x.

| Model | Institute | TOC | | Surface Reflectivity | | CMF | | AOD | |
|---|---|---|---|---|---|---|---|---|---|
| | | RCP | RCP | RCP | RCP | RCP | RCP | RCP | RCP |

| | | 4.5 | 8.5 | 4.5 | 8.5 | 4.5 | 8.5 | 4.5 | 8.5 |
|---|---|---|---|---|---|---|---|---|---|
| ACCESS1-0 | CSIRO-BOM | | | x | x | x | x | x | x |
| ACCESS1-3 | CSIRO-BOM | | | | | | | x | x |
| BCC-CSM1-1-M | BCC | | | x | x | x | x | | |
| BNU-ESM | BNU | | | x | x | x | x | x | x |
| CanESM2 | CCCMA | | | | | x | x | | |
| CCSM4 | NCAR | | | x | x | x | x | | |
| CESM1-CAM5 | NSF-DOE-NCAR | | | | | | | x | x |
| CESM1-WACCM | NSF-DOE-NCAR | x | x | | | | | | |
| CNRM-CM5 | CNRM-CERFACS | | | x | x | x | x | | |
| CSIRO-Mk3-6-0 | CSIRO-Mk3.6 | | | x | x | x | x | x | x |
| FGOALS-g2 | LASG-CESS | | | | | x | x | | |
| GFDL-CM3 | NOAA GFDL | | | x | x | x | x | x | x |
| GFDL-ESM2G | NOAA GFDL | | | x | x | x | x | x | x |
| GFDL-ESM2M | NOAA GFDL | | | x | x | x | x | x | x |
| GISS-E2-H | NASA-GISS | | | | | | | x | x |
| GISS-E2-R | NASA-GISS | | | | | | | x | x |
| HadGEM2-CC | MOHC | | | x | x | x | x | x | x |
| HadGEM2-ES | MOHC | | | x | x | x | x | x | x |
| INCM4 | INM | | | x | x | x | x | | |
| IPSL-CM5A-LR | IPSL | | | x | x | x | x | | |
| IPSL-CM5A-MR | IPSL | | | x | x | x | x | x | x |
| IPSL-CM5B-LR | IPSL | | | x | x | x | x | x | x |
| MIROC5 | MIROC | | | x | x | x | x | x | x |
| MIROC-ESM | MIROC | | | x | x | x | x | x | x |
| MIROC-ESM-CHEM | MIROC | | | x | x | x | x | x | x |
| MPI-ESM-LR | MPI-M | | | x | x | x | x | | |
| MPI-ESM-MR | MPI-M | | | x | x | x | x | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| MRI-CGCM3 | MRI | | | x | x | x | x | x | x |
| NorESM1-M | NCC | | | x | x | x | x | x | x |

Most of the assumptions that have been made in the simulations are the same as in Fountoulakis et al [41], where an analytical description and the associated uncertainties can be found. In the same study, most of the uncertainties which are related to the simulations and the input data from the climate models are analytically described. In order to extend the study of Fountoulakis et al [41] over land it was additionally assumed that the land surface reflectivity for the total (shortwave) and UV radiation is the same. Furthermore the mean AOD from the CMIP5 models that provide aerosol projections was used instead of the climatological AOD that was used in Fountoulakis et al [41]. The associated uncertainties for these two parameters (surface reflectivity and AOD) are discussed below.

Over the high latitudes of the northern hemisphere, the non-urban land areas, which represent the main fraction of each grid cell, are mainly covered by snow, ice, green forests and tundra [77]. For these areas, the difference between the surface reflectivity for UV and visible radiation is very small, ranging from 0 to 0.06, and becomes more important between the UV and the infrared part of the spectrum [78-80]. Considering the mean values for each grid cell, the difference between the surface reflectivity for the UV and the total solar radiation is estimated to 0.1 or less. Over a flat terrain, an error of 0.1 in the reflectivity results into ~2-5% error in the simulated clear-sky UV irradiance. Over complex, highly reflective terrains and under cloudy conditions the surface UV irradiance can be up to 60% higher [81-83] than the irradiance over flat surfaces with the same reflectivity. If surface reflectivity remained the same through the period of study , the above uncertainties would have negligible impact on the estimated changes in surface UV irradiance [57]. Climate models predict that the seasonal cycle of the surface reflectivity over several high latitude land areas of the northern hemisphere will change because of changes in the duration of snow-cover which is already decreasing and is projected to continue decreasing during the next decades [84, 85]. For these cases, the above uncertainties will be transferred directly to the calculated differences in UV irradiance.

One additional source of uncertainty is the underestimation of the trend towards a reduced spring snow cover extent - thus towards a reduced surface reflectivity - by most of the CMIP5 models [86]. Furthermore, the models do not describe satisfactorily the interactions between the solar irradiance, the different features of the surface and the clouds [72, 86, 87]. In general, for each grid cell, the agreement among the monthly mean surface reflectivity estimates from all models within 1σ is better than 0.25 for both the past and the future. The corresponding agreement for the monthly mean AOD is of the order of 70% of the multi-model average or lower. The uncertainties in the projected changes in AOD are in many cases similar to the magnitude of the changes. Further discussion regarding the uncertainties in TOC, cloudiness, sea surface reflectivity and aerosol optical properties can be found in Fountoulakis et al. [41] and the references therein.

Uncertainties in the projections of the VID arise also from the action spectrum of vitamin D which has been used to weight the model-derived irradiance spectra. In contrast to the CIE action spectrum, which has been thoroughly investigated and defined, the action spectrum for the formation of pre-vitamin $D_3$ is still controversial [88] and different studies recommend the use of different versions for the calculation of the VID [19, 66, 89]. In the present study the action spectrum suggested by Bouillon et al. [66] is used. The specific action spectrum is recommended by the CIE and has been used in several recent studies for weighting the solar spectra to obtain effective doses for potential vitamin D production [60, 61, 90, 91]. The uncertainties in this action spectrum arise mainly from the complexity of the UV driven reactions for the conversion of 7-dehydrocholesterol to pre-vitamin $D_3$ in the human skin and from insufficient data that have been used to derive the spectrum at wavelengths between 315 and 330nm [92]. However, the uncertainties in the VID differences due to the uncertainties in the action spectrum are of minor importance compared to those due to the uncertainties in the input parameters.

## 3. Results and discussion

### 3.1. Past and future changes of the noon UV index

The estimated monthly mean changes in noon UVI under clear skies are presented in figure 1, which shows percentage differences between the past and the present (panels a-c) and between the future and the present (panels d-f for RCP 4.5 and panels g-l for RCP 8.5) for April, June and August. The corresponding results for all skies are shown in figure 2.

Over most of the high latitudes (with the exception of north Pacific) the estimated clear-sky noon UVI for April is lower in the past compared to present, particularly near the Vilkitsky Straight in Siberia and over the Baltic area where the UVI is lower by up to 20%. This pattern is mainly attributable to the higher TOC values prevailing in the past. For the Baltic, the smaller values of UVI in the past are sustained also for the summer months, while over the rest of the high latitudes the UVI was higher in the past by up to ~10%, particularly over the Arctic sea in August. The UVI changes in the summer months are mainly driven by changes in aerosols and surface reflectivity. Compared to the present, the AOD in the past was higher over Europe and lower over East Asia, leading to lower UVI over Europe and higher over East Asia. The effect of changes in reflectivity is more evident in August when the loss of the Arctic sea-ice results in less UV radiation over the ocean (higher UVI in the past).

The projected future levels of UVI depend strongly on the assumed emissions scenario. For April, the clear-sky noon UVI is projected to continue decreasing over the greatest part of the Arctic, mainly due to the projected super recovery of stratospheric ozone [93] and decreasing surface reflectivity [47]. Over specific parts of the Arctic Ocean the UVI is estimated to be lower compared to present by up to ~25% for RCP 4.5 and ~35% for RCP 8.5. However, these decreases over the ocean would influence mostly the aquatic ecosystems and not the human populations. The projected decreases in the UVI over land, where surface reflectivity would change less compared to the ocean [47], are generally below 10% for RCP 4.5 and between 10 and 25% for RCP 8.5.

For June and August, the reductions in the noon UVI between the future and the present for RCP 4.5 are mainly due to the projected reductions in aerosols and surface reflectivity, while for RCP 8.5 the projected increases in TOC contribute too.

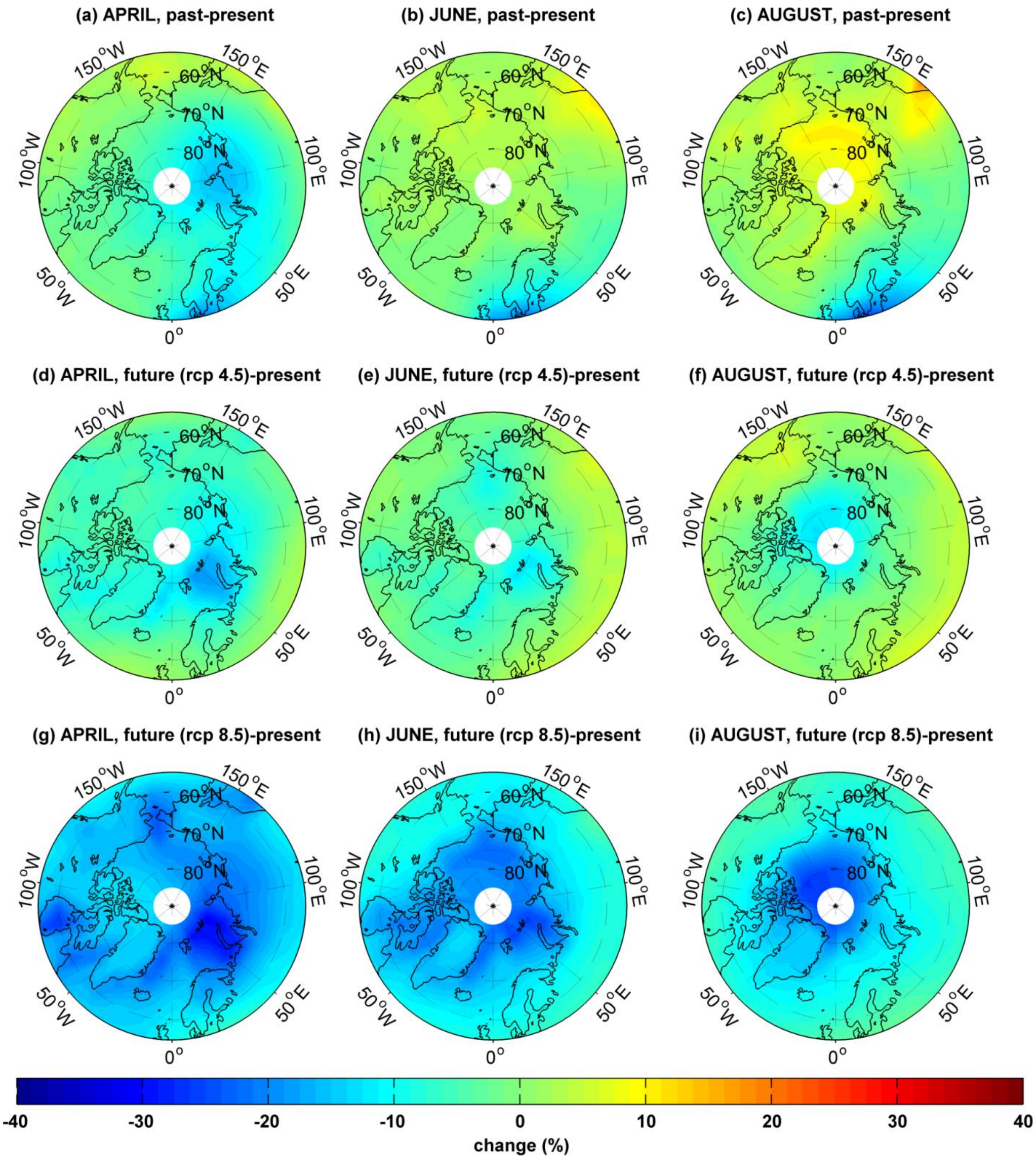


**Figure 1.** Percentage differences in monthly mean noon UVI for clear skies between the past and the present (panels a-c) and the future and the present (panels d-f for RCP 4.5 and panels g-l for RCP 8.5).

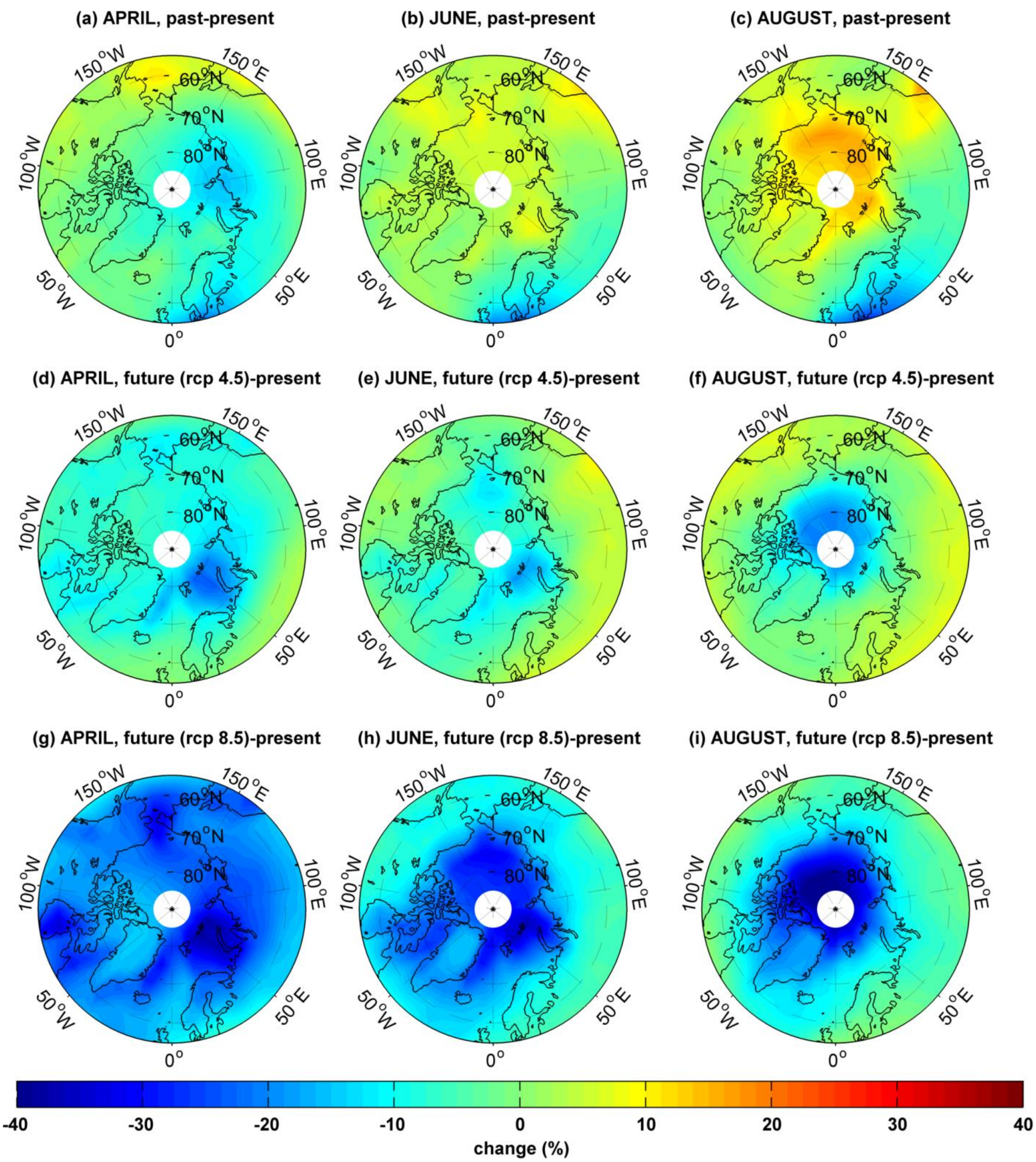


**Figure 2.** Same as in figure 1 but for all skies.

For RCP 4.5, decreases of the order of 10% in noon UVI are projected only over the Ocean. The small increases in Europe and Asia between 55°N and 65°N are mainly due to the improvement in air quality;

thus to reductions in aerosols. For RCP 8.5 the projected increases in TOC in conjunction with the severe sea ice melting lead to decreases in UVI that may reach 30% over the Arctic Ocean. Over land, the greatest decreases for June, of the order of 20%, are projected for the Northeast part of Canada, Alaska, the shores of Siberia and the lower-altitude areas of Greenland. For August, decreases of similar magnitude are projected for the northern islands of Canada and the northern part of Greenland. The reductions in UVI are larger over the Arctic Ocean than over land due to the projected larger reductions in sea-ice compared to ice on land, which leads to lower surface reflectivity and hence to lower UVI.

By comparing figures 1 and 2 (panels a-c) it can be perceived that differences in cloudiness between the past and the present have an important impact on UVI over the Arctic Ocean and the neighboring land areas. Over this region, the monthly mean noon UVI under all skies in the past was estimated up to 25 % higher than in the present. Over the mainland the impact of the reduced cloudiness in the past is evident over north-east Asia and Alaska, where in June and August the increases in all-sky noon UVI are up to 10% higher than for clear skies. In the future, the most important changes in cloudiness are projected over and near the areas of the greatest reductions in the volume and extent of sea-ice [47]. Thus, for latitudes above 70°N, the decreases in all-sky UVI are projected to be stronger than for clear skies. Over land areas between 55° N and 70° N, decreases in cloudiness lead to increases in clear-sky UVI for RCP 4.5, and balance the UVI reduction due to the super-recovery of stratospheric ozone for RCP 8.5. It is noteworthy that for RCP 8.5 the all-sky UVI is projected to decrease by up to 40% over the islands of the Novaya Zemlya archipelago (near the shores of Siberia) in April and June and over the northern islands of the Beaufort Sea in August. Almost half of this effect is caused by increased cloudiness.

### 3.2. Past and future changes in Vitamin D effective dose

While both the UV-B and the UV-A parts of the solar spectrum contribute significantly to the effective dose for erythema, only the UV-B part has an important contribution to the effective dose for the production of vitamin D in the human skin. Thus, changes in TOC affect the VID more drastically than the UVI. The changes of the monthly mean clear-sky noon VID are presented in figure 3 while the corresponding changes in VID under all skies are presented in figure 4.

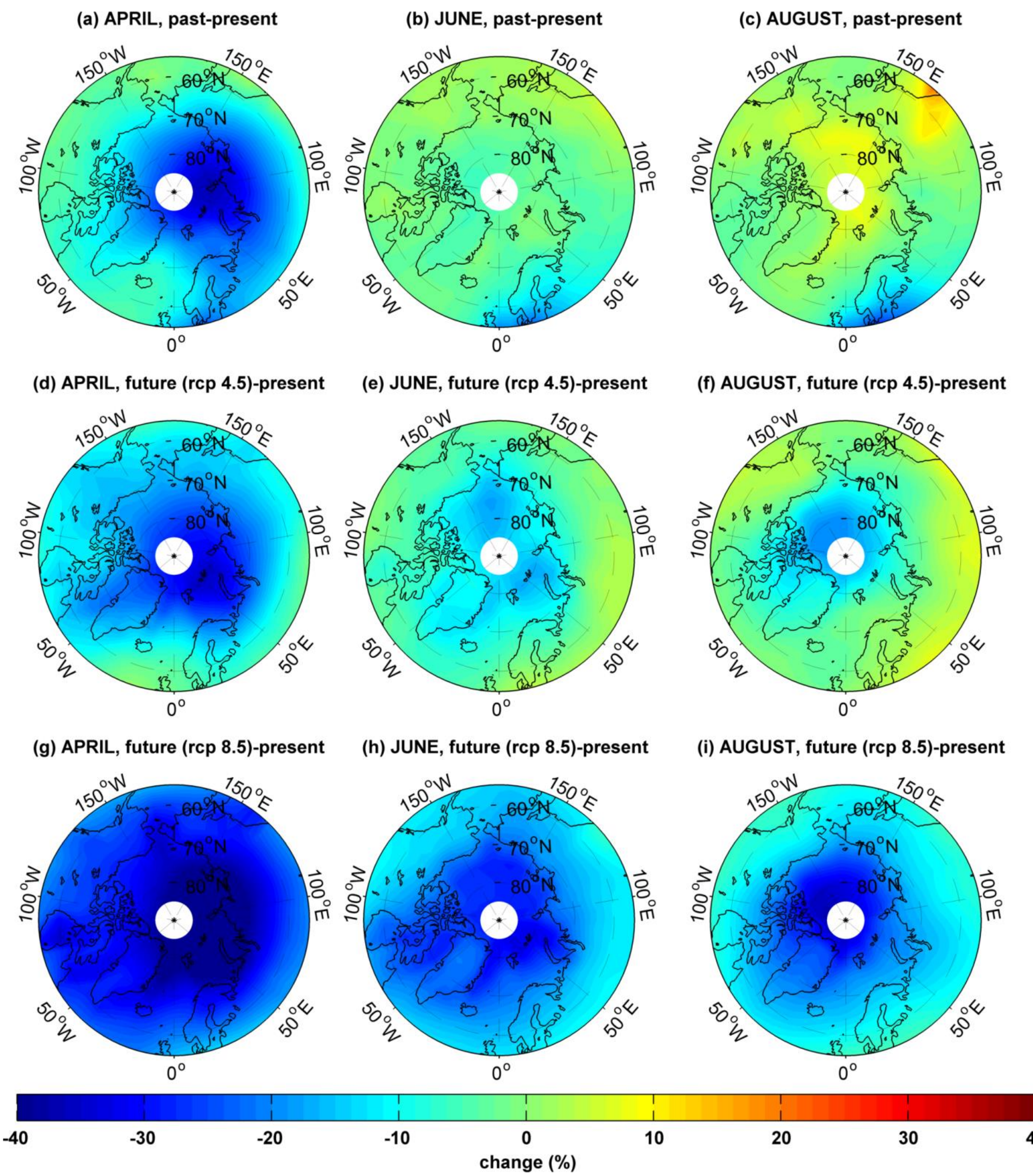


**Figure 3.** Percentage differences in monthly mean noon VID for clear skies between the past and the present (panels a-c) and the future and the present (panels d-f for RCP 4.5 and panels g-l for RCP 8.5).

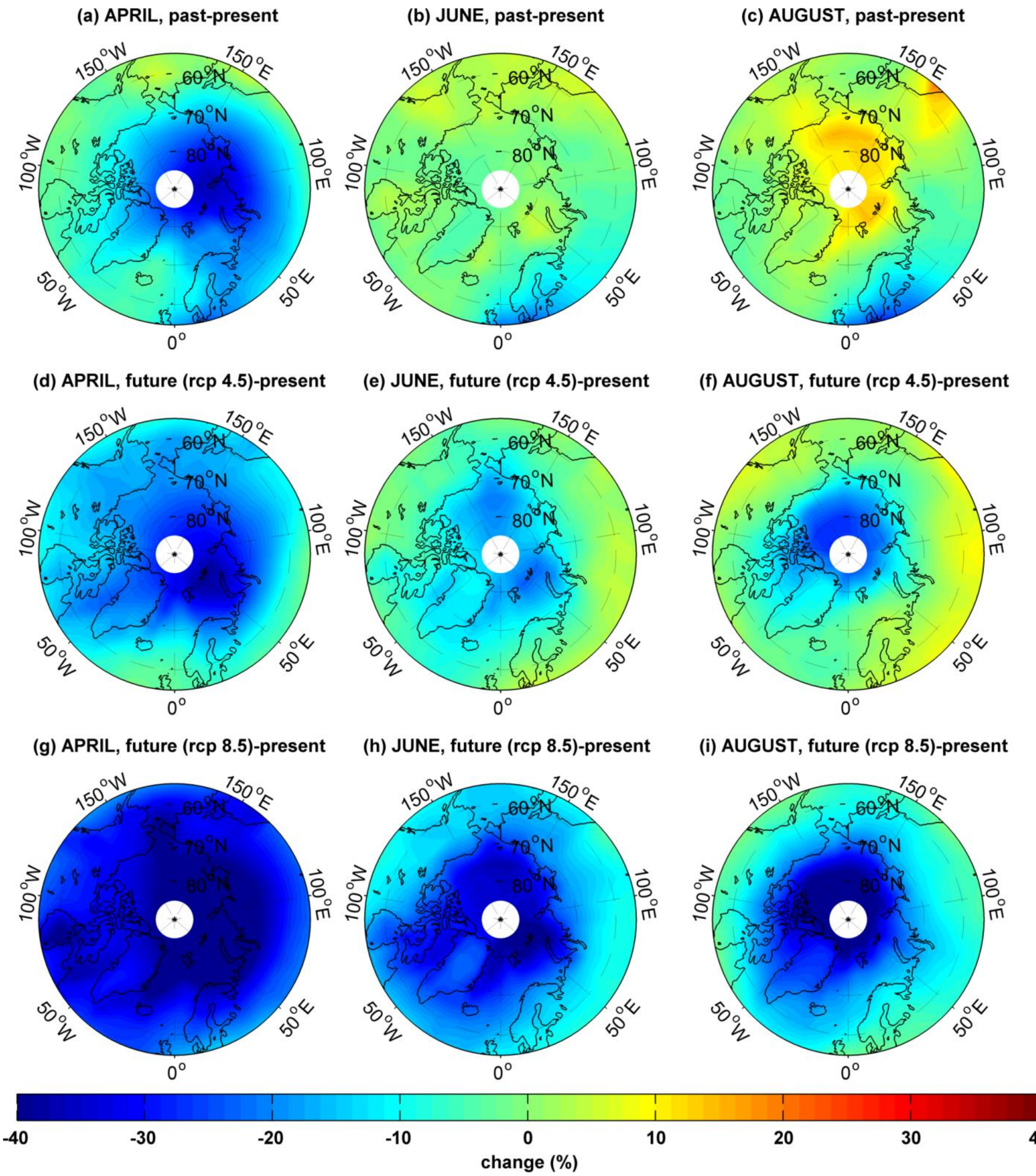


**Figure 4.** Same as in figure 3 but for all skies.

For the past, the greatest differences in the monthly mean noon VID from its present levels are found for April, both for clear and all skies. Lower values by 20-40% are found over a large fraction of the northern Eurasia, both for clear skies and all skies, while values ~20% lower are estimated for northern Greenland,

and below 10% over Alaska and Canada. For June and August the results are similar to those for the UVI, since the main drivers are factors other than ozone. For these months the TOC changes are important only for latitudes above 75°N. Thus the only notable difference is the changes in VID over the Arctic Ocean and the neighboring land areas that are ~5% smaller compared to the corresponding changes in the UVI.

For the future, the increasing levels of TOC lead to reductions in VID that are larger than those for the UVI. As for the UVI so for the VID, increases for the future were found only for RCP 4.5 for June and August between 55° N and 65° N, due mainly to changes in aerosols and clouds. For April, both the clear-sky and the all-sky VID is projected to decrease everywhere with a maximum of 40% over the Barents Sea for RCP 4.5, and by more than 20% over most of the area north of 60° N for RCP 8.5, due to increases in TOC and reductions in surface reflectivity. For RCP 8.5 the maximum decrease in VID of about 50% is found over the central Arctic Ocean and the northern part of Asia. For June and August the spatial pattern of the maximum decreases of VID is similar to that for the UVI, but the reductions are 10-20% larger. Increasing cloudiness in the future leads to larger reductions in VID by up to 10% compared to clear skies.

## 4. Discussion

For both the UVI and the VID, the greatest changes are projected over the ocean, thus humans would not be affected directly. However, the changes over land are not negligible. In the past, the estimated mean monthly values of both quantities over the greatest part of Europe are up to 20% lower than in the present during all months, but up to 20% higher over East Asia for August. In April, substantially lower VID have been simulated for the past over wide areas of Greenland and North Eurasia, due to higher TOC. However, compared to the present the levels of the UVI over these areas are not as low as for the VID. Recent studies reveal positive trends of melanoma in northern European countries, such as Denmark [94, 95] and Northern Ireland [96], which are possibly related with ozone depletion induced increases of the erythemal irradiance during the last decades. Other studies suggest that during periods of extreme low

TOC[97], hence of extreme high clear-sky UVI, the mortality of arctic mammals, such as seals and whales, has increased due to harmful sunburns[98, 99]. About half of the population living in the Arctic cycle reside in northern Russia[100] and would have been likely experienced increased levels of VID. However, no studies describing how the number of people who do not get sufficient vitamin D has changed during the last decades were found.

The projected changes in UVI and VID for the future are highly dependent on scenario. The projections for RCP 4.5 indicate that the noon UVI will decrease substantially, mainly over the ocean, while over land, decreases of up to 20% are projected only for April over the higher latitudes. The decreases are larger for the monthly mean noon VID, ranging in April under all sky conditions between 0 and 40% over land. For June and August the spatial extent of the projected changes in VID is confined mainly over Greenland and the northern parts of Eurasia, Canada and Alaska and the maximum decreases do not exceed 20%. Over the latitude band 55° - 65° N, the projected reductions in aerosols and cloudiness during the summer lead to small increases (less than 10%) of both UVI and VID.

The projected decreases in UVI and VID are larger for RCP 8.5 than for RCP 4.5 due to stronger influences by climate change. Over the Arctic Ocean the monthly mean clear-sky UVI is reduced by up to 30%, while VID by up to 50%. The most important factor for the future is the decreasing surface reflectivity due to the projected loss of sea-ice which accounts for more than 30% of the projected decreases in VID over the ocean for RCP 8.5, while the effect of increased cloudiness leads to an additional reduction of about 10%. Over land, the changes in noon UVI for April under all skies range between -30% and -10%, while for VID the changes range from -50% to -10%. The decreases in UVI and VID over land become smaller from April towards August. In August the effect of decreased cloudiness counteracts the effect of increased TOC over wide areas within the latitude band 55°-65° N; consequently future levels of UVI and VID are projected to remain near present values.

The population of the Arctic is currently increasing, and is expected to further increase during the next decades as a result of industrial development and increased competition for resources [100]. The reduced erythemal irradiance in the future may lead to less sunburns and skin cancer for both the native populations and the new immigrants. However, recent studies indicate that people from lower latitudes who are usually adapted to higher levels of UV irradiance are more likely to suffer from vitamin D insufficiency when they will move to such high latitudes [101, 102]. This problem might be intensified by the projected reduction in VID. It should be mentioned that over wide areas of Russia and Alaska where about 2.5 million non-native people are already living [100], future levels of VID under RCP 8.5 are projected to be 10 -50% lower than in the present for all months.

The temporal and spatial analysis of UVI and VID changes in this study are different than in previous studies, allowing only qualitative comparisons. As already discussed, changes in clear-sky UV irradiance over northern Europe are mainly driven by changes in TOC and AOD. For this reason our estimated changes in clear-sky UVI and VID are in good agreement with those reported by Correa et al [61], although they do not take into account changes in surface reflectivity. The results of Kazantzidis et al [60] for the Arctic and sub-Arctic regions for the past are generally close to the results of this study . However, for the future the mean reduction of the clear-sky UVI and VID for RCP 8.5 is almost double than projected by Kazantzidis et al [60]. This is mainly due to the more realistic changes in surface reflectivity and the greater increases in TOC used in this study. For RCP 4.5, the agreement between the two studies is better. Finally, simulations of UV-B irradiance for the past and the future resulting from changes in ozone, surface reflectivity, cloudiness and aerosols were also discussed in Watanabe et al. [49, 56]. However, their results are not representative for UVI or VID and cannot be directly compared with the changes reported here.

## 5. Conclusions

This study aims at quantifying past and future changes in solar irradiance relevant for vitamin D production and induction of erythema in human skin resulting from changes in total ozone column, surface reflectivity, aerosols and cloudiness. The focus is on the high latitudes of the northern hemisphere because future changes in surface UV irradiance are expected to be of major importance for the health and the quality of life of populations living in these areas [1]. Despite the high uncertainties of the projections [41, 47], the estimated magnitude and spatial distribution of the changes are useful for identifying areas of greater risk and allow forward planning to mitigate the risks.

The past and future levels of the UVI and the VID over land are mainly driven by changes in TOC, affecting more the VID than the UVI. Changes in aerosols have more important effects in Europe and East Asia and mainly for the changes in UV irradiance between the past and the present. The reduced surface reflectivity in the present and in the future compared to the past is also an important driver for the UV changes over latitudes north of 70°N. The changes in cloudiness are important mainly near and over the ocean where the sea-ice cover is changing. For the past and for the future (mainly for RCP 4.5) the projected changes for latitudes below 65° N are more uncertain than those for higher latitudes since the former are mainly driven by changes in aerosols and cloudiness.

In general, the past and future changes in VID are more widespread and greater than the corresponding changes in UVI, mainly due to the higher sensitivity of VID to changes in TOC. The results of this study are not adequate to estimate the effects of the changing atmosphere on the optimal exposure of humans to avoid the hazardous effects of UV radiation and at the same time to form adequate vitamin D. Although the exposure to avoid hazardous effects is well documented [103-107], the effects of factors other than UV radiation that may affect the formation of vitamin D at high latitudes are yet far from clear [1]. Considering the large changes in the future levels of the VID reported here, further studies of the relationship between solar radiation, lifestyle of populations and the formation of the vitamin D are needed in order to quantify the impact on optimal exposure. Although the high uncertainty of the input parameters [41] is the major limiting factor in the accuracy of the UV simulations, studies of higher spatial resolution and/or with the use of three-dimensional models can reduce the uncertainties, especially over complex terrains.

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