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ELDONET—A Decade of Monitoring Solar Radiation on Five Continents

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ABSTRACT

The European light dosimeter network (ELDONET) comprises more than 40 stations in 24 countries on 5 continents. The present report compares solar radiation data in the photosynthetic active radiation, UV-A (315–400 nm) and UV-B (280–315 nm) wavelength ranges for 17 stations at different latitudes on the northern and southern hemispheres for up to 10 years of monitoring. While the maximal irradiances on clear days follow a latitudinal gradient due to the cosine dependence on the solar angle, the total doses strongly depend on the local climate and atmospheric conditions as well as the day-length distribution over the year. UV-B irradiances and doses are strongly influenced by the total column ozone, which is recorded for all covered stations.

INTRODUCTION

Solar radiation is the fundamental prerequisite for life on earth. But not only biologists have a need for systematic monitoring irradiances in several wavelength bands. A number of instruments have been developed for manual or automatic measurement of light, and networks have been established for long-term monitoring of solar radiation (1–3). In addition to broad-band instruments, which cover a wide range of solar wavelengths, two types of instruments have been developed: spectroradiometers, which scan the solar emission spectrum at distinct wavelength intervals to provide spectrally resolved irradiance data (4), and filter dosimeters, which monitor one or more narrow or broader wavelength ranges over time. In addition, chemical and biological dosimeters have been developed that determine UV-induced changes in molecules such as DNA (5,6) or photosensitive chemicals (7–9).

The solar emission spectrum has been subdivided into distinct wavelength ranges (Commission Internationale d'Eclairage, CIE). Today UV-C (< 280 nm) does not play a role for the biota as it is completely absorbed by the oxygen and ozone in the atmosphere and consequently does not reach the earth's surface. Also most of the UV-B (280–315 nm) radiation is absorbed by the atmosphere and only 7.3% of the 26 W m^{-2} in the extraterrestrial solar spectrum penetrate to the ground in, *e.g.* central Europe in midsummer. About 25.5% of the longer-wavelength UV-A (315–400 nm) and about 89.3% of the photosynthetic active radiation (PAR, 400–700 nm) reach the earth's surface.

One of the oldest radiometer networks is the Robertson–Berger network, which has been established at eight stations in the United States in 1974 (10–12). The spectral sensitivity (peaking in the 290–330 nm range) covers the wavelength range associated with erythemal activity but does not coincide with the CIE definition for UV-B (280–315 nm). These instruments had been originally installed to determine the possible increase in ozone-related UV-B but the data showed a long-term decrease in solar UV radiation over the years (12), while total ozone mapping system (TOMS) satellite data showed a gradual ozone depletion over the same time range at mid latitudes (13,14). The explanations for this contradiction were long-term drifts in wavelength and sensitivity and the fact that most Robertson–Berger meters had been installed near airports, where increasing atmospheric pollution more than compensated the increase in solar UV-B reaching the surface (15,16).

Later, solar radiation networks had been installed by the Umweltbundesamt and the Bundesamt für Strahlenschutz consisting of four stations (Offenbach, Schauinsland, Neuherberg, Zingst) (17). This German network was designed to measure solar UV radiation at high spectral resolution (0.5–5 nm) as well as the integral of the total UV spectrum. Another European initiative was the SUVDAMA (spectral UV data and management) project initiated by Seckmeyer (Institut für Meteorologie und Klimatologie, Universität Hannover, Germany) (18,19) for the determination of UV-radiative transfer using simultaneous spectroradiometry (20–22). Other projects had been initiated by Bais (University of Thessaloniki, Greece) for the intercomparison of existing spectroradiometers as well as radiation measurements in New Zealand (24), Spain (1), Italy (25), the European Alps, South America (2,26,27) and the Antarctic (30,31). Simultaneously, satellite-based instruments such as the TOMS were used to determine the ozone concentration in the atmosphere (14,32).

The European light dosimeter network (ELDONET) was originally designed within an EU project and initially involved about a dozen measurement sites along a latitudinal gradient within Europe from the polar circle (Abisko, North Sweden) to

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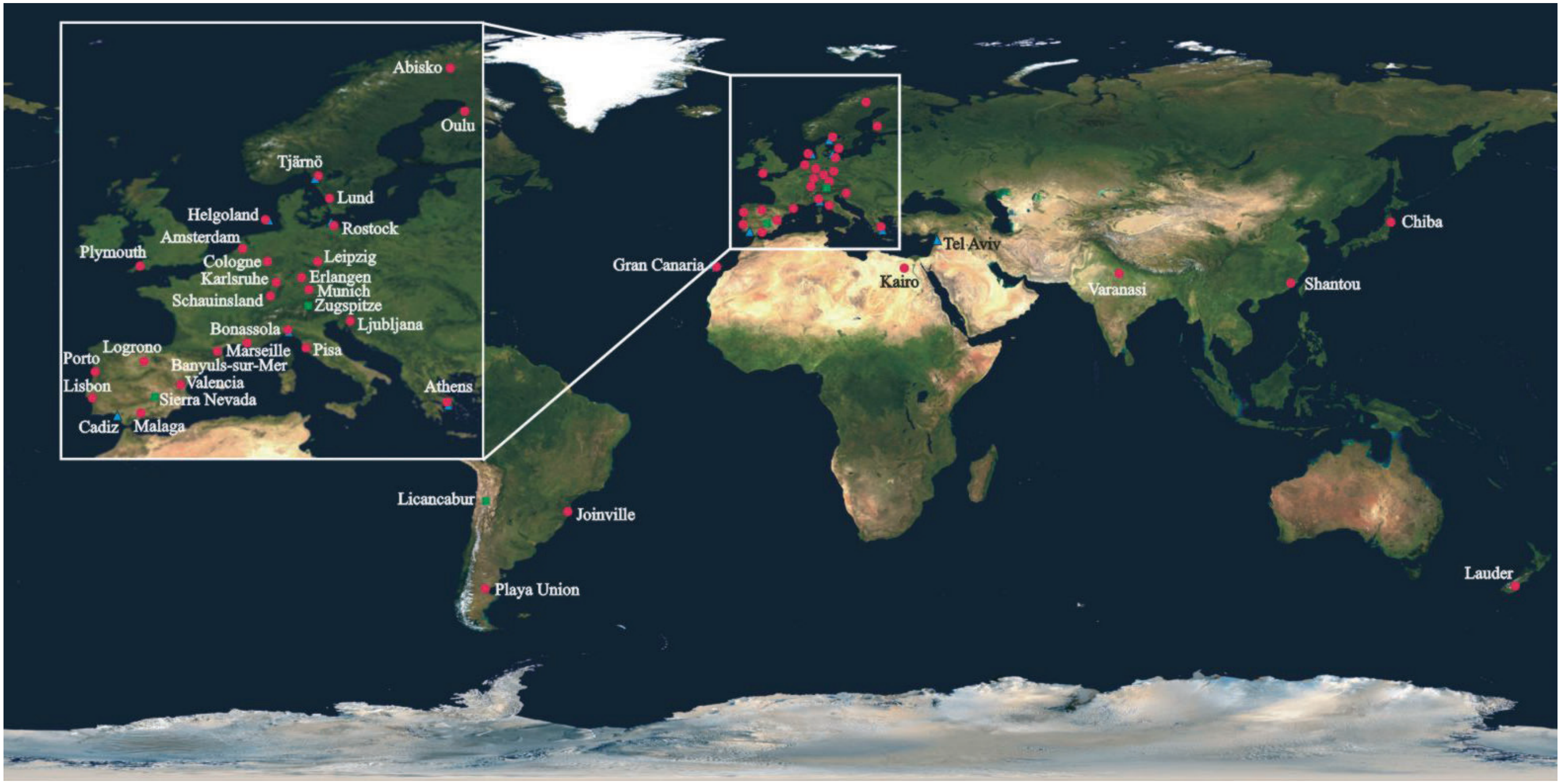

Figure 1. Map of the terrestrial ELDONET instruments in the world and in Europe (inset).

the subtropics (Canary Islands, Gran Canaria) (33–36). The instruments developed for this purpose are three-channel dosimeters for UV-B (280–315 nm), UV-A (315–400 nm) and PAR (400–700 nm) in accordance with the definitions by CIE. Over the years the instruments have been technologically improved including an Ulbricht integrating sphere as optical entrance (37), microprocessor control for automatic monitoring and a mechanical shutter to determine the dark current of the UV-B photodiode. Recent developments include flash memories, which hold data for up to 2 years, and a GPS (global positioning system) circuitry (38) which determines the geographical position of the instrument as well as the precise time.

A server has been installed in Pisa (Italy, www.eldonet.org) (39) as well as a mirror site in Erlangen (Germany, http://www.biologie.uni-erlangen.de/botanik1/html/eng/eldo_r3d_eng.htm) to store the measured data and make them available to the public. Not all instruments are being used for long-term monitoring of solar radiation. Some of the initial stations have been measuring data for over 9 years while some have been set up only recently. Previously, fully automatic instruments have been developed for the NASA program on life in extreme environments (http://www.astrobio.net/news/article1787.html), which operate autonomously without being connected to a host computer. These instruments have been deployed on high volcanoes in northern Chile to measure solar radiation at > 6000 m height unattended for up to 1 year.

The purpose of the present report is to compare solar irradiance data from 17 selected long-term ELDONET monitoring stations at different latitudes on the northern and southern hemispheres. As solar radiation not only depends on the atmospheric absorbance but also on the climatic conditions, solar monitoring can also be the basis for a systematic light climate recording. As UV-B radiation strongly depends on the stratospheric ozone concentration, irradiances are compared with available satellite ozone data.

MONITORING STATIONS

The ELDONET project currently comprises more than 40 stations in 24 countries on 5 continents. Some of these have been active for more than 9 years while others have been added to the network more recently. Not all stations deposit their data on the server on a regular basis. For this reason we have selected for this report 17 stations that have an extended history and have provided data on a regular basis. Most ELDONET stations are located in Europe (Fig. 1). The northernmost station of the network is located at Abisko (Northern Sweden) north of the polar circle at an elevation of 385 m above sea level (a.s.l.). It is one of the original stations and has recorded solar radiation for over 9 years. The geographical data (longitude, latitude and elevation above sea level) are summarized in Table 1, which also indicates the recording period for each of the selected stations. The station of Erlangen (Germany) is located at 49°35′N, 11°01′E at 280 m a.s.l. Other European stations are (from north to south) Lund (Southern Sweden), Helgoland (Island in the North Sea, German Bight), Karlsruhe (Western Germany), Ljubljana (Slovenia), Bonassola and Pisa (northern Italy), Logrono (northern Spain), Lisbon (Portugal), Athens (Greece), Malaga (southern Spain). Sierra Nevada is a high mountain station at 2850 m a.s.l. The southernmost station in Europe is located on Gran Canaria (Canary Islands). The stations in the southern hemisphere are located in Lauder (New Zealand), Playa Union (Patagonia, Argentina) and Joinville (southern Brazil). There are many more stations located in several other European countries as well as in China, Japan, Siberia, India, Israel, Egypt, Ivory Coast and Chile. However, these stations are either not active all the time or do not provide their data to the network or are used only during experimental campaigns.

CALIBRATION PROCEDURE

Each instrument is calibrated against a 1000 W quartz halogen lamp operated with a highly stabilized power supply (SL 1000 W, Powertronic Lab. 710 D). The absolute calibration was controlled in an intercomparison of several spectroradiometers and the ELDONET instrument in September 1997 in Garmisch-Partenkirchen (southern Germany [33]). A more recent international intercomparison took place during 10–15 August 2006 at the Physikalisch-Meterologisches Observatorium in Davos, Switzerland, at an altitude of 1610 m a.s.l.

Table 1. Location, geographical data and recording period of 17 ELDONET stations.

Location	Latitude	Longitude	Elevation (m a.s.l.)	Recording period	Percentage of days included
Abisko	68°50′N	19°00′E	385	1997–2005	58
Lund	55°07′N	13°04′E	50	1997–2000	58
Helgoland	54°10′N	07°51′E	61	1997–2000	60
Erlangen	49°35′N	11°01′E	280	1997–2005	96
Karlsruhe	49°03′N	08°23′E	200	1997–2000	63
Ljubljana	46°04′N	14°33′E	300	1998–2003	67
Bonassola	44°10′N	09°30′E	10	1998–2004	40
Pisa	43°43′N	10°23′E	100	1997–1999	56
Logrono	42°28′N	02°27′W	380	2001–2004	79
Lisbon	38°42′N	09°10′W	105	1997–2005	69
Athens	37°58′N	23°46′E	110	1997–2000	78
Sierra Nevada	37°04′N	03°20′W	2850	1997–2003	73
Malaga	36°43′N	04°23′W	18	1997–2003	59
Gran Canaria	27°55′N	15°35′W	8	1997–2004	76
Joinville	26°15′S	48°55′W	120	2001–2002	37
Playa Union	43°15′S	65°00′W	20	1999–2005	90
Lauder	45°01′S	169°41′E	370	1999–2005	79

(46.8°N, 9.83°E). During calibration the atmospheric conditions were mostly diffuse sky with cumulus clouds on most days and clear sky with some cirrus clouds on 15 August 2006. The absolute spectral irradiance is traceable to the primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany), through the transfer standards F34, F324, F364 and F376. For the ELDONET instrument participating in the test, a calibration coefficient C of 1.0044 has been calculated. The expanded uncertainty of measurement is calculated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%. The instrument carries the certificate number 2006/BB14/1.

Because of the different path lengths through the atmosphere, there is a deviation of the response in dependence of the solar angle especially in the UV-B range for which a correction function was determined by calibration against the output of a double monochromator spectroradiometer (model 754; Optronic, Orlando, FL) for all possible solar angles during the daily cycle on clear days to warrant high-precision measurements (33). As calibrations change over time as the optical components age, the instruments are recalibrated during service. Long-term measurements show that the calibration changes are typically in the range of 1.5% for PAR, 2.4% for UV-A and 4.6% for UV-B. In the field, calibrations are maintained by comparing the output signals with model calculations for clear skies using the model by Björn and Murphy (40).

Cosine response of the detector was characterized in the laboratory using a beam from a 1000 W quartz halogen calibration lamp that could be moved by 180° in all directions around the center of the opening of the Ulbricht sphere. The cosine error is less than 4% for all three wavelength bands except when the direct solar beam hits the baffle inside the integrating sphere. Therefore, the instruments are installed facing north (or south depending on the hemisphere) in such a way that the direct beam only hits the inner surface of the sphere. The overall uncertainty for the instruments is about 8% for the UV-B channel and about 4% for the UV-A and PAR channels.

RESULTS AND DISCUSSION

Figure 2 shows the daily doses for PAR, UV-A and UV-B for a representative station (Erlangen) over the period 1997–2006. There is no substantial variation between the data from year to year in any of the wavelength ranges. This is confirmed when the total yearly doses are plotted over the years (Fig. 3). There is very little variation from year to year despite the subjective recollection of people remembering a "bad summer" or a "sunny winter." The ozone concentrations are recorded by a total column ozone meter (TOMS) on board the NASA Earth Probe satellite and are available on the Internet (http://toms.gsfc.nasa.gov). The monthly ozone concentrations over this site are plotted as well as the annual mean values. The total column ozone varies daily, seasonally and from year to year.

The graphical representation of the enormous amount of data would exceed the space allotted to this paper by far. To present the data, we have identified clear-sky days for the three summer months (May, June, July) for all years for which data are available and likewise for the winter months (November, December, January) in the northern hemisphere, and the

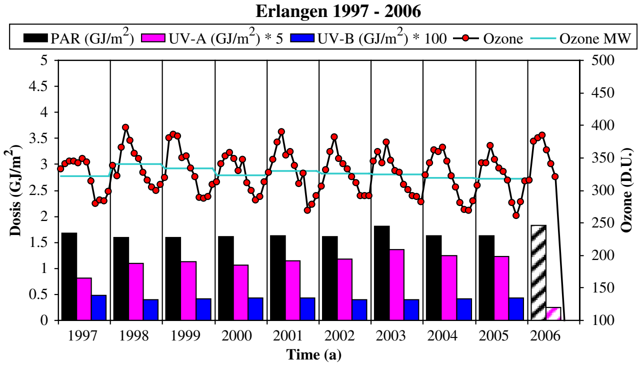

Figure 3. Annual doses of PAR, UV-A and UV-B measured in Erlangen from 1997 to 2005 as well as monthly averaged total column ozone and yearly averages of ozone.

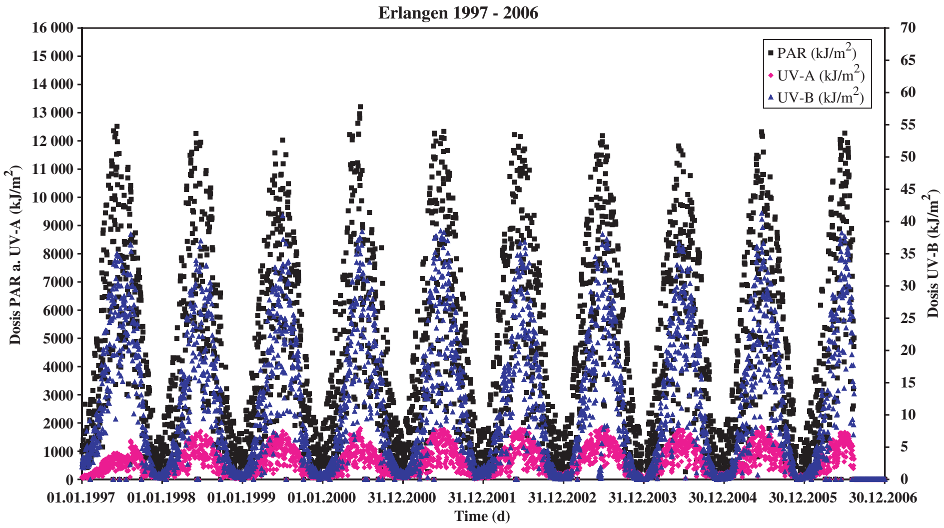

Figure 2. Daily doses of PAR (black symbols), UV-A (cyan symbols, left ordinate) and UV-B (blue symbols, right ordinate) measured at Erlangen from 1997 to 2005.

Table 2. Mean of peak daily irradiances in summer and winter irradiances for clear skies (±SD) in the PAR, UV-A and UV-B wavelength ranges for the selected locations as well as minimum, maximum and mean ozone values (in Dobson units [DU]).

	Summer irradiances [W m^{-2}]			Winter irradiances [W m^{-2}]			Ozone [DU]		
Location	PAR ± SD	UV-A ± SD	UV-B ± SD	PAR ± SD	UV-A ± SD	UV-B ± SD	Maximal	Minimal	Mean value
Abisko	284.69 ± 34.13	33.99 ± 9.05	0.77 ± 0.32	5.16 ± 4.97	0.72 ± 0.73	0.001 ± 0.003	495	218	333
Lund	380.78 ± 32.52	59.92 ± 7.26	1.55 ± 0.47	73.65 ± 17.30	10.07 ± 2.20	0.04 ± 0.03	482	201	328
Helgoland	353.11 ± 54.24	44.08 ± 6.32	0.77 ± 0.34	97.81 ± 12.63	9.52 ± 3.05	0.07 ± 0.03	490	206	328
Erlangen	393.30 ± 35.40	52.70 ± 9.38	1.33 ± 0.30	126.31 ± 25.67	13.77 ± 2.71	0.13 ± 0.06	477	221	326
Karlsruhe	385.14 ± 12.21	49.55 ± 7.14	1.07 ± 0.49	137.15 ± 16.48	18.86 ± 6.31	0.26 ± 0.14	473	219	325
Ljubljana	412.84 ± 27.13	59.97 ± 2.89	1.52 ± 0.15	118.49 ± 31.66	13.43 ± 3.28	0.27 ± 0.14	468	227	325
Bonassola	411.60 ± 37.38	61.23 ± 8.89	1.60 ± 0.29	150.85 ± 15.59	16.02 ± 1.73	0.19 ± 0.04	460	231	324
Pisa	390.28 ± 0.08	55.46 ± 0.61	1.05 ± 0.03	180.35 ± 12.97	20.52 ± 1.64	0.25 ± 0.04	460	235	324
Logrono	387.44 ± 26.45	57.48 ± 5.23	1.53 ± 0.21	170.98 ± 21.69	20.17 ± 3.31	0.28 ± 0.10	452	226	316
Lisbon	398.67 ± 31.68	62.08 ± 8.55	1.60 ± 0.41	186.62 ± 37.08	23.06 ± 6.56	0.28 ± 0.14	433	234	315
Athens	393.82 ± 49.42	55.91 ± 8.03	1.67 ± 0.85	214.06 ± 30.43	27.51 ± 6.62	0.31 ± 0.09	437	245	317
Sierra Nevada	430.87 ± 25.89	61.52 ± 3.76	1.88 ± 0.32	223.16 ± 39.79	28.35 ± 6.58	0.60 ± 0.27	424	232	308
Malaga	414.21 ± 13.32	61.88 ± 2.96	1.90 ± 0.25	219.42 ± 14.39	27.92 ± 2.57	0.52 ± 0.12	414	237	310
Gran Canaria	419.84 ± 20.31	64.26 ± 5.32	2.05 ± 0.24	302.09 ± 27.78	37.44 ± 8.50	1.08 ± 0.22	360	242	290
Joinville	413.81 ± 0.19	55.31 ± 4.77	1.41 ± 0.36	270.63 ± 22.14	37.73 ± 3.96	0.86 ± 0.14	331	237	274
Playa Union	424.26 ± 46.71	62.33 ± 3.68	1.89 ± 0.15	147.43 ± 19.69	18.21 ± 2.41	0.26 ± 0.06	393	227	297
Lauder	429.08 ± 27.43	61.31 ± 5.23	1.70 ± 0.30	136.03 ± 21.61	16.45 ± 2.23	0.19 ± 0.06	419	232	309

opposite for the southern hemisphere locations. The maximal readings for these days have been averaged and the standard deviation calculated. This procedure was repeated for PAR, UV-A and UV-B (Table 2). Minimal and maximal ozone values (in Dobson units [DU], where 1 DU = 2.69×10^{16} molecules cm^{-2}) were averaged over the recording period and are listed in Table 2 as well as the mean values.

When comparing the maximal summer irradiances of all listed stations, there is a clear increase in the summer values from north to south on the northern hemisphere, as expected, with the lowest value for Abisko (Table 2). The values in the UV-A and UV-B more or less follow the same trend. However, there are several remarkable deviations from the latitudinal dependence. Lund in southern Sweden has a higher PAR value than the island station Helgoland; this is even more obvious in the UV-A and UV-B. This is probably due to the high concentration of aerosols in the marine station on the island of Helgoland. Because of Rayleigh scattering, aerosols cause increasing effects with decreasing wavelengths. Athens has similar PAR values as Erlangen, which is probably due to the higher air pollution in Athens. The highest values are found for the southernmost sites in Europe. However, the differences between central Italy, southern Spain, Slovenia and Canary Islands are not very pronounced, which is probably due to the fact that, at high zenith angles, the cosine of the incidence angle does not differ much. The design of the entrance optics of the dosimeters minimizes errors in the cosine response. Sierra Nevada is a high mountain station not far from Malaga. As a consequence of the higher elevation, this site shows significantly higher irradiances. This confirms other studies that show that high altitude stations show higher irradiances than corresponding low-land sites because of reduced atmospheric extinctions (41). The station at Joinville is located at a similar latitude as Gran Canaria but in the southern hemisphere and has similar PAR values, but the UV-A and especially the UV-B values are significantly lower, which corresponds with the high aerosol content and humidity in the Atlantic rain forest in Joinville. Playa Union and Lauder have comparable PAR and UV-A values, which also compares well with those at Bonassola and Ljubljana at a similar latitude on the northern hemisphere. But the UV-B values are significantly higher at Playa Union. Previous studies have shown that latitude for latitude, the UV-B intensities in Lauder were approximately 40% higher than at comparable latitudes in the northern hemisphere (42–45). This is attributable to the effects of the Antarctic ozone hole, which extend into these areas in the southern hemisphere as demonstrated by the far lower ozone values in the corresponding southern sites. The UV irradiances from Lauder in this study are 5–10% lower than in the papers cited above. However, such differences are within the expected combined absolute uncertainties in measurements from the different networks involved.

To validate the precision of the ELDONET radiometer UV data from the ELDONET radiometer and the UVM spectrometer at Lauder are compared for the period January 1999 to September 2006. The UVM spectrometer represents the state-of-the-art for routine ground-based spectral irradiance measurements. It complies with the exacting standards required for acceptance in the NDACC (Network for the Detection of Atmospheric Composition Change), which was formerly known as the NDSC (Network for the Detection of Stratospheric Change [24,46]). As such it is regularly calibrated with tungsten coil filament (FEL) lamps against the NIST (National Institute of Standards and Technology, USA) irradiance standards. In normal operation the spectrometer is programmed to take scans at 5° steps in solar zenith angle (sza), apart from a 2 h period centered on local solar noon, when it takes spectra at 15 min intervals. Typically, during daylight hours (sza < 90°) there are about 30 scans on a summer's day and 20 scans on a winter's day. The spectral resolution is approximately 0.9 nm and takes about 3 min for a complete scan, which covers the wavelength range 290–450 nm.

These differences in daily data coverage limit the accuracy expected in any comparison. The spectrometer seriously undersamples the daily variability of UV radiation. However, for large datasets, such as the 8 year period under study, these differences should average out without bias. We selected peak

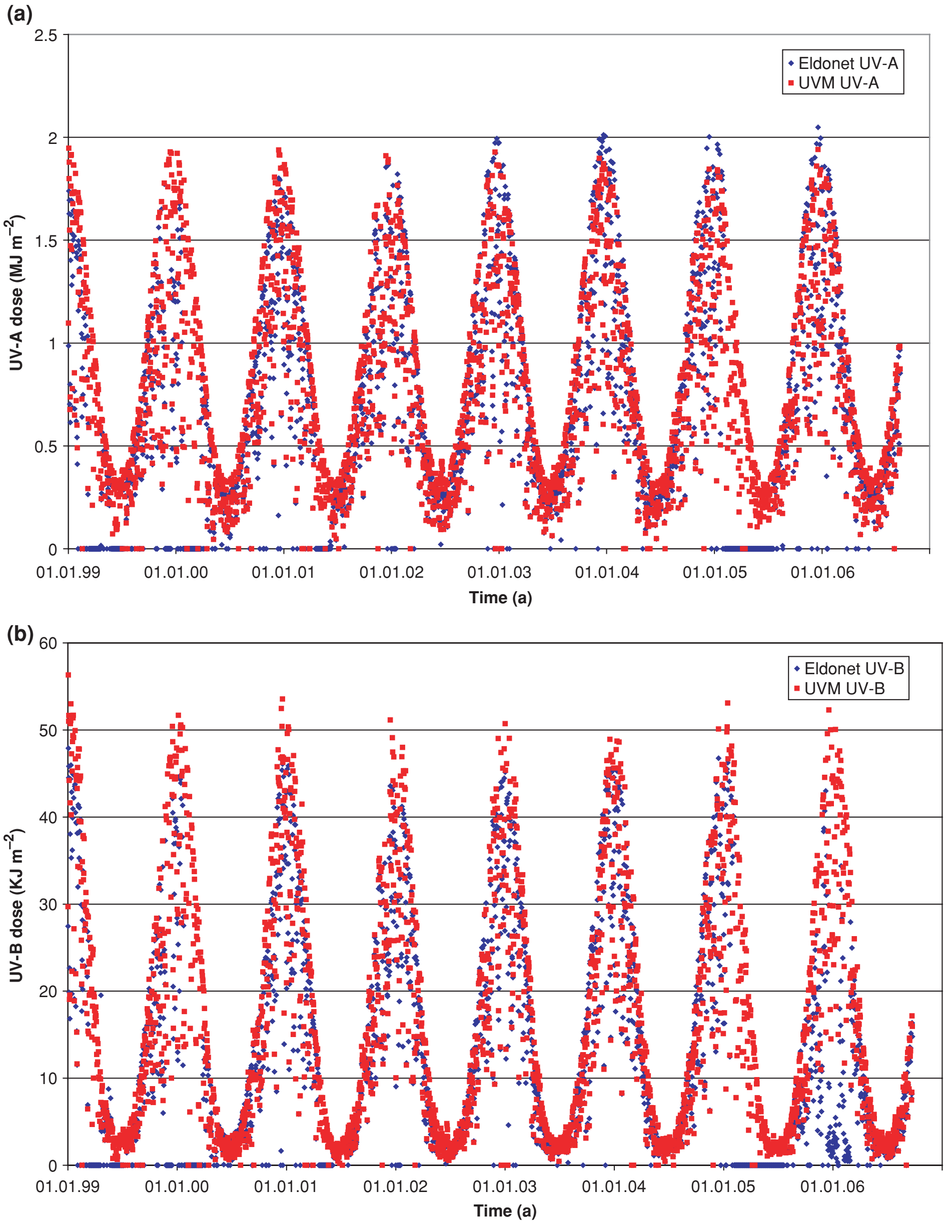

Figure 4. Comparison of the readings of the ELDONET radiometer and the UVM spectrometer both located in Lauder, New Zealand in the UV-A (a) and UV-B (b) range. For details see text.

values, and daily doses of UV-B (280–315 nm) and UV-A (315–400 nm) for the analysis. Daily doses from the spectrometer were included only if all of the following criteria were satisfied: (1) at least 10 scans per day; (2) at least five in the morning and five in the afternoon; (3) at least one within 1.5° of solar noon (*i.e.* the minimum sza); (4) at least three scans within 5° of solar noon; and (5) at least five scans within 15° of solar noon. Figure 4 illustrates the general accuracy of the measurements of the ELDONET instrument as compared to the UVM spectrometer. However, the year-to-year variability is more consistent in the spectrometer data as expected than in the ELDONET data. The general accuracy of the ELDONET reading is further emphasized by the data shown in Fig. 5. The ratio of the UVM spectrometer over ELDONET readings shows most times a value of 1. However, at low solar angles measuring errors are obvious and systematic. Furthermore, a malfunction of the UV-B shutter is clearly visible in the year 2006.

Despite the limitations which are apparent from the previous plot, the regression statistics are remarkably good, showing that on average the UV-B and UV-A measured by the two instruments are in good agreement (Fig. 6). The outliers are not evenly distributed about the regression line. The largest differences tend to be associated with lower irradiances, especially in the case of the UV-B plots. Table 3 summarizes the results. While the general error is well below 10% seasonal variations are obvious.

Comparing the ELDONET as well as other readings to biological monitoring always depends on several factors. One is the spectral sensitivity and the other is, as pointed out above, the availability of the radiometer or spectrometer data close to the site of exposure. The spectral sensitivity of the *Bacillus*

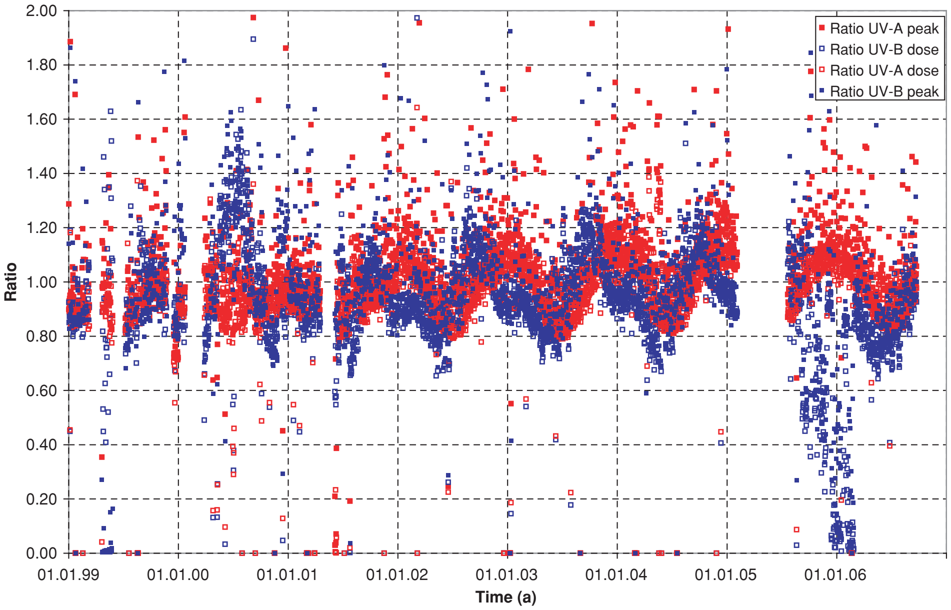

Figure 5. Ratio of UVM over ELDONET readings.

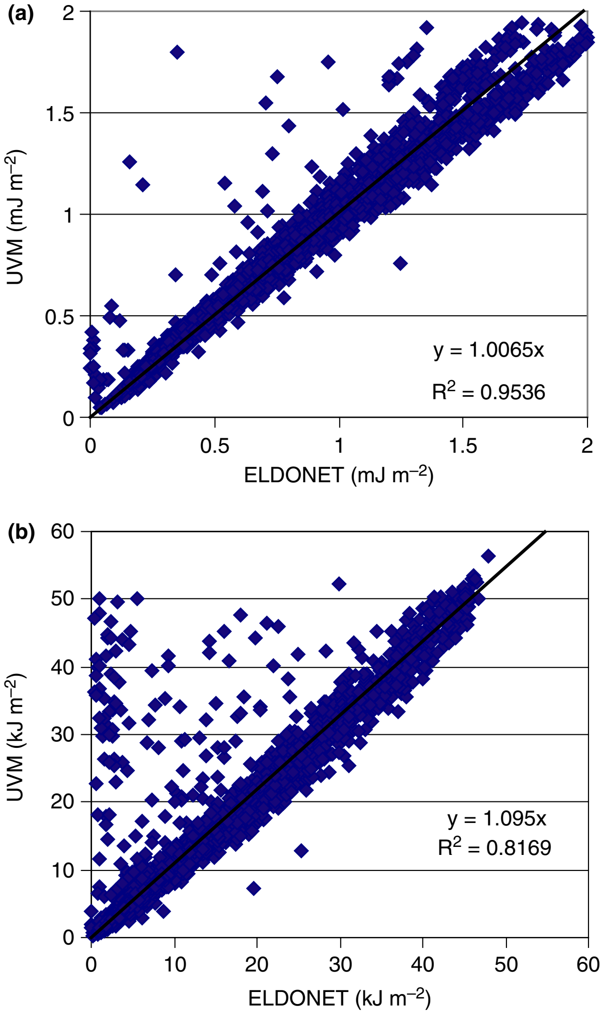

Figure 6. Regression statistics UVM against ELDONET readings in the UV-A (a) and the UV-B (b) range.

subtilis spore exposure assay (45) is heavily biased toward short wavelength due to the mode of spore inactivation by DNA damage. The exposure method also includes an attenuation of radiation by use of plastic foils to increase usable exposure times. However, this limits the sensitivity for short-term events. As neither dosimeter nor spectrometer data are available for the measuring period in the aforementioned paper, an in-depth comparison is not possible. However, the overall findings in terms of latitude dependence and local differences are in good agreement to the findings presented in this paper.

The winter maximal irradiances follow the same latitudinal pattern but the differences are even more drastic. While the summer PAR values of the northernmost station reach 68% of the data determined near the equator, in the winter they reach only 5% because of the polar winter with no sun above the horizon for most of this period. Also UV-A and UV-B are almost negligible in the winter for the northernmost stations. In contrast, the subtropical stations show significant winter irradiances due to the high solar angles even in the winter.

UV-B radiation strongly depends on the solar angle, cloud cover and total column ozone in the atmosphere. Maximal total column ozone values increase towards the poles, and consequently the highest values are found for the station in Abisko and the lowest for the subtropical stations. The minimal ozone values follow an antiparallel pattern with

Table 3. Regression statistics.

Quantity	Regression slope	Correlation coefficient (R^2)
UV-A dose	1.0065	0.9536
UV-B dose	1.095	0.8169
Peak UV-A	0.901	0.8914
Peak UV-B	1.0096	0.8523

Table 4. Doses during the three summer and winter months as well as the total yearly doses for the 17 stations.

Location	Summer doses [GJ m^{-2}]			Winter doses [GJ m^{-2}]			Cumulative yearly [GJ m^{-2}]		
	PAR ± SD	UV-A ± SD	UV-B ± SD	PAR ± SD	UV-A ± SD	UV-B ± SD	PAR ± SD	UV-A ± SD	UV-B ± SD
Abisko	0.582 ± 0.076	0.071 ± 0.012	0.0011 ± 0.0002	0.007 ± 0.005	0.001 ± 0.001	0.000003 ± 0.00001	1.074 ± 0.161	0.634 ± 0.083	0.179 ± 0.040
Lund	0.649 ± 0.033	0.097 ± 0.007	0.0015 ± 0.0002	0.061 ± 0.022	0.009 ± 0.003	0.00003 ± 0.00003	1.353 ± 0.464	1.009 ± 0.248	0.255 ± 0.152
Helgoland	0.729 ± 0.067	0.100 ± 0.013	0.0020 ± 0.0002	0.079 ± 0.020	0.009 ± 0.002	0.00007 ± 0.00006	1.717 ± 0.307	1.139 ± 0.169	0.432 ± 0.149
Erlangen	0.709 ± 0.080	0.100 ± 0.019	0.0021 ± 0.0003	0.103 ± 0.024	0.013 ± 0.003	0.00010 ± 0.00006	1.643 ± 0.075	1.144 ± 0.170	0.425 ± 0.023
Karlsruhe	0.743 ± 0.083	0.097 ± 0.016	0.0019 ± 0.0007	0.112 ± 0.029	0.018 ± 0.008	0.00019 ± 0.00012	1.911 ± 0.162	1.362 ± 0.169	0.456 ± 0.063
Ljubljana	0.801 ± 0.083	0.112 ± 0.018	0.0025 ± 0.0004	0.126 ± 0.030	0.016 ± 0.004	0.00018 ± 0.00007	1.779 ± 0.354	1.213 ± 0.259	0.483 ± 0.096
Bonassola	0.871 ± 0.150	0.134 ± 0.030	0.0024 ± 0.0006	0.152 ± 0.028	0.018 ± 0.003	0.00017 ± 0.00005	2.506 ± 0.595	1.874 ± 0.574	0.616 ± 0.087
Pisa	0.745 ± 0.243	0.110 ± 0.056	0.0018 ± 0.0012	0.158 ± 0.027	0.023 ± 0.002	0.00043 ± 0.00043	2.398 ± 0.207	1.719 ± 0.430	0.546 ± 0.235
Logrono	0.797 ± 0.108	0.114 ± 0.016	0.0024 ± 0.0004	0.183 ± 0.047	0.024 ± 0.005	0.00025 ± 0.00011	2.161 ± 0.182	1.514 ± 0.130	0.581 ± 0.092
Lisbon	0.908 ± 0.147	0.129 ± 0.028	0.0027 ± 0.0010	0.281 ± 0.055	0.036 ± 0.006	0.00031 ± 0.00016	2.953 ± 0.409	2.092 ± 0.322	0.830 ± 0.213
Athens	0.975 ± 0.088	0.129 ± 0.020	0.0033 ± 0.0004	0.299 ± 0.047	0.045 ± 0.015	0.00048 ± 0.00010	2.920 ± 0.065	1.924 ± 0.187	0.869 ± 0.077
Sierra Nevada	0.859 ± 0.110	0.122 ± 0.017	0.0029 ± 0.0006	0.300 ± 0.064	0.040 ± 0.010	0.00055 ± 0.00014	2.208 ± 0.314	1.532 ± 0.261	0.636 ± 0.129
Malaga	0.934 ± 0.124	0.129 ± 0.019	0.0031 ± 0.0005	0.317 ± 0.043	0.041 ± 0.006	0.00056 ± 0.00014	2.743 ± 0.255	1.869 ± 0.218	0.800 ± 0.101
Gran Canaria	0.909 ± 0.102	0.108 ± 0.049	0.0036 ± 0.0008	0.415 ± 0.099	0.044 ± 0.029	0.00118 ± 0.00051	2.848 ± 0.421	1.654 ± 0.830	1.029 ± 0.232
Joinville	0.611	0.097	0.0023	0.323 ± 0.029	0.047 ± 0.005	0.00091 ± 0.00016	1.733	1.322	0.574
Playa Union	0.899 ± 0.128	0.130 ± 0.015	0.0033 ± 0.0004	0.182 ± 0.027	0.025 ± 0.004	0.00034 ± 0.00016	2.186 ± 0.296	1.550 ± 0.147	0.709 ± 0.075
Lauder	0.810 ± 0.101	0.116 ± 0.014	0.0027 ± 0.0004	0.171 ± 0.038	0.023 ± 0.004	0.00023 ± 0.00008	2.130 ± 0.238	1.468 ± 0.096	0.605 ± 0.072

decreasing values towards the poles. However, differences between maximal and minimal values are lowest at low latitudes and increase toward the poles. The mean values calculated over all days of the year and all years of observation are highest at high latitudes and decrease towards the equator. Both the maximal and the mean ozone values for Lauder in the southern hemisphere are significantly lower than the corresponding values for Ljubljana or Bonassola, which are located in the northern hemisphere at comparable latitudes. These results explain why the UV-B values are higher in New Zealand than in central Europe (see above).

When comparing the cumulative doses over all days during the three summer months (irrespective whether they are clear or cloudy) basically follows the latitudinal trend seen in the maximal summer irradiances (Table 4). But the total doses of solar radiation do not only depend on the solar angle of incidence but also on the day length. This varies widely from the tropics to the poles. The mean maximal irradiances for Abisko are about 72% of those measured in Erlangen, but when comparing the cumulative summer doses, that for Abisko reaches 83% of that in Erlangen. This is due to the fact that Erlangen has about 16 h day length during the summer while Abisko has 24 h continuous daylight during about 20 days centered around 21 June. The opposite is true for the winter months, when for many days there is no sunlight at Abisko. Another remarkable finding is that while the maximal irradiances are higher at the high mountain station of Sierra Nevada than in the nearby Malaga (located at sea level), the cumulative doses are lower at Sierra Nevada. This is explained by looking at the aerosol levels at the mountain site: there are many days when there is considerable haze in the morning hours, which clears during noon. This feature reduces the total doses over the day, month or year. Local climate differences exert considerable influences on the doses resulting in higher or lower doses than expected from the geographical position. This explanation also applies for Joinville, which is located in the Atlantic rain forest. Because of frequent rains, the doses are considerably smaller than for Gran Canaria, even though the maximal irradiances during clear days are comparable. The same is true for the winter months, indicating that there are no pronounced dry and rainy seasons in southern Brazil. This is confirmed by a comparison of the yearly doses.

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