Long-term (1936–2003) ultraviolet and photosynthetically active radiation doses at a north Norwegian location in spring on the basis of total ozone and cloud cover

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[1] We have reconstructed a homogeneous and consistent 68-year time series of ultraviolet (UVR) and photosynthetically active radiation (PAR) doses for the spring period at a marine location in northern Norway. The time series is simulated mainly on the basis of the Tromsø total ozone series and routine meteorological observations of cloud cover. All other relevant input parameters were fixed at realistic values determined by local measurements and climatology. Our approach is applicable to a wide range of locations worldwide where routine ozone measurements and cloud observations are done. For the whole period 1936–2003, we find trends of +4.5%, +2.8% and +1.3% per decade for the monthly UVB doses in March, April and May, respectively. UVA and PAR doses, which are not affected by total ozone, reveal smaller trends (+1–2% per decade) in March and April, while the May trend is comparable to UVB. At shorter term, however, the radiation trends were very variable. *INDEX TERMS:* 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 1610 Global Change: Atmosphere (0315, 0325); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Engelsen, O., G. H. Hansen, and T. Svenøe (2004), Long-term (1936–2003) ultraviolet and photosynthetically active radiation doses at a north Norwegian location in spring on the basis of total ozone and cloud cover, *Geophys. Res. Lett.*, *31*, L12103, doi:10.1029/2003GL019241.

1. Introduction

[2] Ultraviolet radiation (UVR) is potentially harmful for a wide range of biological systems, including the human health, ecosystems and agricultural crops. Photosynthetically active radiation (PAR) on the other hand is a necessity for biological production. Both radiation regimes are influenced by solar elevation, topography, cloud cover and atmospheric composition, especially aerosols. In addition, the high energy part of the UV spectrum (UVB and UVC, $\lambda <$ 315 nm) are strongly influenced by ozone, whereas the low-energy part of the UVR (UVA) and the PAR are not. It is, however, the UVB and UVC which are particularly harmful to all forms of life. Therefore, serious depletion of the ozone layer since the late 1970s in both polar regions [e.g., *Solomon*, 1999] caused severe concerns about the potential consequences resulting from an increase of UVR. There are indications of a substantial decrease of ozone at moderate northern latitudes (35–60°N) in winter/spring [*World Meteorological Organization* (*WMO*), 2003]. However, as important as ozone is the cloud coverage, and changes in cloud cover can modify the UVR trends significantly. So in order to derive realistic trends in UV radiation, it is indispensable to include realistic estimates of cloud cover.

[3] Reliable trends can only be determined on the basis of long time series. Accurate and systematic ground-based UVR measurements only exist for the last few decades and most UV series started in the early 1990s [*WMO*, 2003, and references therein]. Satellite reconstructions of UVR have generally excellent spatial coverage, and are only available from late 1970s and onwards [e.g., *Krotkov et al.*, 2002]. For single sites, reconstruction of longer UV series is possible based on local ozone measurements and on various techniques to estimate the effect of cloudiness, e.g., by broadband instruments [*Kaurola et al.*, 2000] and sunshine recorders [*Lindfors et al.*, 2003]. Here we present a consistent and homogeneous time series of UVR and PAR daily doses for a single site, Skrova, (68.17°N 14.67°E), from 1936 to 2003, based on records of ozone at Tromsø and cloud cover observations at Skrova. The Tromsø (69.65°N 18.95°E) ozone time series on which this work is based, is the world's second longest. To our knowledge this paper contains the longest reconstructed UVR time series to date. Such a long time series of all the most widely used dose types provides a unique indication of radiation climate trends.

2. Method

[4] All UVR reconstructions in this work are based on simulations produced by the rigorous and accurate LibRadTran software package version 0.99 (see http://www. libradtran.org). The radiation transfer model allows the user to define the optical properties of most relevant surface and atmospheric constituents, i.e., aerosols, clouds, surface reflection and trace gases. However, only observations of ozone column [*Svenøe*, 2000] and cloud octal fraction (http://met.no/observasjoner) were available on a daily basis (Table 1) throughout the full study period. Ozone column data were available from the Tromsø data series from 1936, with only two major interruptions in spring, 1950 and 1972–1984. Ozone data from the Total Ozone Mapping Spectrometer (TOMS), version 7.1, are available from 1979, and we decided to use these data when available due to their regular availability and well-documented characteristics. From June 1994 to July 1996 no TOMS instruments were in operation, and this data gap was filled with Brewer and Dobson measurements from Tromsø. For the

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Table 1. Daily Variable Input Parameters for libRadtran

Daily Parameter	Period	Location	Source
Ozone column	1979–1994	Tromsø	TOMS satellite instrument
	1997–2003	(69.65°N 18.96°E)	
Ozone column	1995–1996	Tromsø	Brewer spectrometer
Ozone column	1973–1978	Murmansk	M83 filter ozonometer
		(68.97°N 33.03°E)	
Ozone column	1940–1972	Tromsø	Dobson spectrometer
Ozone column	1936–1939	Tromsø	Fery spectrograph
Cloud octal fraction	1936–2003	Skrova	Met.no observations
		(68.17°N 14.67°E)	

missing years 1973–1978 we used the closest ozone series available, i.e., Murmansk [*Bojkov et al.*, 1994]. The full data series contained occasional minor data gaps. All missing daily values were filled by linear interpolation. The largest gap, except for all 1950, was 25 April–30 May 1994 when neither TOMS, nor ground-based ozone measurements were available near Tromsø. The cloud cover was observed in cloud octals from the Skrova meteorological station. Before 1949 a decadal scale was used. In contrast to ozone, cloud octal observations existed for nearly all days, except for a 19-day interruption in 1940.

[5] All remaining model input parameters were fixed at realistic values. The oceanic albedo was set to 0.09 corresponding to a wind speed of 7 m/s, according to the OCEAALBE subroutine of the 6S software [*Vermote et al.*, 1997] (see ftp://loaser.univ-lille1.fr/6S). Maritime aerosol optical depths (τ) were given by $\tau = \beta * \lambda^{-\alpha}$ where the Ångström coefficients α and β were set to 1.3 and 0.02, respectively, and the wavelengths (λ) are in micrometers. These assumptions are close to typical values of aerosol measurements in Tromsø using a Jobin-Yvon HR320 spectrometer of direct solar radiation (T. Persen, University of Tromsø, personal communication, 1997). Otherwise, for all simulations we assumed a sub-arctic winter atmosphere [*Anderson et al.*, 1986].

[6] Apart from cloud fractions, we had to assume all other optical properties of clouds. As "typical" for our site, we chose alto-stratus cloud water droplets of effective radius of 7.2 μm [*Shettle*, 1989], homogeneously distributed between 2 and 5 km altitude [*WMO*, 1956]. The effect of cloud fractions (C) on surface irradiances (I) was computed according to the formula $I = C * I_{overcast} + (1 - C) * I_{clear}$. Unfortunately, no regular cloud thickness data are available anywhere near Skrova throughout the full period. We derived a representative cloud water column from a four-month time series of Ground-based UV radiometer (GUV) measurements at local noon in Tromsø. To maximize the cloud signal, we selected irradiance data for 28 totally overcast days from March through May 1997. Using libRadtran, we simulated the GUV 380 nm channel surface irradiances for various cloud water columns and searched for the minimum least squares fit with the measurements. The selected cloud water column was 220 g m^{-2}, corresponding to a cloud optical depth of 36 at wavelength 360 nm.

[7] For all simulations of the Tromsø GUV data we used effective surface spectral albedos derived during clear days in Tromsø in 1997 [*Kylling et al.*, 2000].

[8] We computed daily doses with spectral weights of CIE erythema [*MacKinley and Diffey*, 1987], PAR (uniform 400–700 nm), UVA (uniform 315–400 nm) and UVB (uniform 290–315 nm) for the months March, April and May.

3. Quality Assessment

[9] As already described, the libRadtran model simulations were benchmarked with GUV measurements (Figure 1) to make an assessment of the uncertainties of the simulations. We used essentially the same model input parameters which were used to derive the cloud liquid water column. The comparison was made to the full record of March through June 1997. The average ratio of the GUV measurements to the corresponding simulations was 1.03 ± 0.36. The corresponding ratios of monthly values were more stable (1.04 ± 0.10) indicating that simulations of monthly values can be done somewhat more reliably. We assess that most of the inaccuracies in simulations of daily dose rates are due to uncertainties of the cloud optical properties such as thickness, phase, droplet sizes and densities. These can fluctuate rapidly throughout the day, while we assume fixed values in our simulations. A major uncertainty in our method is that it cannot account for long-term changes in cloud properties. The cloud observations do not provide any information about the cloud morphology and optical thickness, only cloud cover fractions. Throughout our simulations, we assumed that the ozone columns originating from Tromsø, and for a limited time period, Murmansk (68.97°N 33.03°E), are suitable substitutes for the non-existent ozone information for Skrova. To test the validity of such an assumption we compared TOMS ozone observations in the period 1979–2003 from Murmansk and Tromsø with corresponding TOMS observations at Andenes (69.30°N 16.00°E), which is closer to Skrova. The mean overall ratios were 1.017 ± 0.087 and 1.006 ± 0.033, respectively, indicating that the ozone observations from Tromsø and

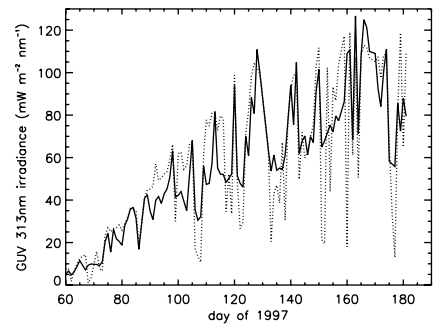

Figure 1. GUV measurements (dotted lines) versus corresponding libRadtran model simulations (solid lines) in the period March through June 1997.

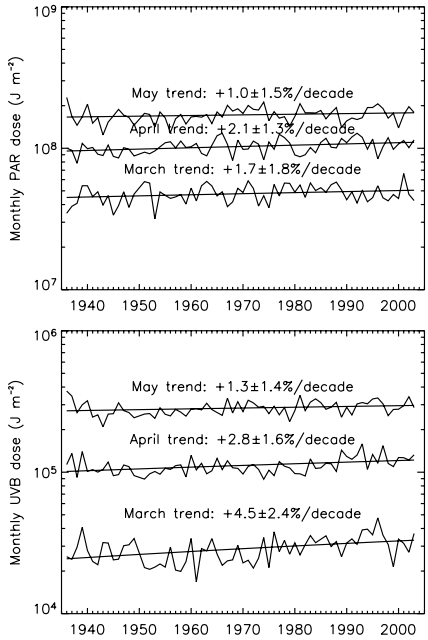

Figure 2. UVB and PAR monthly doses for Skrova in Lofoten Islands from 1936 to 2003. Trends are given in percent increase per decade ±2σ. See color version of this figure in the HTML.

Murmansk should be fairly representative also for the ozone amounts at Skrova. Andenes, Tromsø and Murmansk are located 140, 240 and 750 km from Skrova, respectively. *Lindfors et al.* [2003] found good agreement between ozone measurements from Tromsø and Sodankylä, 400 km apart, and thus support our assumption.

4. Results and Discussion

[10] From the daily dose simulations, we computed a time series of UVB and PAR monthly doses for March, April and May at Skrova from 1936 to 2003 and calculated overall trends (Figure 2). For all months and doses, the radiation trends were positive, ranging from 1.3 ± 1.4%/decade to 4.5 ± 2.4%/decade in UVB, and from 1.0 ± 1.5% to 2.1 ± 1.3%/decade in the case of PAR. For UVA the trends were not very different from that of PAR, i.e., 1.2 ± 1.3%, 1.6 ± 1.0% and 0.8 ± 1.2% per decade for March, April and May, respectively. The UVA and PAR trends were smaller than the UVB trend, and the difference was largest in March. For that month the UVA and PAR trends were only on the verge of being statistically significant whereas the UVB trend was the strongest overall. For all UVR and PAR doses the trends were lower for May than for the other two months. In fact, no trend was statistically significant in May. This is due to the fact that cloud fractions had a more moderately decreasing trend in May than in March and April (Table 2, 2nd column). UVB, UVA and PAR are all strongly attenuated by cloudiness. The negative trends were stronger for UVB than for UVA and PAR, which are mainly due to the additional negative trend of ozone. Ozone absorption is strongest in UVB, and UVB was consequently more affected by the negative ozone trend. For example, the integrated ozone absorption cross-sections at 226 K for UVA and PAR are only 3% and 6% of that for UVB, respectively. The CIE erythemal doses have trend characteristics lying between UVB and UVA (Table 3, 2nd column). This is to be expected since the CIE spectral weights overlap both bands.

[11] The applied time range has a significant impact on the trends and their uncertainties (Table 3). From the periods 1979–1999, 1976–1995 and 1983–1997 we observed strong positive trends of CIE weighted UV doses in April, and much smaller and statistically insignificant trends for the other months. However, for the years 1950–1972, May had the strongest positive trend (8.1 ± 4.7%/decade). The hypothesis that UV trends in spring would be stronger after 1980 because of ozone depletion [*Solomon*, 1999] cannot be supported unconditionally (Table 3, columns 4, 5) due to the effect of clouds. In March, we found an increase in cloudiness (+5 %/decade) in the period 1979–1999 at Skrova (Table 2), which balanced the negative trends in total ozone in the same period (−6 %/decade). In April, on the other hand, both cloudiness and ozone had negative trends (−5% and −7 %/decade), adding to the record UV trend of +9 %/decade. The ozone trends were negative for all periods (but one), with particularly great ozone decrease and associated UVB increase in the 90's. The latter was also detected elsewhere in Europe [*Zerefos et al.*, 1997]. Trends for the long time periods 1950–1999 and 1936–2003 were both moderately positive and with much less uncertainty than the shorter time series. This stresses the importance of lengthy and homogeneous data time series to perform trend analyses.

[12] Tromsø lies near the edge of the polar vortex, and thus experiences large temporal variability of total ozone in the late winter and spring. Skrova is a coastal location with shifting cloud cover. It is thus difficult to find similar studies of surface radiation with comparable atmospheric conditions. *Lindfors et al.* [2003] reconstructed CIE weighted UVR for Sodankylä for 1950–1999, 1950–1972 and 1979–1999, partially on the basis of an earlier version of the total ozone series from Tromsø, and local information on sunshine duration and snow depth. All mean trends for identical time periods are within the bounds of statistical uncertainty (Table 3). The statistically significant trend in March for the period 1950–1999 is confirmed by *Lindfors et al.* [2003], while the trends for the shorter time intervals and in March and April differ considerably at the two stations. The reason for this is probably the meteorological location, with Skrova on the coastal weatherside of the Scandinavian mountain ridge, while Sodankylä is on its

Table 2. Trends (% Increase per Decade ±2σ) for Ozone Columns/Cloud Fractions at Skrova for Various Periods

	1936–2003	1950–1999	1950–1972	1979–1999	1976–1995	1983–1997	1991–1996
March	−1.5/−1.7	−3.2/−0.4	−2.4/−4.4	−5.9/+5.2	−6.9/+9.2	−10.1/+8.1	−21.5/−25.3
April	−0.7/−2.3	−1.6/−1.3	−1.5/−5.6	−5.1/−6.9	−6.6/−7.6	−9.1/−1.3	−15.6/+60.5
May	−0.4/−1.2	−0.9/−2.2	−0.6/−14.2	−0.3/−4.4	−3.2/+1.5	+0.8/−8.4	−5.6/−62.8
Spring	−0.9/−1.7	−1.9/−1.3	−1.6/−8.1	−3.8/−2.0	−5.6/+1.2	−6.1/−0.5	−13.5/−12.0

Table 3. Trends (% Increase per Decade ±2σ) of CIE Erythemal Monthly UV Doses at Skrova for Various Periods

	1936–2003	1950–1999	1950–1972	1979–1999	1976–1995	1983–1997	1991–1996
March	2.5 ± 1.3	4.0 ± 2.1	3.6 ± 7.2	−0.2 ± 6.3	−0.4 ± 5.1	3.6 ± 9.1	37.2 ± 42.1
		$(3.9 \pm 3.0)^{s}$	$(0.4 \pm 8.6)^{s}$	$(7.5 \pm 10.3)^{s}$			
April	2.2 ± 1.2	3.1 ± 1.9	4.0 ± 4.8	9.1 ± 7.4	10.8 ± 7.6	12.6 ± 13.7	−30.1 ± 55.4
		$(1.8 \pm 1.8)^{s}$	$(0.3 \pm 5.5)^{s}$	$(5.2 \pm 7.1)^{s}$			
May	1.2 ± 1.3	2.2 ± 1.7	8.1 ± 4.7	1.6 ± 7.3	3.6 ± 7.5	0.6 ± 12.5	43.7 ± 14.3
		$(0.8 \pm 3.0)^{s}$	$(7.2 \pm 8.5)^{s}$	$(2.9 \pm 11.0)^{s}$			
Spring	1.6 ± 0.9	2.7 ± 1.2	6.5 ± 3.4	3.6 ± 4.8	5.2 ± 4.3	2.9 ± 7.3	21.8 ± 21.6
					$(5.4)^{b}$	$(11.4)^{n}$	$(30)^{t}(90)^{B}(-30)^{r}$

Trends for [s]Sodankylä [*Lindfors et al.*, 2003], [b]Belsk, [n]Norrköping (83-97) [*Kaurola et al.*, 2000], [t]Thessaloniki (91-96), [B]Brussels (93-96), [r]Reykjavik (92-96) [*Zerefos et al.*, 1997] in parenthesis.

continental leeside. The difference in ozone data sets used in the two publications has also some influence on the longest time series. The total ozone used by *Lindfors et al.* [2003] are 2 to 6% (depending on month: least in March, larger in April and May) lower between 1950 and 1965 than the data used by us [*Svenøe*, 2000].

[13] CIE weighted trends in spring from Belsk (May 1975–Dec. 1995), the longest continuous time series of surface UV measurements in Europe, is in good agreement with our trends (Table 3). The spring CIE dose trend at Norrköping as well as the full year trends of 305 nm irradiances elsewhere in Europe do not agree so well, but reflects the uncertainty of trends over such short time periods.

5. Conclusion

[14] We have outlined a simple method to reconstruct UVR and PAR data on the basis of widely available input data. The approach is a reasonable way to produce consistent, long-term UVR time series and trends at many locations worldwide. From our reconstructed 68 years long UVR and PAR time series for Skrova, we found positive UVR and PAR trends within a range of percent. Somewhat stronger trends were observed for March and April and for selected shorter time periods. Ozone columns and cloud fractions had negative trends for all spring months, but can be very different and even have opposite signs at shorter term.

[15] **Acknowledgments.** The access to the TOMS ozone data at the Goddard Space Flight Center, NASA, the Murmansk ozone data via the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) and the LibRadtran software, is gratefully acknowledged. The GUV data is part of the Norwegian UV network funded by the Norwegian Pollution Control Authority. We thank Kåre Edvardsen at NILU for scientific support regarding the GUV data. This work was supported by the European Commission through project EVK-CT-1999-00012 (UVAC) and the Norwegian Research Council.

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