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The Effect of Clouds and Surface Albedo on UV Irradiances at a High Latitude Site

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Abstract. At high latitudes the Earth's surface is covered by snow large parts of the year. In spring the snow cover significantly increases UV radiation for cloudless as well as cloudy situations. In Tromsø (69.65° N, 18.95° E), Norway, independent measurements have been made of the effective regional spectral surface albedo, the total ozone column, the effective cloud optical depth, and the surface UV irradiance. These measurements are used together with model simulations to study the effect of snow and clouds on surface erythemal radiation doses. Snow on the surface increases the monthly erythemal doses by more than 20%. Relative to cloudless sky, the clouds reduce the monthly erythemal doses by 20–40%. During snow free conditions monthly doses derived from Earth Probe/Total Ozone Mapping Spectrometer (EP–TOMS) total ozone and cloud reflectivity agree with the measurements within the experimental uncertainties. In presence of snow, however, the EP–TOMS derived data are too low by 30–40% due to snow covered surfaces being misinterpreted as clouds.

Introduction

Snow covered surfaces may enhance the surface UV irradiance. This is of special importance at high latitudes where snow may be present into the summer season, thus potentially increasing the UV levels substantially above the levels found under snow free conditions. In addition to snow, the surface UV radiation is greatly affected by clouds. To estimate the effects of snow cover and clouds on the surface UV radiation, independent measurements are needed of the effective surface albedo, effective cloud optical depth, total ozone, and UV radiation. In addition, model simulations are required to separate the impacts of the various factors. From spectral measurements and model simulations Stamnes et al. [1990] estimated that clouds reduced the UV irradiance by 40–50% at McMurdo station, Antarctica. They had no independent measurements of the effective surface albedo and therefore assumed a constant value of 0.75.

During 1997, UV radiation was measured by various instruments at the Auroral Observatory, Tromsø, (69.65° N, 18.95° E), Norway. A Jobin-Yvon HR 320 single monochromator measured the direct and global irradiances which were used to derive an effective surface albedo [Kylling et al., 2000]. A Ground–based Ultraviolet Radiometer (GUV-541, Biospherical Instruments Inc., San Diego) multichannel moderate bandwidth filter instrument provided high time resolution estimates of total ozone and effective cloud optical depth which were used as input to a radiative transfer model to derive erythemal doserates. The results were compared against UV irradiance derived from measurements of total ozone and cloud reflectivity by the total ozone mapping spectrometer (TOMS) onboard the Earth Probe satellite (EP).

Measurements

The effective regional spectral surface albedo was determined using an inversion technique based on the ratio of direct and global irradiance measured by the HR 320 instrument. The effective albedo is the albedo value that when used in a radiative transfer model with all other input fixed from independent measurements, provides the best agreement with the measured direct/global irradiance ratio. Details of the instrument, the method, and the results have been described by Kylling et al. [2000]. Figure 1 shows the effective albedo at 320 nm for the year 1997. The snow depth reached a record 240 cm on 29 April and disappeared during the second week of June. Only cloudless sky data were used for this analysis because the determination of the effective surface albedo relies on accurate model values of direct and global irradiance.

The GUV-541 measured the UV irradiance in five channels centered at 305, 313, 320, 340, and 380 nm with a bandwidth of approximately 10 nm at FWHM. It is part of the Norwegian UV monitoring network that was established in 1995. The instrument was calibrated in May 1995 against a SUV–100 spectroradiometer in San Diego [Dahlback, 1996]. The network includes a travelling standard that once a year is shipped to the manufacturer for calibration against a NIST traceable lamp as well as against a SUV–100 spectroradiometer. The GUV-541 in Tromsø is compared with the travelling standard once a year and drifts are corrected if neccessary. The GUV-541 samples at 2 Hz. One minute averages are calculated and logged. It was in operation year round. Erythemal irradiance was derived from these data in a two-step process. First, following Stamnes et al. [1991] and Dahlback [1996], the ratio of the 305 nm and 320 nm channels was used to determine total ozone, and the 340 nm channel was used to retrieve effective cloud optical depth. By effective cloud optical depth is meant the optical depth that when used in the model best reproduces the measurements. Hence, the effective cloud optical depth includes both aerosol and cloud optical depths. However, Tromsø is located far from any major pollution sources and infrequent aerosol optical thickness measurements indicate that the aerosol loading is low [Kylling et al. 2000]. Thus clouds are the major contributors to the effective cloud optical depth. In contrast to previous methods, the effective

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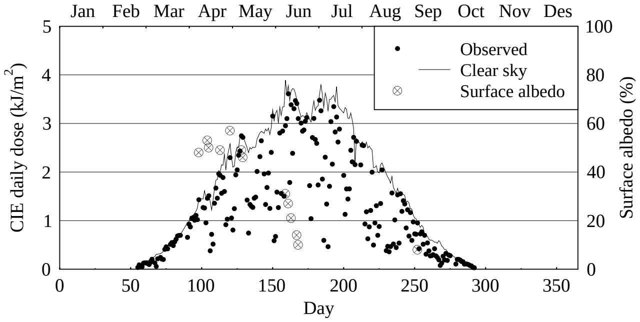

Figure 1. (dots) The daily erythemal dose derived from measurements made by a GUV-541 multichannel narrowband filter instrument. (circled crosses) The effective surface albedo as deduced from HR320 measurements. (solid line) The cloudless sky daily erythemal dose from model simulations using the effective surface albedo and total ozone.

surface albedo from Kylling et al. [2000] was used as input to the retrieval process because the derived effective cloud optical depth is very sensitive to surface albedo. In a second step, the derived total ozone and effective cloud optical depth were used together with the effective surface albedo as input to the tested and verified uvspec radiative transfer model [Mayer et al., 1997; Kylling et al., 1998] in order to calculate spectral global irradiance.

The retrieval of the effective cloud optical depth according to Stamnes et al. [1991] and Dahlback [1996] is sensitive to uncertainties of both measurement and model. The dominant factors are the uncertainty in the absolute calibration and the cosine error of the instrument as well as the uncertainty in the extraterrestrial irradiance used by the model. In order to reduce uncertainties in the derived optical depth, the GUV-541 data were corrected according to the following procedure. From a comparison between GUV-541 measurements and uvspec model simulations on day 208, during snow free and cloudless conditions, individual correction factors were established for each channel as a function of the solar zenith angle. Under the assumptions that the absolute calibration was stable, which has been assured by the travelling standard, and that the cosine correction is only a factor of solar zenith angle, these factors were applied to the whole GUV-541 time series in order to correct for systematic deviations between model and measurement which would offset the derived effective cloud optical depth. The correction factors consisted of a constant component of between 0.86 and 0.88 which accounts for the calibration uncertainty of the instrument and the uncertainty in the extraterrestrial irradiance, and an additional solar zenith angle dependent variation of 0.02 - 0.08 which is due to the cosine error of the entrance optics. Daily averaged GUV-541 ozone values were $(3 \pm 4)\%$ higher than daily averaged ozone values from direct sun measurements [Brewer, 1973] by a colocated Brewer MK III double monochromator.

Model simulations

The measured effective albedo [Kylling et al., 2000] as well as the total ozone and effective cloud optical depth retrieved by the GUV-541 instrument were used as input to the uvspec radiative transfer model [Mayer et al., 1997; Kylling et al., 1998] which is based on the discrete ordinate radiative transfer (DISORT) algorithm of Stamnes et al. [1988]. As outlined above, this model was used to reconstruct the global spectral irradiance at 1 nm resolution from the GUV-541 measurements. Using the derived parameters to reconstruct spectral irradiance, allowed us to separate the effects of clouds and surface albedo. Two scenarios were simulated in addition to the reconstructed spectra: (1) actual surface conditions and cloudless sky; (2) snow free surface and actual effective cloud optical depth.

All spectra were weighted with the CIE erythema action spectrum [McKinlay and Diffey, 1987]. Although the GUV-541 data were available every minute, for the simulation of daily, monthly, and yearly doses spectra were calculated only every 10 min. This was a compromise between speed and accuracy. The arising uncertainty in daily doses is estimated to be smaller than ±2–3% while the uncertainty in monthly and yearly doses is negligible. For the calculation of daily doses, solar zenith angles larger than 80° were neglected. While radiation at large solar zenith angles is important for those short days when the sun is just above the horizon, it has negligible effect on the doses presented here. The overall uncertainty in the daily, monthly and weekly UV doses is estimated to be ±16% (comprising ±5% uncertainty in the absolute calibration; ±4% total ozone; ±15% GUV-541 correction factor).

Finally, estimates of the surface erythemal irradiance were derived from EP–TOMS measurements. The pseudo-spherical discrete ordinate solver of the TUV model [Madronich and Flocke, 1997] was used to calculate cloudless sky daily erythemal doses on the basis of EP–TOMS total ozone. TUV and uvspec have been carefully compared by Weele et al. [2000] and Koepke et al. [1998]. The agreement between the two models is excellent. The surface albedo was set to 0.05. Reduction by clouds was considered by multiplying the cloudless sky value with a cloud modification factor derived from EP–TOMS cloud reflectivity according to Eck et al. [1995]. For this analysis, the original EP–TOMS overpass data with a footprint size of 26×26 km^2 were used instead of the EP–TOMS level 3 gridded data in order to reduce uncertainties due to the scale mismatch between the Tromsø measurement and the large EP–TOMS pixel.

Results

The reconstructed daily erythemal dose exhibits large temporal variations, mainly due to changing cloud cover

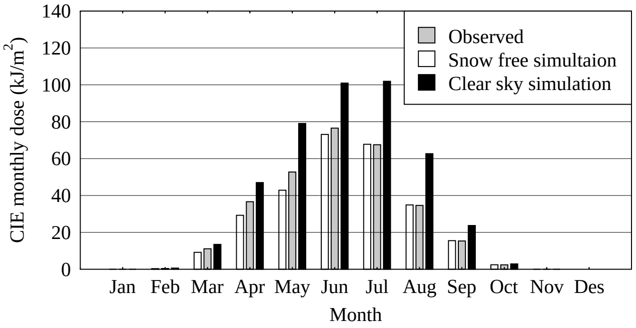

Figure 2. The observed monthly erythemal dose (white); (black) simulations for cloudless sky and observed surface conditions; and (grey) simulations using actual sky conditions but snow free surface.

(dots, Figure 1). Compared to the simulated cloudless sky erythemal dose (solid line, Figure 1) the daily cloudy doses are reduced by as much as 85%. The small short–term variations in the cloudless sky erythemal dose are caused by variations in total ozone.

The observed monthly erythemal dose is shown in Figure 2 together with model simulations for cloudless sky and actual surface conditions, and actual sky conditions but snow free surface. The presence of clouds reduced the monthly erythemal dose by 20–40% (Figure 3, black). The ratio between the observed monthly erythemal dose and the simulated dose for a constant (snow free) albedo of 0.1 is shown in Figure 3 (grey). Multiple reflections between the snow covered surface and atmosphere caused an increase by more than 20% in the monthly erythemal dose for February–May. The maximum increase of a daily dose compared to snow free conditions is 63% for day 122 (May 2) which was a rather cloudy day. However, for overcast conditions the absolute value of the irradiance was always substantially smaller than for cloudless conditions, even in the presence of high surface albedo. The annual observed erythema dose was 297.6 kJ/m^2 and the cloudless sky simulated dose 432.7 kJ/m^2. Clouds thus reduced the annual dose by 31%. The simulated annual dose without snow, but including clouds, was 275.5 kJ/m^2. Hence, the snow increased the annual dose by 8%.

The ratio between the ground based measurement of the daily erythemal doses and the EP–TOMS doses are shown in Figure 4. There is a large day to day scatter caused by the assumption that the cloud situation at the satellite overpass time is representative for the whole day. For monthly doses the agreement between the EP–TOMS and the GUV-541 doses is excellent when there is no snow on the ground, July–September. When comparing TOMS irradiances with a Brewer spectroradiometer located in Toronto, Canada, Herman et al. [1999] found TOMS values to be 20% higher. The much better agreement found here may be due to cleaner air over Tromsø and the cosine correction applied to the data. Herman et al. [1999] estimate that these effects contribute 11% and 6% respectively to the overall difference for Toronto. For the earlier months, March–June, the EP–TOMS doses are too low by 50–60%. This discrepancy is due to the use of a too low albedo in our EP–TOMS calculations and an overestimate of cloudiness. The too low albedo value causes EP–TOMS doses to be approximately 20% too low for those months when there is snow on the ground. The overestimate of cloudiness is due to the EP–TOMS instrument being unable to distinguish between reflection of snow and clouds. Reflection at the snow covered surface is erroneously interpreted as cloudiness, and, when used as input to the UV algorithm instead of an albedo representative for snow cover, surface irradiances are systematically under–estimated. Although this is a well–known fact, Figure 4 demonstrates that this problem is not neccessarily confined to a short period of the year where irradiances are low anyway. On the contrary, at the high latitude site of Tromsø, the UV irradiance was significantly under-estimated half of the time, and well into May and even June, when the radiation levels are approaching their maximum values. The yearly EP–TOMS dose is 219.2 kJ/m^2 which is about 26% lower than the dose observed at the surface. Finally, the large scatter of the ratio in Figure 4 shows that EP–TOMS derived doses have to be averaged over several days to yield representative results.

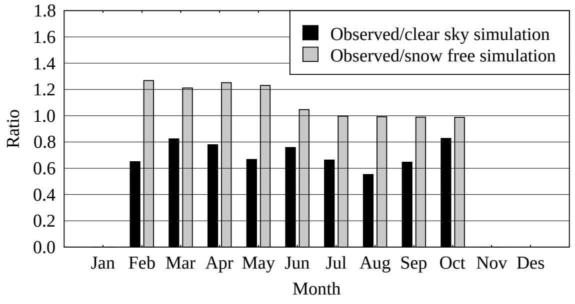

Figure 3. The ratio between (black) the observed and cloudless sky simulated monthly doses, and (grey) the ratio between observed doses and doses simulated with snow free surface conditions.

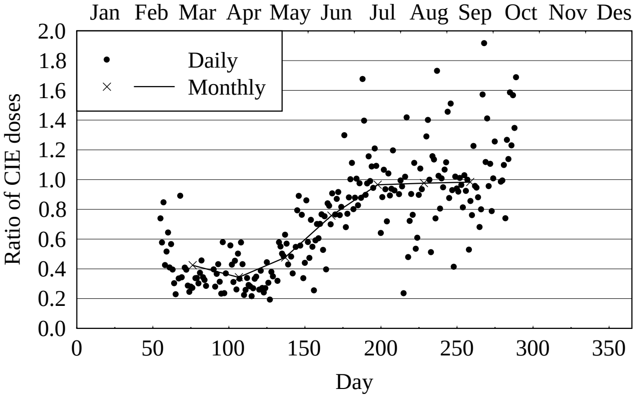

Figure 4. The ratio between erythemal doses derived from GUV-541 and EP–TOMS measurements. (black dots) Daily doses and (solid line with ×) monthly doses.

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