Helgol Mar Res (2001) 55:35–44
DOI 10.1007/s101520000059

ORIGINAL ARTICLE

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European light dosimeter network (ELDONET): 1998 data

Received: 4 February 2000 / Received in revised form: 12 May 2000 / Accepted: 19 May 2000 / Published online: 26 January 2001

Abstract The European light dosimeter network of over 40 stations has been established in Europe and other continents equipped with three-channel filter dosimeters to measure solar radiation in three channels, UV-B (280–315 nm), UV-A (315–400 nm) and photosynthetically active radiation (PAR). The recorded data have been evaluated, and the monthly doses in all three channels show a strong latitudinal dependence from northern Sweden to the Canary Islands. There are a few remarkable exceptions such as the data recorded at the high mountain station on the Zugspitze (German Alps) and unequal doses at stations at comparable latitudes which indicate the impact of local weather conditions and mean sunshine hours. While generally peak values are recorded in the months of June and July, the UV-B maxima are shifted later into the year, which is due to the antagonistic functions of decreasing solar angles and increasing transparency of the atmosphere as the total column ozone decreases in the second half of the year for the Northern Hemisphere. This is supported by comparison with modelled total column ozone and satellite-based measurements. Also the ratios of UV-B:UV-A and UV-B:PAR as well as UV-A:PAR peak during the summer months, with the exception of the northernmost station at Abisko (north Sweden) where the UV-A:PAR ratio peaks in the winter months which is due to the specific photoclimatic conditions north of the polar circle. The penetration of solar radiation into the water column was found to strongly depend on the transparency of the water column. In Gran Canaria more than 10% of the surface UV-B penetrated to 4–5 m depth. The path of the solar eclipse on 11 August 1999 could be followed in several stations with different degrees of occlusion of the sun disk.

Keywords European light dosimeter network (ELDONET) · High-altitude stations · Photosynthetic active radiation · Solar ultraviolet radiation · Underwater measurements

Communicated by K. Lüning

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Introduction

Solar radiation affects all forms of the biota on our planet, and scientists studying these effects need reliable measurements of this irradiation. In the first studies sporadic monitoring of solar radiation was established, and later systematic monitoring, to satisfy this need. Since specific wavelength bands induce different responses, it became important to measure spectrally resolved data. After the discovery of stratospheric ozone depletion caused by anthropogenic pollution, scientists became concerned as to what effects the resulting increased UV-B radiation [280–315 nm, Commission Internationale d'Eclairage (CIE) definition] has on the earth's biota (Acevedo and Nolan 1993; UNEP 1998). One of the first concerns was an increase in certain forms of human skin cancers (van der Leun 1993). In addition, UV-B is suspected to cause cataracts, affect the human immune system and to be responsible for other health effects in humans and animals (Noonan and de Fabo 1990; De Fabo et al. 1990; Longstreth et al. 1998).

Other concerns about adverse UV-B effects focus on reduced productivity, decreased food quality and other changes in terrestrial plants, with respect to both wild and crop plants (Panagopoulos et al. 1989; Björn 1989; Bornman 1991; Caldwell et al. 1998). Solar UV radiation impairs photosynthesis (Strid et al. 1990; Renger et

al. 1991), stomatal movement (Negash 1987; Negash et al. 1987), and the growth and development of a large percentage of plants investigated so far (Teramura et al. 1990a, 1990b; Cen and Bornman 1990).

The third area of research concentrates on adverse effects of enhanced solar UV-B radiation on aquatic ecosystems (Smith et al. 1992; Häder et al. 1995; Gerber et al. 1996; Jiménez et al. 1996; Häder et al. 1998; UNEP 1988) which are responsible for the production of about 50% of the biomass on our planet and, in addition, play a decisive role in global carbon fluxes (Sarmiento and Le Quéré 1996). Primary aquatic producers dwell in the top layers of the water column and have been found to be very sensitive to UV radiation (Cullen and Lesser 1991; Raven 1991; Häder 1997; Häder and Worrest 1997).

In order to estimate the effects of the various wavelength bands of solar radiation, a network of monitoring stations is needed. A number of networks monitoring solar radiation have been installed or are in the planning stage. One network is the Brewer network which uses spectroradiometers (Diffey 1996; Webb 1998). The Umweltbundesamt and the Bundesamt für Strahlenschutz have installed a network consisting of four stations (Offenbach, Schauinsland, Neuherberg, Zingst). This German network measures solar radiation at high spectral resolution (0.5–5 nm) as well as the integral of the total UV spectrum. A major drawback is that in principle the data are available to interested scientists, but currently there is only limited personnel available to evaluate the data and the bureaucratic obstacles to actually receive and use them seem to be difficult to overcome. Other European initiatives are the SUVDAMA (Spectral UV DAta and MAnagement) project initiated by Seckmeyer (Fraunhofer Institut für atmosphärische Umweltforschung, Garmisch-Partenkirchen, Germany) and the investigation of processes affecting UV-radiative transfer using simultaneous spectroradiometry with a set of well-defined instruments (Webb, Reading, England). Another project has been proposed by Bais (University of Thessaloniki, Greece) which is based on the intercomparison of data from existing spectroradiometers. All these projects plan to use spectrally resolved radiation data.

Some networks aim specifically at the UV-B band to monitor stratospheric ozone depletion. The Robertson-Berger network has been measuring UV-B irradiance at eight stations in the United States since 1974. The wavelength range (290–330 nm) covers the wavelength range associated with erythemal sensitivity which does not coincide with the CIE definition of UV-B (280–315 nm). Several other UV measuring networks have been installed worldwide using both terrestrial and satellite-based instruments (Booth and Lucas 1994; Kerr 1997; Lubin and Jensen 1997). Therefore, the European light dosimeter network (ELDONET) was installed. The ELDONET stations are arranged along a north-south transect from north Sweden (Abisko, 69°N) to the Canary Islands (Gran Canaria, 28°N) and extend east to west from Greece (Korinth, 24°E) to the Canary Islands (16°W) to cover the major light climate areas in Europe (Häder et al. 1999). In addition, stations have been installed in Africa, India, South America and New Zealand. Other stations can easily join the network, since the hardware and installation costs are comparatively low. The data are transferred to the central server of the network in Pisa on a regular basis and are available on the internet (http://power.ib.pi.cnr.it:80/eldonet) free of charge for non-commercial use (Marangoni et al. 2000).

Accurate and reliable, but low-cost, three-channel dosimeters were developed with filter functions corresponding to the UV-B (280–315 nm, CIE definition), UV-A (315–400 nm) and photosynthetically active radiation (PAR; 400–700 nm) wavelength ranges. The measured values can be compared with any biological filter function (e.g. DNA or plant sensitivity) to determine the biological effectiveness of the radiation. In addition to the more than 40 terrestrial stations, seven underwater stations have been installed in the North Sea, Baltic Sea, Kattegat, Mediterranean and Atlantic. The underwater stations are operated in conjunction with terrestrial instruments so that the attenuation in the water column can be determined. Two high-altitude stations have been installed in the European Alps (Zugspitze) and the Spanish Sierra Nevada.

Materials and methods

Hardware

The dosimeters connected in the network are three-channel broadband filter instruments. The entrance optic consists of an integrating Ulbricht sphere with an internal barium sulphate coating (Khanh and Dähn 1998). Large-area silicon photodiodes (BPX60 for the PAR range and SFH291 for the two UV ranges, both Siemens, Germany) are used in combination with custom-made filters to select the wavelength ranges for UV-B, UV-A and PAR. A mechanical shutter is used to close the UV-B channel to determine the dark value at regular intervals in order to eliminate age- and temperature-related drifts of the photodiodes. The dark values of the other two channels are stable, so that it is not necessary to determine them frequently. The instruments are housed in weatherproof cases with internal metallic shielding and thermal insulation. The internal temperature is kept at an elevated value of above 35°C. All instruments have identical optical and electrical properties in order to warrant intercomparison between the different sites. Only the optical entrance configuration is different in the underwater instruments to account for the immersion effect under water. The underwater instruments are bolted on heavy rocks or concrete slabs and have been shown to withstand even strong currents during winter storms. The internal temperature in the underwater instruments is not controlled since the water mass around them limits the temperature range. They have a calibrated pressure sensor to measure the depth of the water column above the instrument.

Software

The software package WinDose for the ELDONET instruments has been developed in Visual Basic (Microsoft, Redmond, Wash.) and runs under Windows 95/98 (Häder et al. 1999). The measurements commence in the morning when the sun is 12° below the horizon and end in the evening at the same solar angle which is calculated from the latitude and longitude of the location and the

time offset to universal standard time. Internally the software calculates in Greenwich mean time but displays the local time for convenience. The measured data are averaged over 1-min intervals and stored once every hour on the hard disk drive of the computer as ASCII files which facilitates further analysis of the data by the analysis program (WinData) developed for this purpose.

The central server of the network has been installed in Pisa to collect the data from all stations (Marangoni et al. 2000). The data are transferred either automatically by file transfer process, modem or manually. The data sets are checked for validity and integrity before being entered into the database. The data are available in graphical form and can be downloaded in numerical form from the server.

Calibration

Each instrument is accurately calibrated against a 1,000-W quartz halogen calibration lamp operated with a highly stabilized power supply (SL 1,000 W, Powertronic 710 D). The temperature dependence of the dark value is calibrated for each instrument between 20°C and 60°C. All calibration factors are stored in the individual.INI file. The absolute calibration was performed in an intercomparison of several spectroradiometers and the ELDONET instrument in September 1997 in Garmisch-Partenkirchen (southern Germany). Intercomparison of instruments to measure solar radiation is a vital tool for quality control and documentation (Seckmeyer et al. 1994; Leszczynski et al. 1998). All instruments are recalibrated at least every year.

Results

Figure 1A shows a measurement at Ljubljana (Slowenia, 46°N and 15°E) on 11 August 1999. In addition to some scattered clouds, the solar eclipse with a covering of 96.6% at around 12:48 hours is clearly visible in all spectral channels. Figure 1B represents the data for an almost clear day in Gran Canaria (Canary Islands, 28°N and 16°W) on 19 February 1998. PAR reaches almost 370 W m^{-2} during local noon in this station and UV-A amounts to 58 W m^{-2}. The UV-B irradiance peaked at about 1.8 W m^{-2}. The terrestrial instrument is located on the roof of a larger building with an almost unobstructed view of the horizon. A second instrument is located in the harbour less than 100 m away, so that the local weather conditions are comparable. Figure 1C shows the irradiances in the three channels at a depth of 4.3–5.3 m during the tidal cycle. PAR irradiance peaked at about 145 W m^{-2} and UV-A reached a maximal value of 17 W m^{-2}. The UV-B channel recorded a maximum at 0.25 W m^{-2}. During this time of the year the water is very clear while it becomes more turbid later in the year. At that time the measured values decrease to <25% of the ones reported for early spring (data not shown).

When the daily doses are added to calculate the monthly doses a broad peak is found for Gran Canaria during the summer months reaching 320 MJ m^{-2} in the PAR channel, 48 MJ m^{-2} in the UV-A and 1.3 MJ m^{-2} in the UV-B channel (Fig. 2A). The number of measured days in each month is indicated numerically above each set of columns. A few missing measurement data are interpolated from the existing data. The UV-B irradiance strongly depends on the solar angle and thus on the time of the year. In addition, it is affected by the total ozone column. In order to eliminate the effect of the changing cloud cover the ratio of UV-B:PAR and UV-B:UV-A can be calculated for all cumulative daily doses in the year (Fig. 2B). It is interesting to note that the UV-B:UV-A ratio peaks in early autumn rather than in the summer. This is also obvious when the UV-B:PAR ratios are calculated for every day (Fig. 2C). The autumn peak corresponds with lower ozone values as measured by the TOMS instrument on the NASA Earth Probe satellite. Also the predicted ozone concentration calculated on the basis of Green’s model (Green and Chai 1988) with a computer program shows higher Dobson units in spring than in autumn. Gran Canaria is the southernmost station of ELDONET in Europe (but not of other continents).

Erlangen (Germany, 50°N, 11°E) represents a typical central European station. The cumulative monthly doses reach about 244 MJ m^{-2} for PAR during the summer (Fig. 3A), but in July a higher cloud cover was observed during June or August. The peak in UV-A and UV-B irradiances was observed during June as predicted from the monthly mean solar angles. Also the ratio UV-B:UV-A peaks in June while the ratios UV-B:PAR as well as UV-A:PAR have their maximum in July (Fig. 3B). Also, plotting the UV-B:PAR ratios on a daily basis indicates a clear maximum in July which correlates with decreasing total ozone column values and the ozone values measured from the NASA satellite (Fig. 3C). The peak position is controlled by the antagonistic functions of the decreasing total ozone column values and the increasingly lower solar angles in autumn.

Lisbon (Portugal, 39°N, 9°W) shows a typical southern European (Mediterranean) light climate with highest irradiances in June with about 380 MJ m^{-2} in the PAR, 54 MJ m^{-2} in the UV-A and 1.4 MJ m^{-2} in the UV-B range (Fig. 4A). The UV-A:PAR, UV-B:PAR and UV-B:UV-A ratios also peak in June (Fig. 4B).

Also the northernmost station of the network (Abisko, north Sweden, 69°N, 19°E) showed maximal irradiances in June (Fig. 5A). This station is located above the Nordic polar circle, and during winter the sun does not rise above the horizon resulting in extremely low irradiances. However, it is interesting to note that the PAR peak doses in summer exceed those measured in Erlangen, which is due to the fact that in this month the sun does not sink below the horizon at the Arctic circle and the doses are effectively accumulated over 24-h periods. The ratios for Abisko are surprising (Fig. 5B): While UV-B:PAR and UV-B:UV-A peak in July, an opposite trend is found for UV-A:PAR, which has a maximum in December and January. This may be due to the higher amount of diffuse skylight during the winter months in comparison to the direct radiation which increases with longer wavelengths.

Figure 6 show the cumulative yearly doses for 1998 for the stations at which measurements were performed on about 250 or more days of the year arranged in a north-south gradient. There is a clear dependence on latitude, but there are also a few notable exceptions. Helgo-

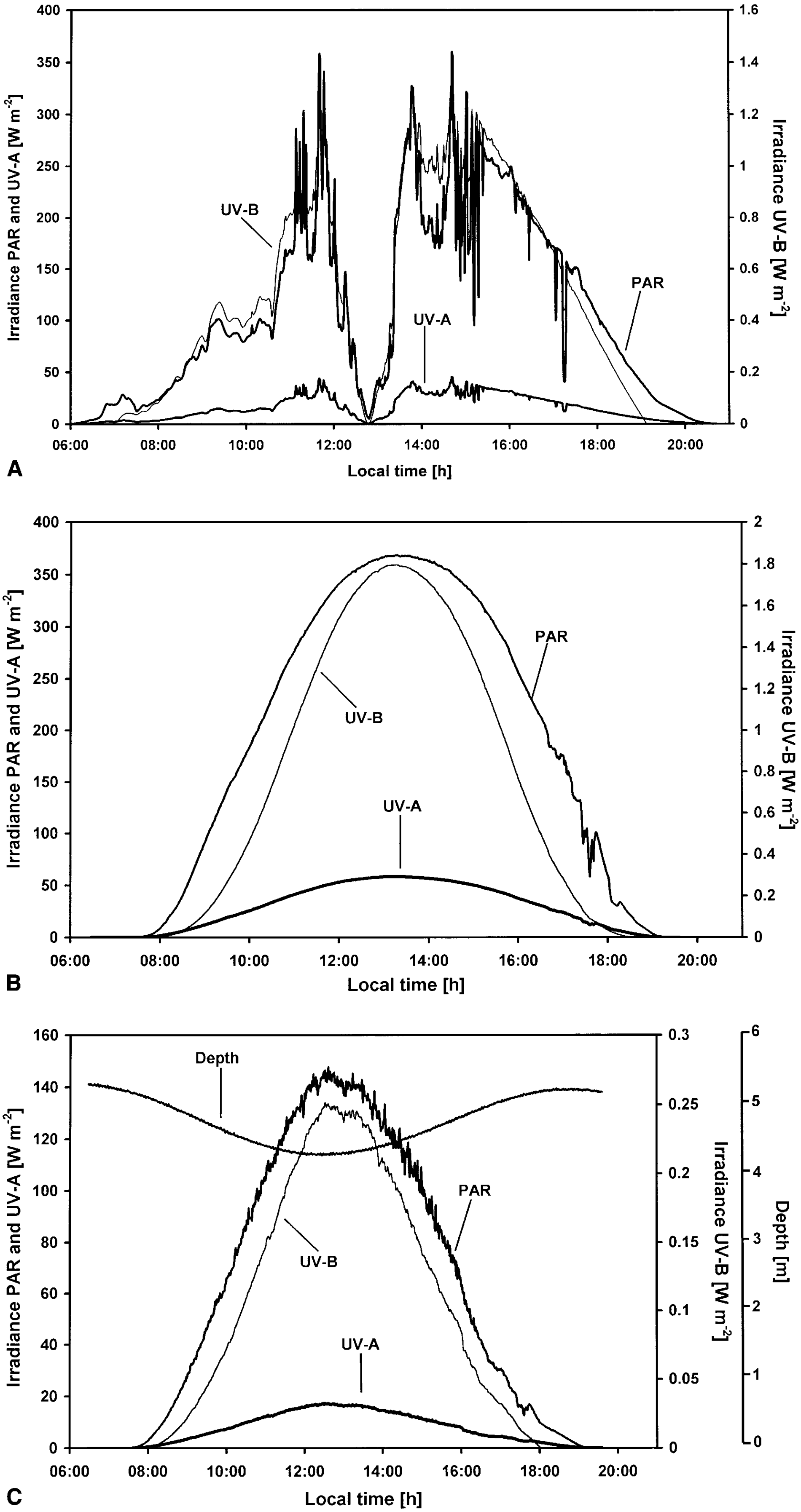

Fig. 1 Solar radiation on 11 August 1999 at Ljubljana (Slowenia, 46°N, 15°E) **(A)** in the ultraviolet (UV)-B (*fine line*), UV-A and photosynthetically active radiation (PAR) channels indicating the effect of the solar eclipse with 96.6% coverage. **B** Solar radiation on 19 February 1998 in Gran Canaria in comparison to the solar radiation which penetrates into the water column at 4–5 m depth (**C**)

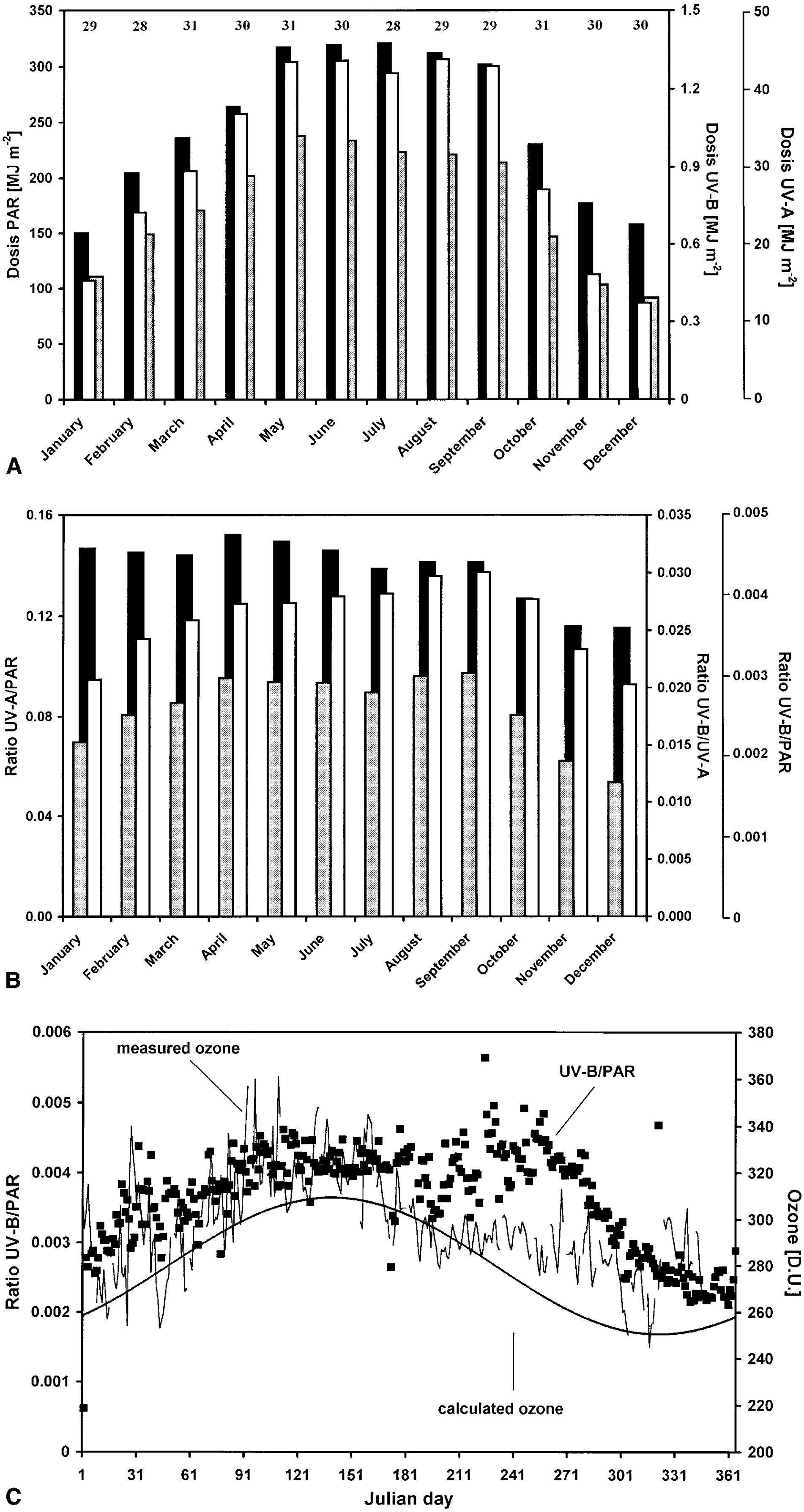

Fig. 2 **A** Monthly doses for Gran Canaria (Canary Islands, 28°N, 16°E) in 1998 in the UV-B (*white columns*), UV-A (*grey columns*) and PAR (*black columns*) ranges calculated for 30 days month^{-1} from the measured daily data indicated by the *numbers above each set of columns* and **B** the UV-A:PAR (black bars), UV-B:PAR (*grey bars*) and UV-B:UV-A ratios (*white bars*). **C** Daily ratios of UV-B:PAR (*black squares*) compared with the predicted total ozone column calculated with a computer program based on Björn and Murphy (1985) and satellite based measurements by the TOMS instrument on the Earth Probe satellite. For abbreviations, see Fig. 2

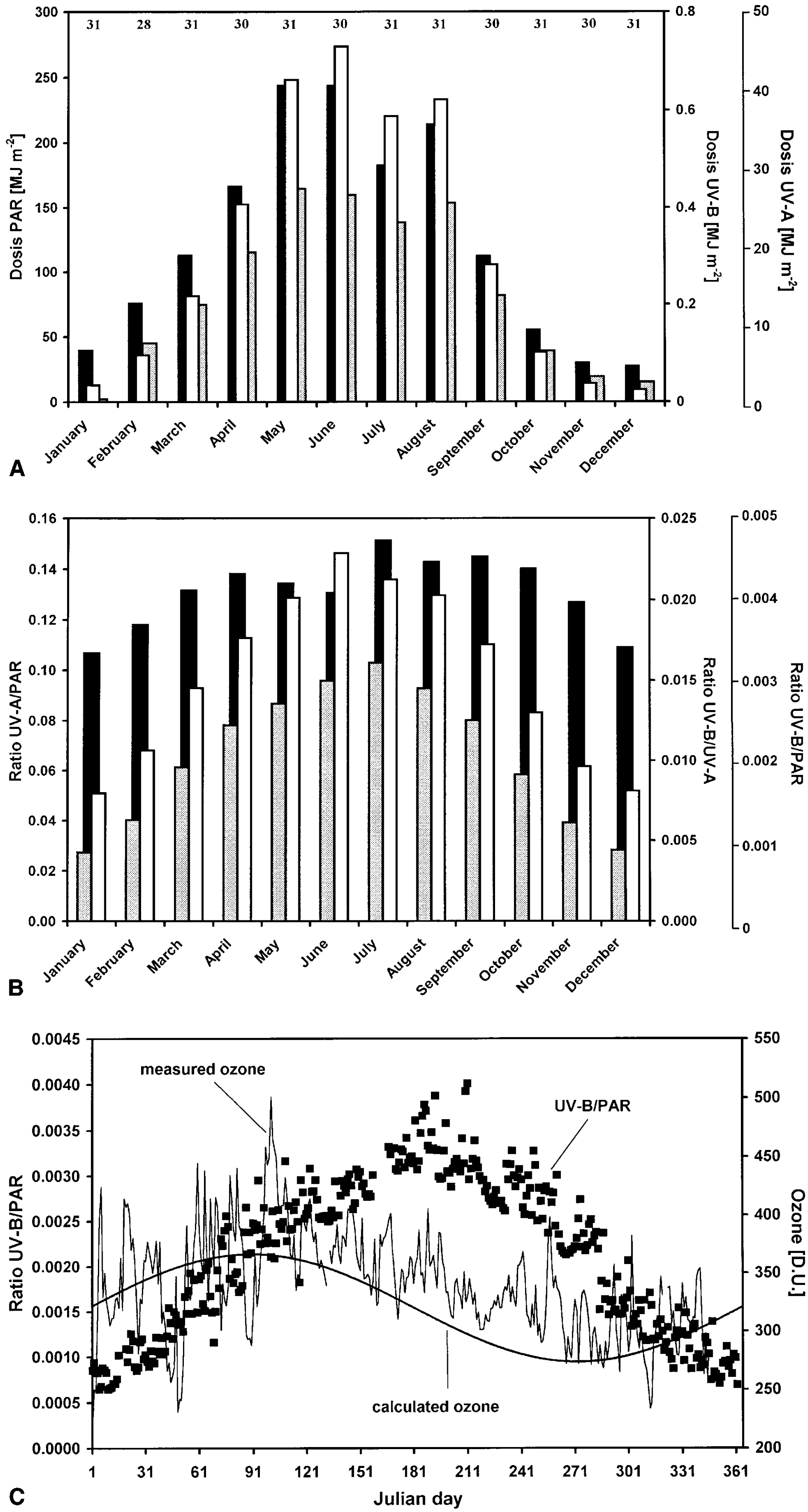

Fig. 3 **A** Monthly doses for Erlangen (Germany, 50°N, 11°E) 1998 in the UV-B (*white columns*), UV-A (*grey columns*) and PAR (*black columns*) ranges calculated for 30 days $month^{-1}$ from the measured daily data indicated by the *numbers above each set of columns* and **B** the UV-A:PAR (*black bars*), UV-B:PAR (*grey bars*) and UV-B:UV-A (*white bars*) ratios. **C** Daily ratios of UV-B:PAR (*black squares*) compared with the predicted total ozone column calculated with a computer program based on Björn and Murphy (1985) and satellite-based measurements by the TOMS instrument on Earth Probe. For abbreviations, see Fig. 2

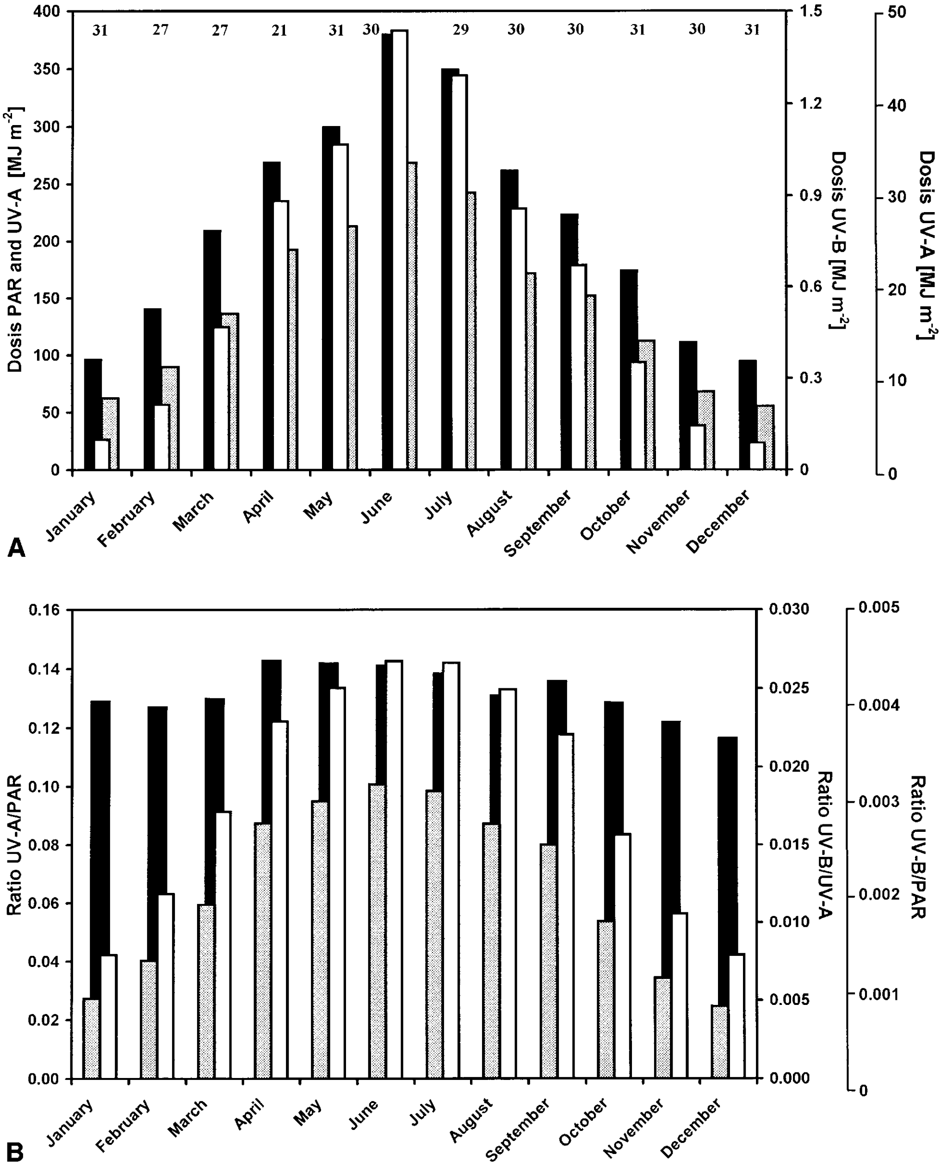

Fig. 4 **A** Monthly doses for Lisbon (Portugal, 39°N, 9°W) 1998 in the UV-B (*white columns*), UV-A (*grey columns*) and PAR (*black columns*) ranges calculated for 30 days month^{-1} from the measured daily data indicated by the *numbers above each set of columns* and **B** the UV-A:PAR (*black bars*), UV-B:PAR (*grey bars*) and UV-B:UV-A (*white bars*) ratios. For abbreviations, see Fig. 2

land (island in the German bight, 54°N, 8°E) shows comparatively higher doses than Rostock (on the southern coast of the Baltic Sea, 54°N, 12°E) even though the latitude is comparable. Karlsruhe (Germany, 49°N, 8°E) also has higher doses than Erlangen, which reflects the statistically higher number of clear days during the year in the former city.

The high mountain station on the Zugspitze (German Alps) has higher irradiances than other stations with a similar latitude, underlining the altitude effect and clear sky conditions in pristine Alpine locations. As expected, Gran Canaria has the highest yearly doses in all three wavelength bands.

Discussion

High-precision measurements of solar radiation are affected by several problems. Using highly accurate technology and taking extreme care during calibration can minimize these errors. The resolution and detection limits of the instrument are <0.1 W m^{-2} for PAR, <0.01 W m^{-2} for UV-A and <0.0005 W m^{-2} for UV-B. All currently available tools for quality control and documentation are used to ensure a high standard of precision. During their lifetime up to now – some instruments have been in use for over 5 years – the deviation from high-precision calibrated spectroradiometers was found to be <10% for the UV-B, 5% for the UV-A and 2% for the PAR channel.

Another problem is the long-term stability. The Robertson-Berger network had been installed to measure UV-B irradiances at eight stations in the United States since 1974 (Scotto et al. 1988). In contrast to the satellite data which indicated a gradual ozone depletion over the years (Frederick 1992), the Robertson-Berger meter network showed a consistent decrease in measurements of solar UV radiation. This apparent contradiction was

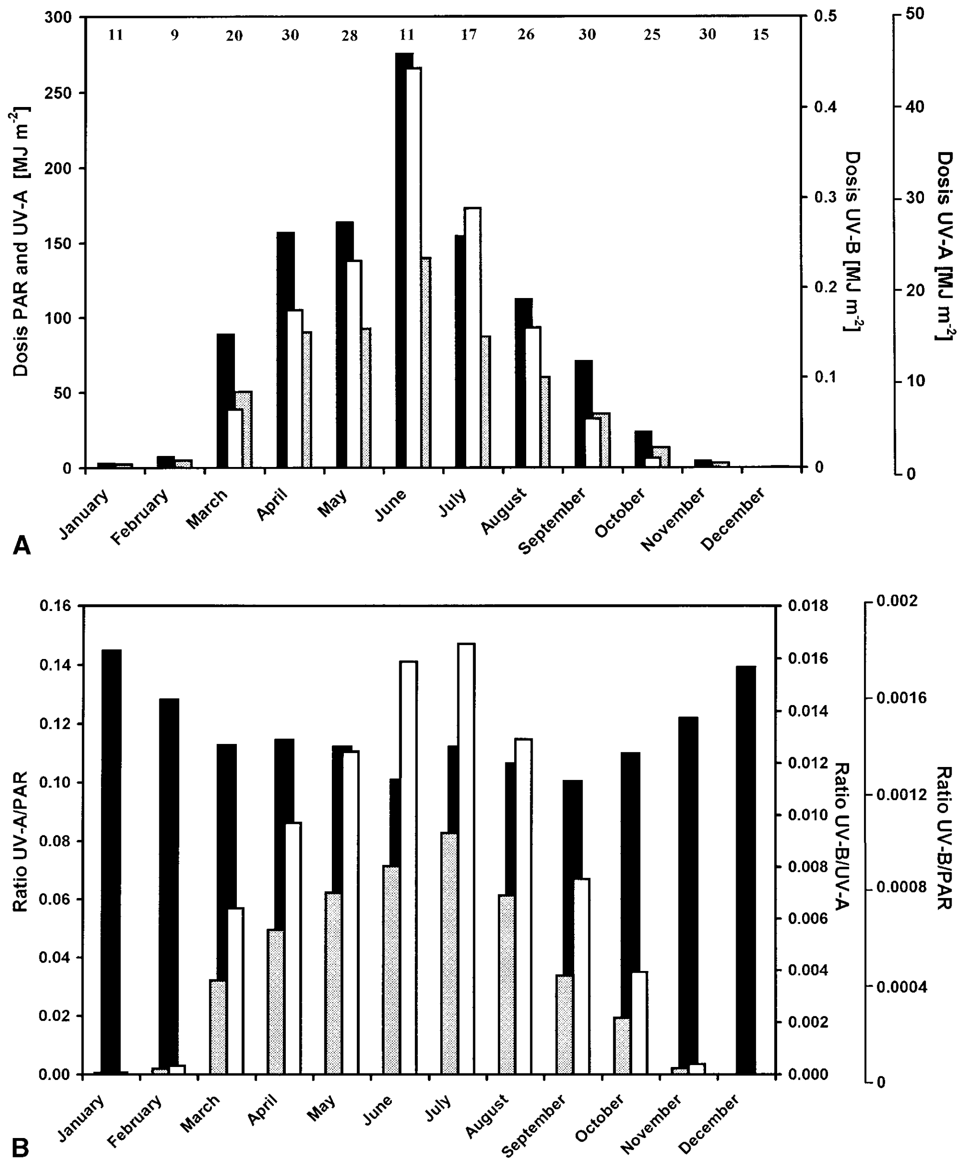

Fig. 5 **A** Monthly doses for Abisko (north Sweden, 69°N, 19°E) 1998 in the UV-B (*white columns*), UV-A (*grey columns*) and PAR (*black columns*) ranges calculated for 30 days month^{-1} from the measured daily data indicated by the *numbers above each set of columns* and **B** the UV-A:PAR (*black bars*), UV-B:PAR (*grey bars*) and UV-B:UV-A (*white bars*) ratios. For abbreviations, see Fig. 2

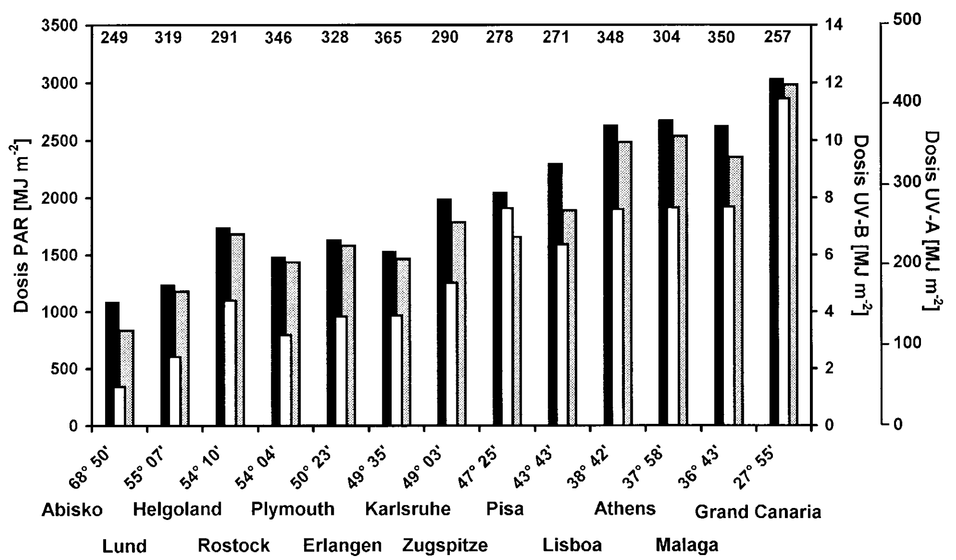

Fig. 6 Yearly doses for 1998 at selected stations of the European light dosimeter network along a latitudinal gradient (in °N) from north to south in the UV-B (*black columns*), UV-A (*grey columns*) and PAR (*white columns*) ranges. The *numbers above the stations* indicate the measured number of days from which the total dose was extrapolated. For abbreviations, see Fig. 2

eventually explained in part by the fact that most Robertson-Berger meters were installed at meteorological stations in the neighbourhood of airports, so that the increasing atmospheric pollution due to higher air traffic offset the increase in UV-B reaching the ground. As a consequence the Robertson-Berger readings were in contradiction to the predicted UV-B and ozone data, both in their numerical values and even in the sign of the trend (Kennedy and Sharp 1992). In addition, a significant temperature sensitivity of the Robertson-Berger meters as well as drifts both in wavelength accuracy and absolute irradiances due to aging were found which were larger than and offset the actual increases in UV-B reaching the ground (Johnson and Moan 1991; DeLuisi et al. 1992; Frederick and Weatherhead 1992). For the ELDONET instruments the reproducibility over several years was measured to be 1.4±1.0% for the PAR channel, 1.9±1.5% for UV-A and 3.8±3.8% for UV-B, based on a total of 41 instruments, indicating a long-term stability of the instruments (Häder et al. 1999).

Generally speaking, high-precision measurements can be obtained with spectroradiometer networks. However, both the price of the instruments and the large investment in maintenance prohibit the installation of a dense European or global network. One of the advantages of the ELDONET instruments is the low cost (about 2,300 Euros) which allows the number of instruments in the network to be easily increased. A disadvantage is that there is no spectral resolution within the channels, but the measured values can be converted with a given biological weighting function. In contrast to the networks described above, the aim of the ELDONET was to develop an instrument which satisfies the specific interest and needs of the scientific community involved in the study of the effects of solar radiation.

The measured monthly doses show a strong dependence on the latitudinal gradient within ELDONET. However, there are a few remarkable exceptions due to local weather conditions, indicating that the ELDONET is a solid approach to establishing data on European photoclimatology. The monthly total doses for a given station reflect the expected annual changes with peak values in June and July which correspond with the highest solar angles for northern latitudes.

The ratio of UV-A:PAR follows a general pattern for all stations with maximal values in the summer. However, there is one noticeable exception: the northernmost station in Abisko. Here the ratio peaks during the winter, which may be accounted for by the specific conditions north of the polar circle. During winter the sun does not rise above the horizon for several months, so that only the diffuse skylight is measured but no direct solar radiation. Since, according to Rayleigh, scattered shorter-wavelength radiation has a higher proportion in diffuse skylight, UV-A is favoured more than the longer-wavelength PAR. This phenomenon does not hold for UV-B probably because of the strong attenuation of UV-B in its long pathway through the atmosphere at low solar angles.

There are only seven stations which measure solar radiation in the water column and they have not all been active for the whole measuring period, but there are sufficient reliable data. Penetration of solar radiation into the top layers of the water column strongly depends on the turbidity of the water. While in the coastal waters off Helgoland solar UV-B could not be measured below 1 m of water, the penetration is much stronger in the Atlantic station in Gran Canaria. Especially during the winter months the transparency is very high, and >10% of the surface radiation penetrates through 4–5 m of water, depending on the tide.

Another interesting feature is the effect of the solar eclipse which was recorded by several stations along the path of this phenomenon. It could be observed by the stations in Plymouth, Karlsruhe, Erlangen, Zugspitze, Lubljana, Athens, Pisa and Cairo to a various extent because of the different cloud cover at the respective stations.

Acknowledgements This work was supported by the European Union (Environment programme, EV5V-CT94–0425; DG XII). The authors acknowledge A. Gaberscik, J. Pinchetti, and A. Pircher for running the ELDONET stations and thank L.-O. Björn for supplying a version of the computer program to model solar radiation and the ozone layer thickness. The authors thank M. Schuster for excellent technical assistance and R. Marangoni for managing the ELDONET server.

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