Solar Ultraviolet Radiation in Great Britain (1989-2008)

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ABSTRACT

A long-term trend of an ongoing survey of solar radiation levels at the six different latitude sites in Great Britain (GB) is investigated. The network consists of three HPA sites at Chilton, Leeds and Glasgow and three Meteorological Office stations at Camborne, Kinloss and Lerwick. At each site in the network, measurements of solar ultraviolet radiation (UVR), including erythemally effective ultra violet radiation exposure ($UVR_{eff,}$ 280–400 nm), UVA (320–400 nm) and photopically weighted visible radiation, have been measured simultaneously using a three detector measurement system. Overall, it has been found that UVR_{eff} and UVA measurements have indicated a statistically significant increasing linear trend between 1989 and 2008 in the UK with a mean rate of 0.23 kJ/m^2 eff./year (95% CI: 0.01-0.45) or 1.68% per year for the UVR_{eff} and 0.15 MJ/m^2/year (95% CI: 0.05-0.25) or 1.36% per year for the UVA. Changes in UVR_{eff} solar radiation in relation with ozone depletion and sunshine hours in GB have been investigated. Although an increase in UVR_{eff} in response to decreasing ozone and increasing sunshine hours has been detected in GB, it is not statistically feasible to draw any conclusion regarding an underlying dependence of ozone concentration and sunshine hours on changes in UVR_{eff} in GB.

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EXECUTIVE SUMMARY

Measurements of ultraviolet radiation (UVR) at the Earth's surface have attracted increasing attention over the years. This is because of the widespread concern about depletion of the ozone layer. It is anticipated that this will result in an increase in the amounts of ultraviolet radiation received at ground level, with potential effects on human health, including skin cancers, and effects on the environment e.g. animals; plants may be similarly affected.

Monitoring solar ultraviolet radiation at different latitudes has been continued within England and Scotland from six different sites. In 1988 the former NRPB (now part of HPA CRCE) set up three monitoring stations at Chilton, Leeds and Glasgow. This network was extended, in co-operation with the UK Met Office, to three additional sites at Met Office observatories from 1993 at Camborne and Lerwick, and at Kinloss from 1995. At each site, measurements of erythemally effective ultra violet radiation (UVR_{eff}) irradiance (280-400 nm) and UVA (320-200 nm) are made simultaneously using Macam Photometrics SD-104A detectors for UVA and Robertson-Berger meter (RB-500 and RB-501) detectors for UVR_{eff} exposure. Photopically weighted visible radiation is measured using Macam SD-104L detectors.

We have investigated the long-term trend behaviour of UVR_{eff} irradiance and UVA from these six sites by using additional new data (covering period 2006-2008) and those available previously from 1989 to 2005. A statistical analysis of the results shows evidence that the total annual UVR_{eff} and UVA values are consistent with there being a small, but significant increase trend between 1989 and 2008 in the annual integrated radiant exposures in GB with a rate of 0.23 kJ/m^2 eff. (95% CI: 0.01-0.45) or 1.68% per year for the UVR_{eff} and with a mean rate of 0.15 MJ/m^2 (95% CI: 0.05-0.25) or 1.36% per year for the UVA. Influential factors such as ozone and sunshine hours to UVR_{eff} have also been examined. There is a lack of a clear evidence of any underlying dependence of ozone concentration and sunshine hours on changes in UVR_{eff} in GB.

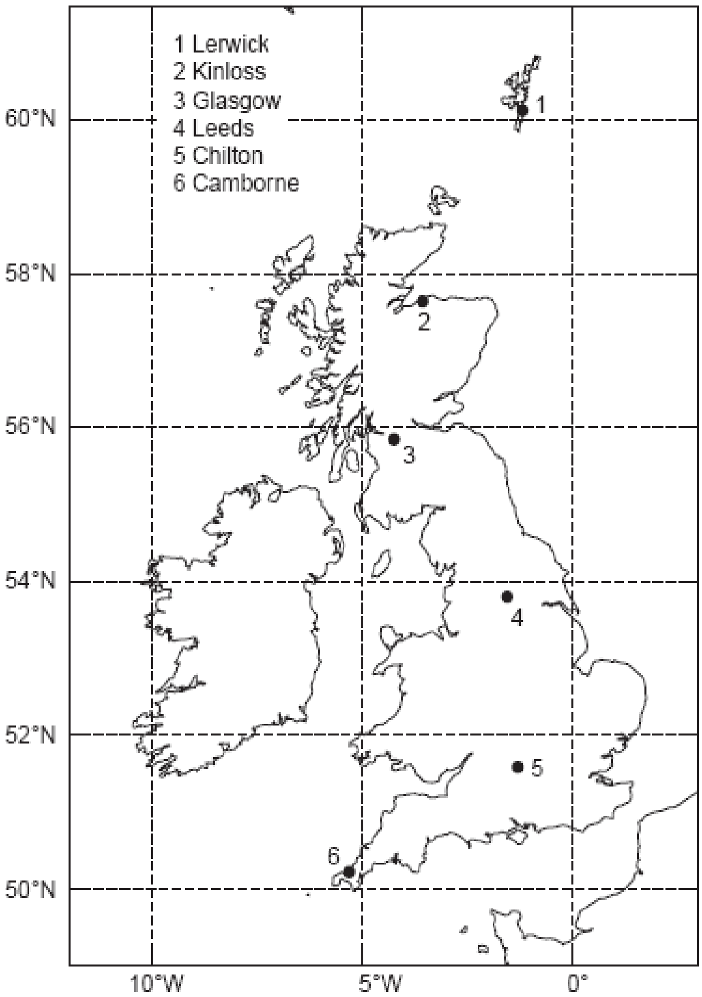
CONTENTS

1 INTRODUCTION

Ultraviolet radiation (UV) is only a small portion of the radiation we receive from the sun, but has a large impact on biological activity. UV radiation has become a topic of increasing concern because of ozone depletion observed since 1970s. An increase in UV radiation at ground level can result in an increase in numerous harmful effects on the environment and health, including various skin cancers.

In 1988, the former National Radiological Protection Board (NRPB - now part of CRCE) set up three monitoring stations to measure continuously terrestrial solar radiation at different latitudes within GB. These were at NRPB sites at Chilton, Oxfordshire, at latitude of approximately 52° N; Leeds (at about 54° N) and Glasgow (at about 56° N). This network was extended, in cooperation with the UK Met Office, to three sites at Met Office observatories at Camborne (since 1993, about 50° N), Lerwick (since 1993, about 60° N) and Kinloss (since 1995, about 58° N), see Fig.1.

Figure.1: Locations of the UV monitoring stations in UK. In additions ozone measurements are made at Camborne (Station 6) and Lerwick (Station 1) and recently at Reading near Chilton (Station 5).



Monitoring solar ultraviolet radiation has been continued for a longer period at HPA sites and over a shorter period at the Meteorological Office sites. However, reliable data starts at different years for each site. The data set at Chilton is complete over the full measurement period 1989–2008, the data sets at Leeds and Glasgow are complete over at least sixteen years of the measurement period, with a few breaks in the complete monthly data during the early years. The Meteorological Office sites have fourteen or less years of measurement data. Further measurement data will contribute to detailed statistical analysis at these sites in the future.

The three detectors which were used in the HPA Solar Radiation Monitoring System (SRMS) were obtained from commercial suppliers, but have been incorporated in a high stability and environmentally controlled instrumentation system. The UVA and photopic detectors are Macam Photometrics SD-104A and SD-104L detectors. The erythemally weighted UVR detector is a specially adapted version of the Robertson-Berger (RB) meter (Berger, 1976) (see for further explanation about the detectors and quantities measured in Appendix A). At each site in the network, measurements of solar UVR [erythemally effective ultra violet radiation (UVR_{eff}) and UVA (320–400 nm)] are made simultaneously.

The results of previous measurements obtained from 1988 to 2005 have been published in various reports (Driscoll et al, 1989-2003; Pearson et al, 2004; Pearson et al 2006). The latest results for the long term changes between 1989 and 2005 in UVR_{eff} and UVA for the six sites has been published in a RPD-HPA report (Pearson et al 2006). The analysis of total UVR_{eff} and UVA measurements over England and West Central Scotland revealed a statistically significant upward linear trend between 1989 and 2005. The variability and long-term changes in the UVR_{eff} have also been studied in relation to ozone depletion and sunshine hours' etc for the same period. The relation between changes in UVR_{eff} and stratospheric ozone concentrations showed differing patterns making it impossible to draw any obvious conclusions. As for sunshine hours, there was no significant linear correlation between UVR_{eff} values and sunshine hours.

The aim of this study is to re-examine the long-term trend behaviour of erythemally effective ultra violet radiation (UVR_{eff}) and UVA at different latitudes with year for the same sites by using new additional data (2006-2008) and those available previously from 1989 to 2005. Again we have also determined the extent to which the long term behaviour of the measured UVR_{eff} can be explained by known geophysical factors, e.g. ozone depletion and sunshine hours.

2 DATA FOR 2006-2008

The results from January 2006 to December 2008 for each of the sites are presented in the form of the mean values averaged across an hour at noon GMT for each month in figures 2-7. It can be seen that generally the further north a site is, the lower its mean noontime illuminance and irradiance. This is due to the decreased solar elevation at noon as distance from the equator increases. The effects of latitude can also be seen by plotting monthly radiant exposure data from different sites on top of each other: this has been done for Camborne and Lerwick, which are the extreme southerly/northerly sites. These data, for the period January 1994 to December 2008, are presented in figure 8.

As well as varying with latitude, solar altitude varies with time. The effects of solar altitude can also be seen by looking at the mean monthly radiant exposure for a given site. Data for Chilton, from January 1989 to December 2008, are presented in figure 8.

Figure 2: Mean noon illuminance (in klux) at the three sites in England for 2006-2008.

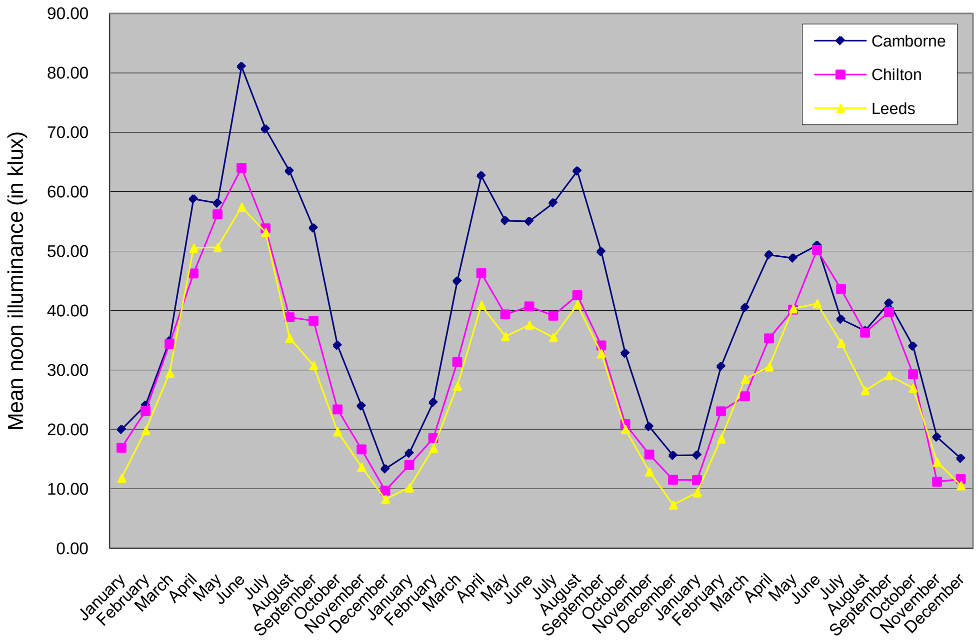


Figure 3: Mean noon illuminance (in klux) at the three sites in Scotland for 2006-2008.

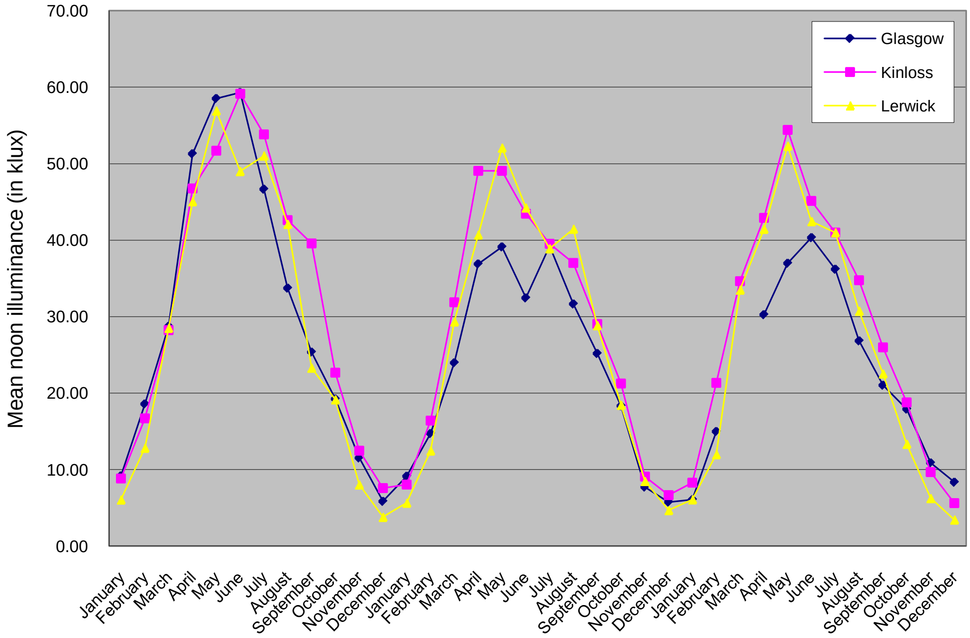


Figure 4: Mean noon UVA irradiance (W/m^2) at the three sites in England for 2006-2008.

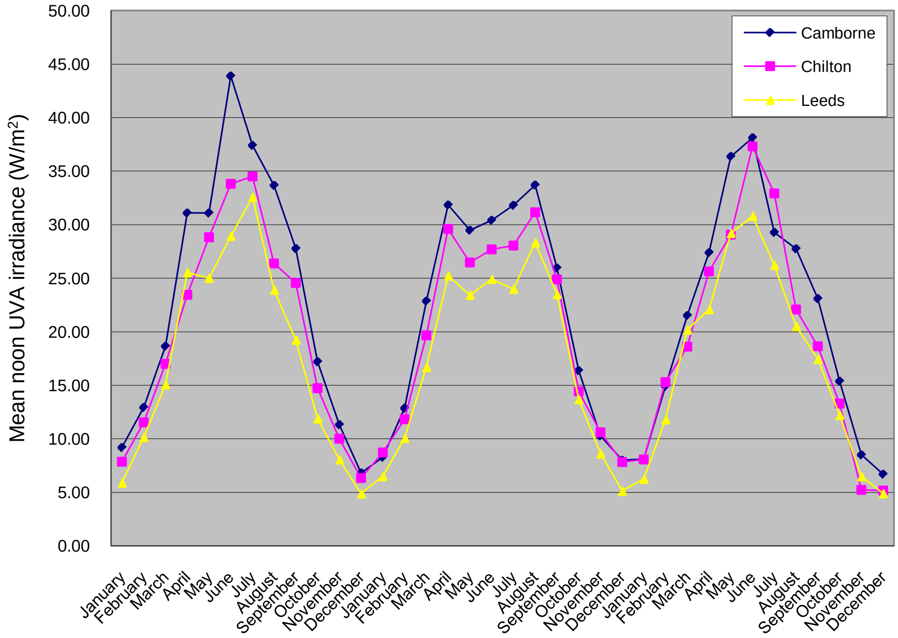


Figure 5: Mean noon UVA irradiance (W/m^2) at the three sites in Scotland for 2006-2008.

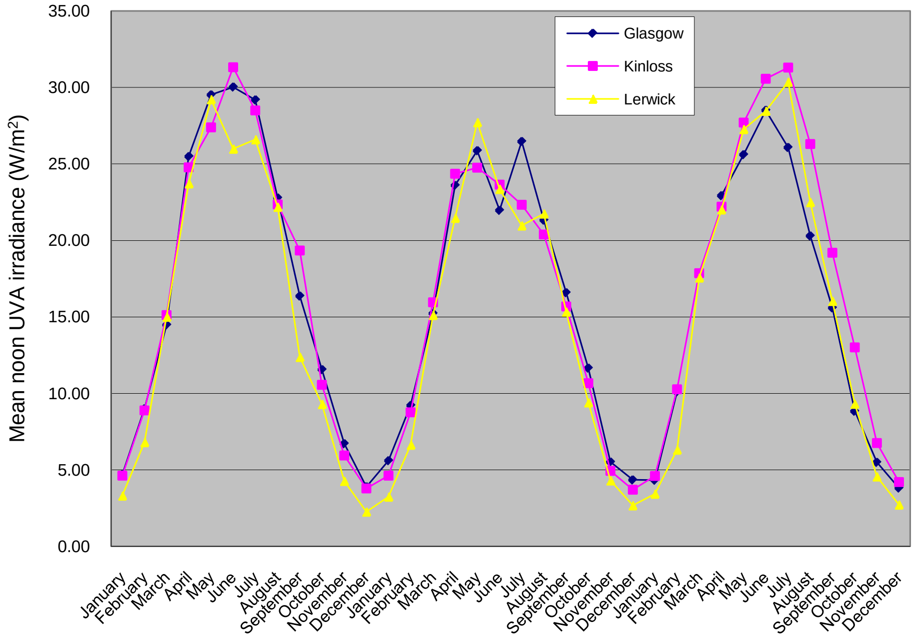


Figure 6: Mean noon erythemally weighted UVR irradiance (mW/m^2) at the three sites in England for 2006-2008.

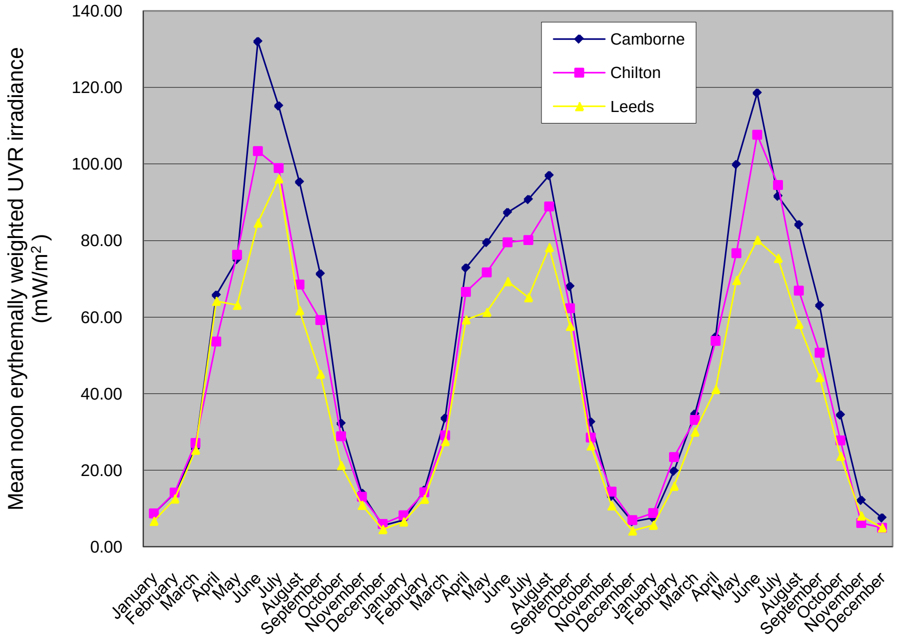


Figure 7: Mean noon erythemally weighted UVR irradiance (mW/m^2) at the three sites in Scotland for 2006-2008.

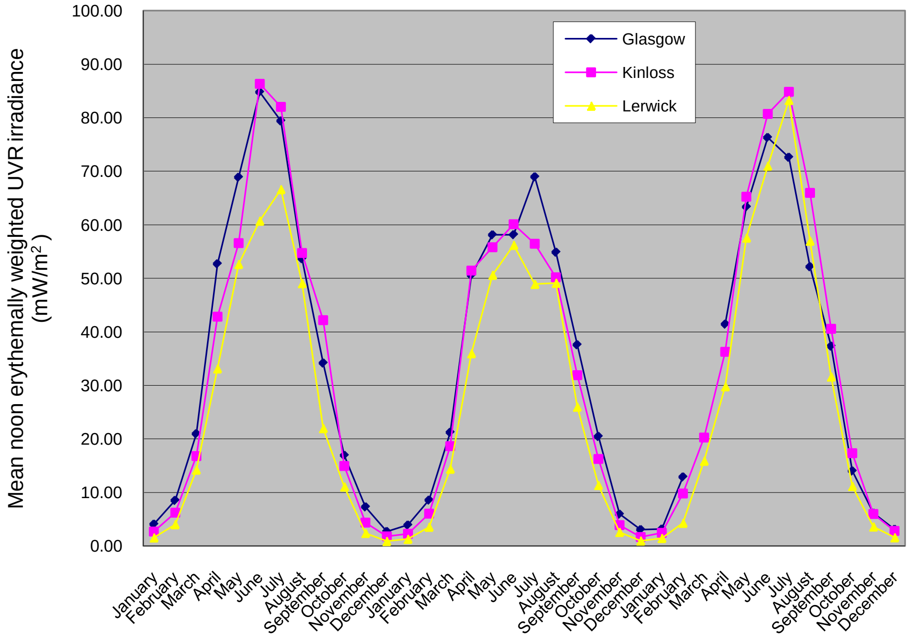


Figure 8: Monthly erythemally effective radiant exposures (UVR_{eff}), 1994-2008, (kJ/m^2) for Camborne and Lerwick

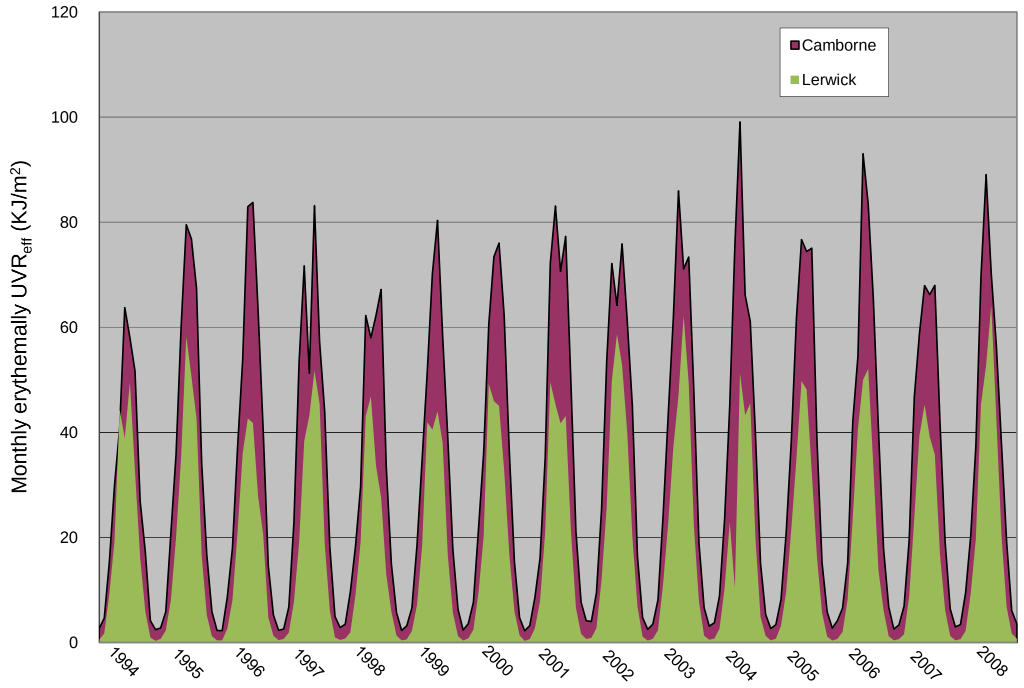
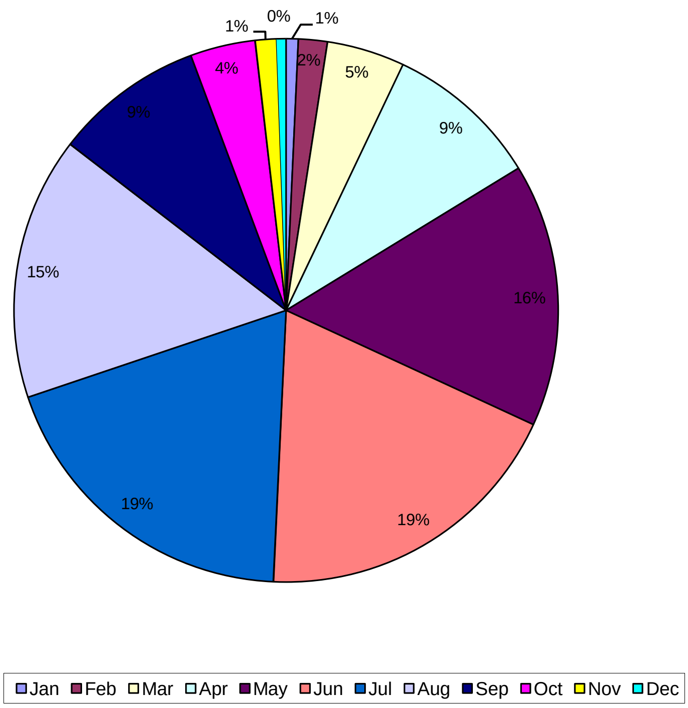


Figure 9: Pie chart for the mean monthly erythemally effective radiant exposures (UVR_{eff}), 1989-2008, (expressed as approx. % of mean annual exposure) for Chilton.



3 STATISTICAL ANALYSIS

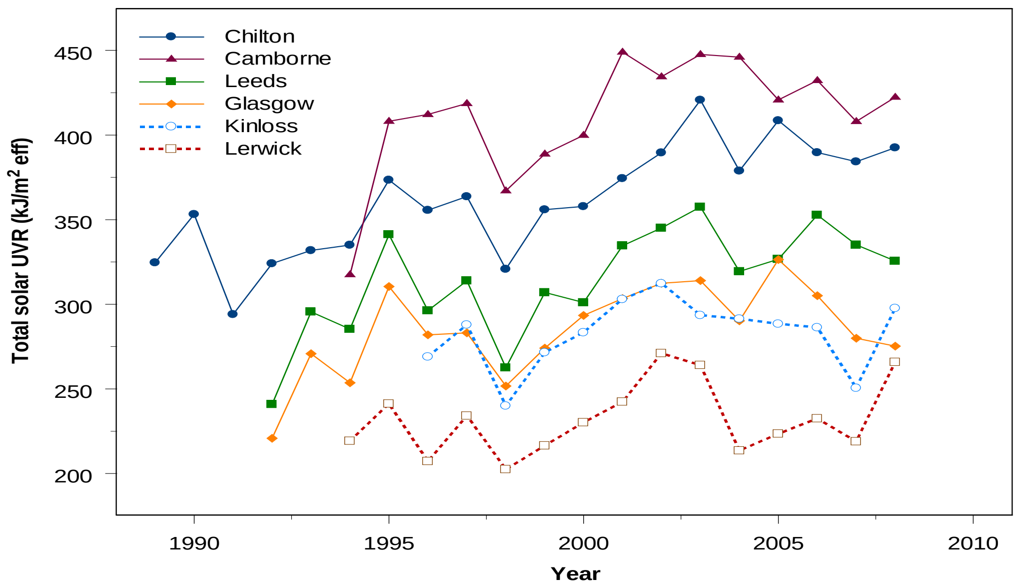
3.1 Methods

A linear regression analysis was carried out for each site in order to test whether the estimated slope in this particular sample of measurements reflects a real trend in the underlying UVR_{eff} or UVA data and to explore long term trends in solar UVR_{eff} and UVA for the six sites in GB. The trend analysis was performed on annual averages and a t-test was used to determine whether the slope of the fitted trend model was significantly different from zero, where the significance level $P<0.05$ was considered statistically significant. For each set of data, where the trends were statistically significant, the percentage trends were calculated.

3.2 Erythemally effected ultraviolet radiation (UVR_{eff})

Figure 10 shows the seasonal variations of total erythemally effected ultraviolet radiation (UVR_{eff}) exposure for these six sites in GB. It should be noted that the year in which reliable and full data started to be collected varies by site, each site ranging between 13 and 20 years (Table 1). The Figure illustrates that the pattern of the trend is similar for all of GB sites. There was no significant upward trend before 1998, but a consistent rise until 2003 thereafter. A clear peak was observed in 1995 and 2003 for most sites. More recently it appears that the trends may be stable for all sites, but not for Kinloss and Lerwick sites in Scotland.

Figure 10: Total yearly erythermal UVR_{eff} data for the six UK sites. Chilton (1989- 2008), Glasgow (1992–2008), Leeds (1992–2008), Camborne (1994-2008), Lerwick (1994-2008) and Kinloss (1996-2008).



As expected, Camborne in Cornwall is where the highest and Lerwick in the Shetland Islands is where the lowest UVR_{eff} radiant exposures were measured throughout the year. Generally, the UVR_{eff} level at a high-latitude is relatively low this may be due to the solar elevation even in summer. The remainder of the sites in descending order in terms of UVR_{eff} exposure from south to north were Chilton, Leeds, Glasgow and Kinloss (see Fig.10).

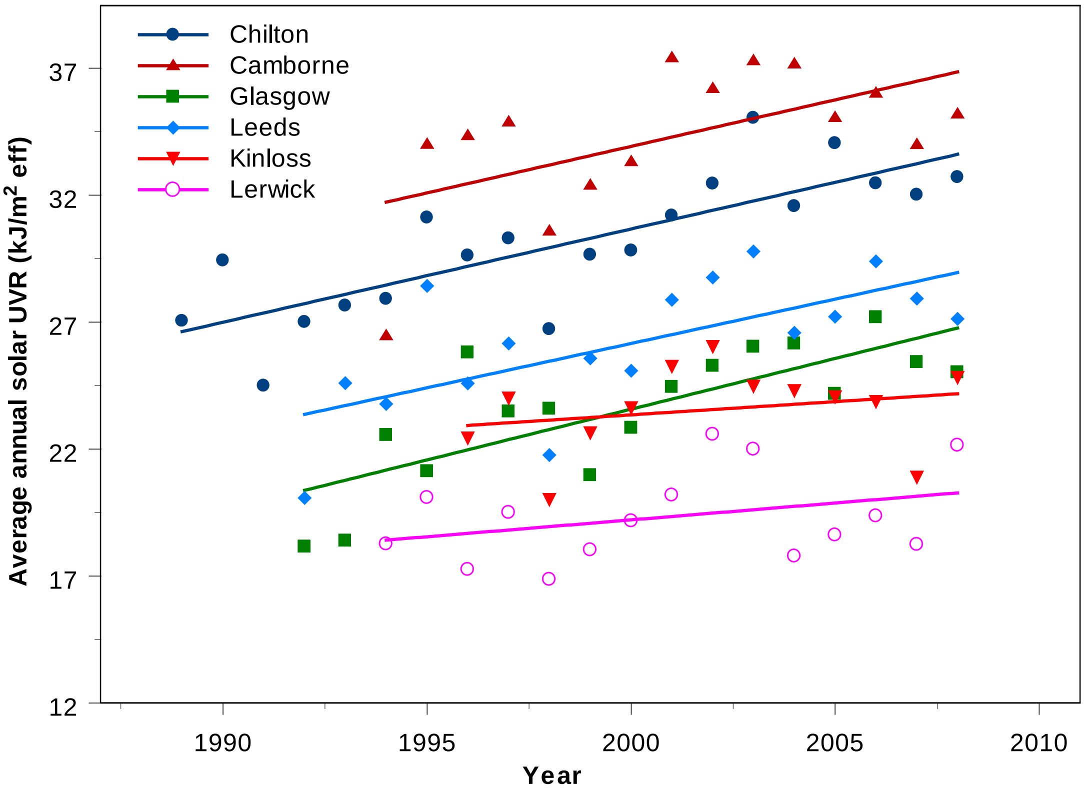
Table 1 shows statistical summaries from the linear trend analyses for the annually-averaged solar UVR_{eff} at each site, including the estimates of the linear slopes with their standard errors (SE) and the percentage change in UVR_{eff} per year for Camborne, Chilton, Leeds and Glasgow sites. Figure 11 presents the linear trend of straight line fit to annually-averaged UVR_{eff} for each site. The long term averages of the annual solar effective radiant exposure in GB range between 0.10 ± 0.15 kJm^{-2} eff./year in Kinloss (has the second highest latitude, 58° N) and 0.37 ± 0.15 kJm^{-2} eff./year in Camborne (has the lowest latitude, 50° N). Statistically significant increases in Solar UVR_{eff} were observed at Camborne (P=0.03), Chilton (P<0.01), Leeds (P<0.01) and Glasgow (P<0.01). However, at the Camborne site, there is a clear indication in Fig.11 (shown in triangles) that the first data point appears to deviate markedly from the other data points. When this data point was removed, the trend was not statistically significant anymore (P=0.14) and the slope of the trend line was reduced to 0.19 ± 0.12 kJm^{-2} eff./year. The trend for Kinloss and Lerwick was found to be not statistically significant, P=0.43 and P=0.22 respectively. The highest increase in UVR_{eff} was observed for the Glasgow site (0.40 ± 0.09 kJm^{-2} eff./year or 2.20% per year) and for the Leeds site, the increase was 0.35 ± 0.10 kJm^{-2} eff./year or 1.74% per year. For the Camborne and Chilton site, the average annual increase was estimated to be similar 0.37 ± 0.15 kJm^{-2} eff./year or 1.40% per year and 0.37 ± 0.06 kJm^{-2} eff./year or 1.37% per year respectively. We also performed a test of heterogeneity in slopes between sites and the test showed that there was a statistically significant difference in the slopes between sites (P<0.01). Overall, the increase in GB for the UVR_{eff} data was statistically significant (P=0.04) and the average annual increase between 1989 and 2008 in the GB was estimated to be 0.23 ± 0.11 kJm^{-2} eff./year, which corresponds to 1.68% per year.

Table 1: Linear regression estimates for the UVR_{eff} data, with their standard error ($\pm$ SE) for six GB sites.

Sites	Latitude, ° N	Measurement period (yr)	Length (yr)	Estimated linear slope $\pm$ SE (kJ/m^2 eff./ year)	Increase per year (%) $\pm$ SE	Durbin-Watson statistics, *d*
Camborne	50	1994-2008	15	0.37 ± 0.15*	1.40 ± 0.56	1.36
Chilton	52	1989-2008	20	0.37 ± 0.06**	1.37 ± 0.22	2.03
Leeds	54	1992-2008	17	0.35 ± 0.10**	1.74 ± 0.50	1.90
Glasgow	56	1992-2008	17	0.40 ± 0.09**	2.20 ± 0.50	1.63
Kinloss	58	1996-2008	13	0.10 ± 0.13	-	1.73
Lerwick	60	1994-2008	15	0.13 ± 0.10	-	1.73

*: significant at <5% level; **: significant at <1% level

Figure 11: The trend for Average annual erythermal UVR_{eff} data versus time for the six GB sites: Chilton (1989- 2008), Glasgow (1992–2008), Leeds (1992–2008), Camborne (1994-2008), Lerwick (1994-2008) and Kinloss (1996-2008) with separate linear best fit from a linear regression for each site.

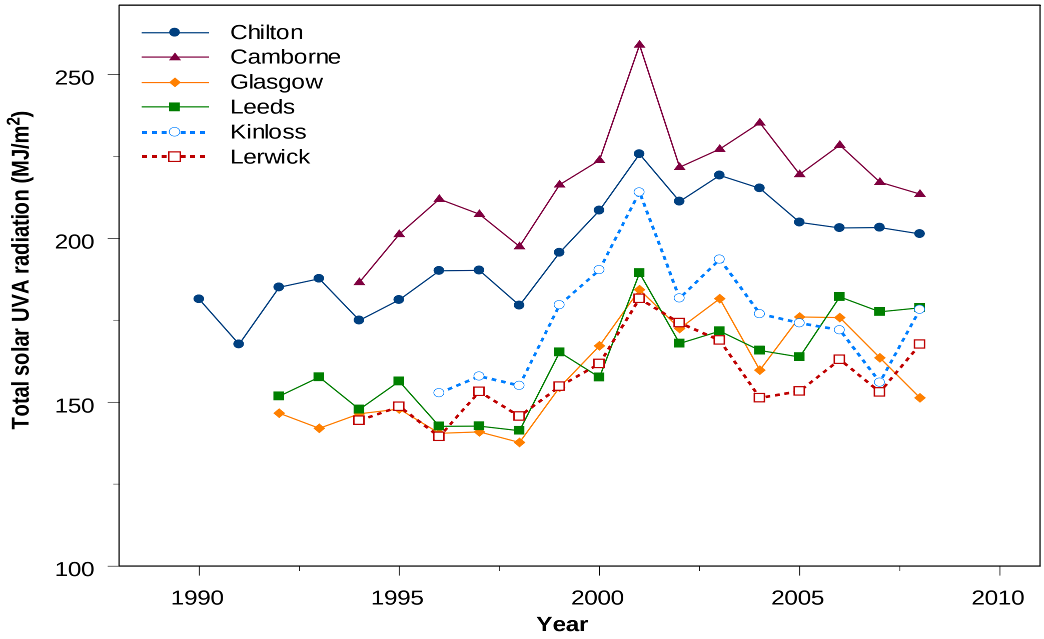


The evidence for autocorrelation in the residuals of the regression analysis was also tested for each site using the Durbin-Watson (DW) statistic (see Table 1). The test compares the residual for time period t with the residual from time period t-1 and develops a statistic that measures the significance of the correlation between these successive comparisons (Chatfield 1984). In order to test the significance, we compared the values in Table 1 with the Durbin-Watson critical values in Appendix B (Appendix B gives a brief summary of the Durbin-Watson test and the critical values). The Durbin-Watson statistic, *d* for Chilton is 2.03 (Table 1) and the critical values in Table B1 for N= 20 and for the 5% significance levels are D_L = 1.08 and D_U = 1.36. Since the test statistics 2.03 is greater than D_u there is no significant positive autocorrelation. We also found no evidence for autocorrelation in the errors for any of the sites. However, the DW test for Camborne is inconclusive this is because *d* value 1.36 is equal to the D_u.

3.3 UVA radiation

The total annual solar UVA radiant exposure values are shown in Figure 12 for all of the UK sites. From this plot, it can be seen that the UVA data for all sites follow similar patterns of variation. As expected, Camborne was recorded to be the highest total annual UVA radiant exposures throughout the year. However, at Kinloss solar UVA radiant exposure was higher than was recorded at Leeds or Glasgow. Moreover, Leeds, Glasgow and Lerwick were observed to be reasonably consistent in UVA data throughout the year (Fig.12). There was no apparent upward trend until 1998 for the UVA data. However, there was a consistent rise between 1998 and 2001 with a clear peak in 2001 for all of the UK sites. UVA values now appear to be decreasing or are stable for most sites.

Figure 12: Total Yearly UVA dose for the six GB sites. Chilton (1990- 2008), Glasgow (1992 – 2008), Leeds (1992 – 2008), Camborne (1994-2008), Lerwick (1994-2008) and Kinloss (1996-2008).



Time trends appear to have changed direction, in other words both linear and quadratic changes in trend over time might be seen for some sites (e.g. Camborne, Chilton, Kinloss and Lerwick). A F-test was carried out to compare the fit of the linear model versus the linear-quadratic (LQ) model. For Camborne and Kinloss, the LQ trend appeared to be a statistically significant better fit than the linear fit ($P<0.01$) (see Fig.13). However, including a quadratic term in addition to the linear term for Chilton, Leeds, Glasgow and Lerwick did not improve the model and the linear-quadratic (LQ) fit was not statistically significant compare to the linear fit ($P>0.05$).

Figure 13: The trend for average annual UVA dose data versus time for the six GB sites: Chilton (1990-2008), Glasgow (1992 – 2008), Leeds (1992 – 2008), Camborne (1994-2008), Lerwick (1994-2008) and Kinloss (1996-2008).

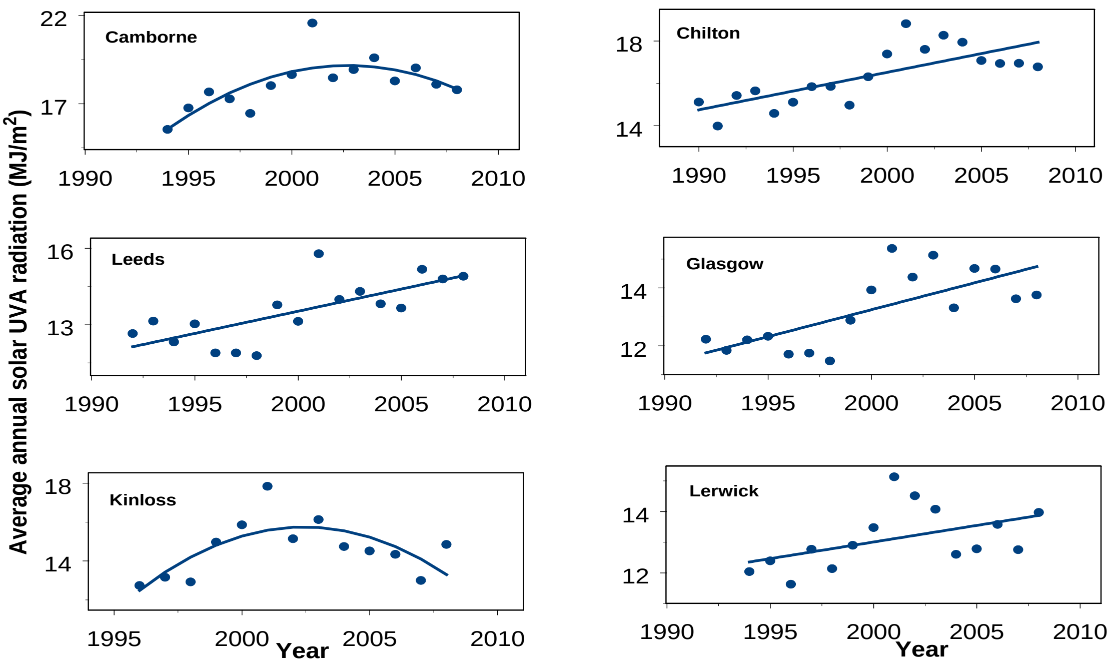


Table 2 shows the estimates of the linear slopes with their standard errors (SE) of the UVA data for the four GB sites, together with the percentage change in UVA per year for these sites and LQ estimates for Camborne and Kinloss. The observed increasing linear trends were found to be statistically significant for Glasgow (P<0.01), Chilton (P<0.01) and Leeds (P<0.01) and a borderline significance for Lerwick (P=0.06). The linear-quadratic trend for Camborne and Kinloss sites was found to be statistically significant (P<0.01). The average annual increase for Chilton site was estimated to be 0.18 $\pm$ 0.04 MJm^{-2} / year or 1.19% per year and the corresponding estimates for Leeds and Glasgow were similar 0.17 $\pm$ 0.04 MJm^{-2} / year or 1.34% p, 0.19 $\pm$ 0.05 MJm^{-2} / year or 1.55% per year respectively (Table 2). A test of heterogeneity in slopes between these sites for the UVA data found no statistically significant differences (P=0.13). When all the sites were combined together, the linear-quadratic (LQ) fit was not statistically significant compare to the linear fit (P=0.21). Hence, overall the linear increase in GB for the UVA data was statistically significant (P=0.003) and the average annual increase between 1989 and 2008 in GB was estimated to be 0.15 $\pm$ 0.05 MJm^{-2} / year or 1.36% per year.

Table 2: Linear regression estimates from the linear model for the UVA data, with their standard error (SE) for four sites.

Sites	Measurement period (year)	Length (yr)	Estimated linear slope ± SE (MJ/m^2 / year)	Estimated quadratic slope ± SE (MJ/m^2 / year)	Increase per year (%) ± SE	Durbin-Watson statistics, *d*
Cambourne	1994-2008	15	191 ± 61.2	-0.06 ± 0.02	-	1.33
Chilton	1990-2008	19	0.18 ± 0.04**	-	1.19 ± 0.27	0.99*
Leeds	1992-2008	17	0.17 ± 0.04**	-	1.34 ± 0.32	1.80
Glasgow	1992-2008	17	0.19 ± 0.05**	-	1.55 ± 0.41	1.06*
Kinloss	1996-2008	13	50.7 ± 29.6	-0.01 ± 0.007	-	0.97
Lerwick	1994-2008	15	0.11 ± 0.05	-	-	1.11

*: significant at 5% level; **: significant at <1% level

The evidence for autocorrelation in the residuals of the regression analysis is also tested for the UVA measurements for each site using the Durbin-Watson (DW) statistic, *d* values are shown in Table 2. For Leeds *d*,1.80 is greater than D_U (1.38 from Table B1) which implies that there is statistical evidence that the error terms are not positively autocorrelated. However, *d* is smaller than D_L ($d<D_L$) for the Chilton(0.99<1.18) and Glasgow (1.06<1.13) sites at 5% borderline level that the error terms are positively autocorrelated. Furthermore, the result for Camborne, Kinloss and Lerwick were inconclusive because *d* values were between D_L and D_U from Table B1.

3.4 UVR_{eff} versus stratospheric ozone

Atmospheric scientists have estimated an increase in the UV radiation reaching the earth's surface because of observations that the global ozone layer has thinned since the late 1970s. Stratospheric ozone protects life on earth by absorbing dangerous UV radiation, and scientists have expected that a decrease in ozone leads to increases in the amount of UV radiation reaching the earth's surface, but long-term records of UVR are more difficult to explain. Hence, we have looked at whether this long-term behaviour of the measured UVR_{eff} in GB can be related to ozone depletion.

Data points on ozone concentrations at stratospheric level were available for the Camborne and Lerwick sites. In addition to these sites, monitoring ozone levels also continued over a shorter period at the new sites in Manchester (measurements available from year 2003) and in Reading (measurements available from year 2003 and 35km distant from Chilton). Data points and other information from these sites were obtained from the following air quality web-site (http://ozone-uv.defra.gov.uk/). In this web-site stratospheric ozone data were tabulated for the Camborne, Lerwick and Reading sites, and for Manchester the data were presented in graphs only. It should be noted that the Camborne site was closed in December 2003 for measuring ozone.

Figure 14 shows the relationship between annual total solar UVR_{eff} values and ozone at stratospheric level for Lerwick and Camborne and also compared Chilton solar UVR_{eff}

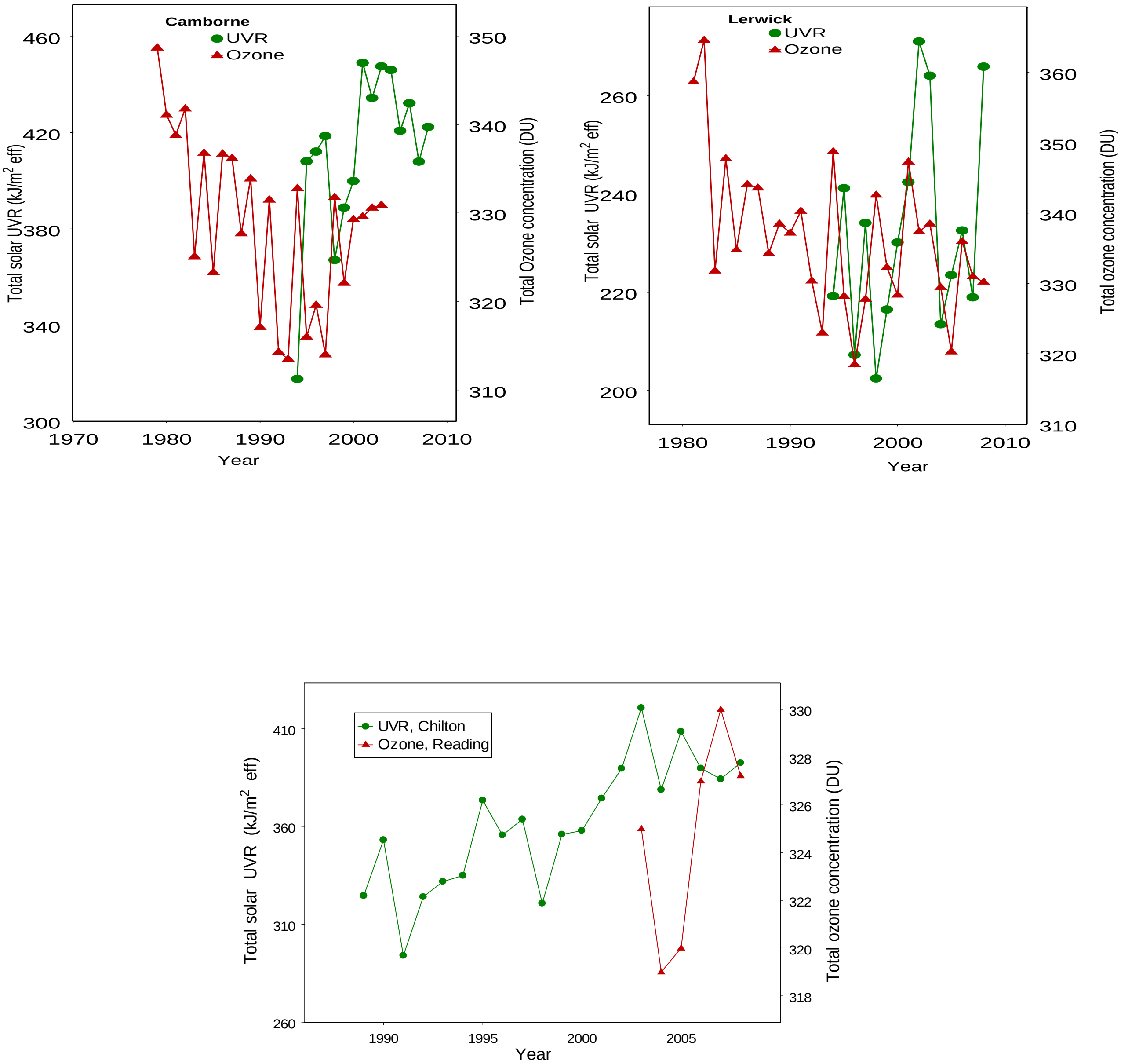
with stratospheric ozone data at the Reading site. Stratospheric ozone values at Camborne between 1980 and 2000 and at Lerwick between 1980 and 2005 sites showed a consistent drop in levels. However, it now appears that the ozone values at Camborne have become stable, but the site was closed after 2003 while values at Lerwick have continued to decrease and appear to be stable from 2007. In contrast, solar UVR_{eff} values at Camborne increased between 1994 and 2001, but started to decrease from 2003 while values at Lerwick showed a decrease between 1994 and 1998, a sharp increase after 1998, followed by a rapid fall from 2003 and a sharp increase during 2008. At Chilton solar UVR_{eff} values increased between 1991 and 2003, but started decreasing from 2005 whereas ozone at Reading started increasing from 2004. From Fig.14 the relationship between ozone and UVR_{eff} appear to be UVR_{eff} being low when ozone is high and vice versa.

The regression analysis of stratospheric ozone level over Camborne and Lerwick has shown a statistically significant downward linear trend ($P<0.01$). The estimated slope value for Camborne between 1979 and 2003 was found to be about -0.65 $\pm$0.24 DU/year or 2 $\pm$ 0.07 % decrease per year. In contrast, for solar UVR_{eff} at Camborne a statistically significant an upward linear trend ($P=0.01$) was observed and the increase per year was 1.40% between 1994 and 2008. For Lerwick, the slope for stratospheric ozone was about -0.66 $\pm$0.25 DU/year or 2 $\pm$0.07 % decrease per year between 1981 and 2008 whereas for the solar UVR_{eff} at Lerwick the upward trend was not statistically significant ($P=0.54$).

A t-test was used to investigate the relation between total UVR_{eff} and total ozone data for Camborne and Lerwick during the time period from 1994 to 2003 and from 1994 to 2008 respectively. For Camborne, the estimated slope was negative (i,e. UVR_{eff} decreased as Ozone increased), but the correlation between UVR_{eff} and ozone concentration was not statistically significant ($P=0.58$). In contrast, for Lerwick, the estimated slope was positive and the correlation again was insignificant ($P=0.55$). This means that there is no indication of a relationship for both sites. Due to the limited data at Reading, it is difficult to draw any conclusion between UVR_{eff} values at Chilton and ozone concentrations at Reading.

The overall result shows that although there appear to be an indication of the inverse relationship between changes in UVR_{eff} and total ozone concentrations at ground level in Camborne and Lerwick during 1994-2008, it is not statistically feasible to draw any conclusions regarding any underlying dependence of ozone concentrations on changes in UVR_{eff} in GB.

Figure 14: Total annual erythemally weighted UVR_{eff} for Lerwick (1994-2008), Camborne (1994-2008) and Chilton (1989-2008) and ozone concentrations (DU: Dubson Unit) for Camborne (1979-2003), Lerwick (1981-2008) and Reading (2003-2008).



3.5 UVR_{eff} versus sunshine hours

Sunshine duration is known to be the most relevant proxy for cloud cover. Total yearly records of duration of bright sunshine have been obtained from the Met Office website for Camborne, Glasgow, Lerwick and Oxford (30km distant from Chilton),

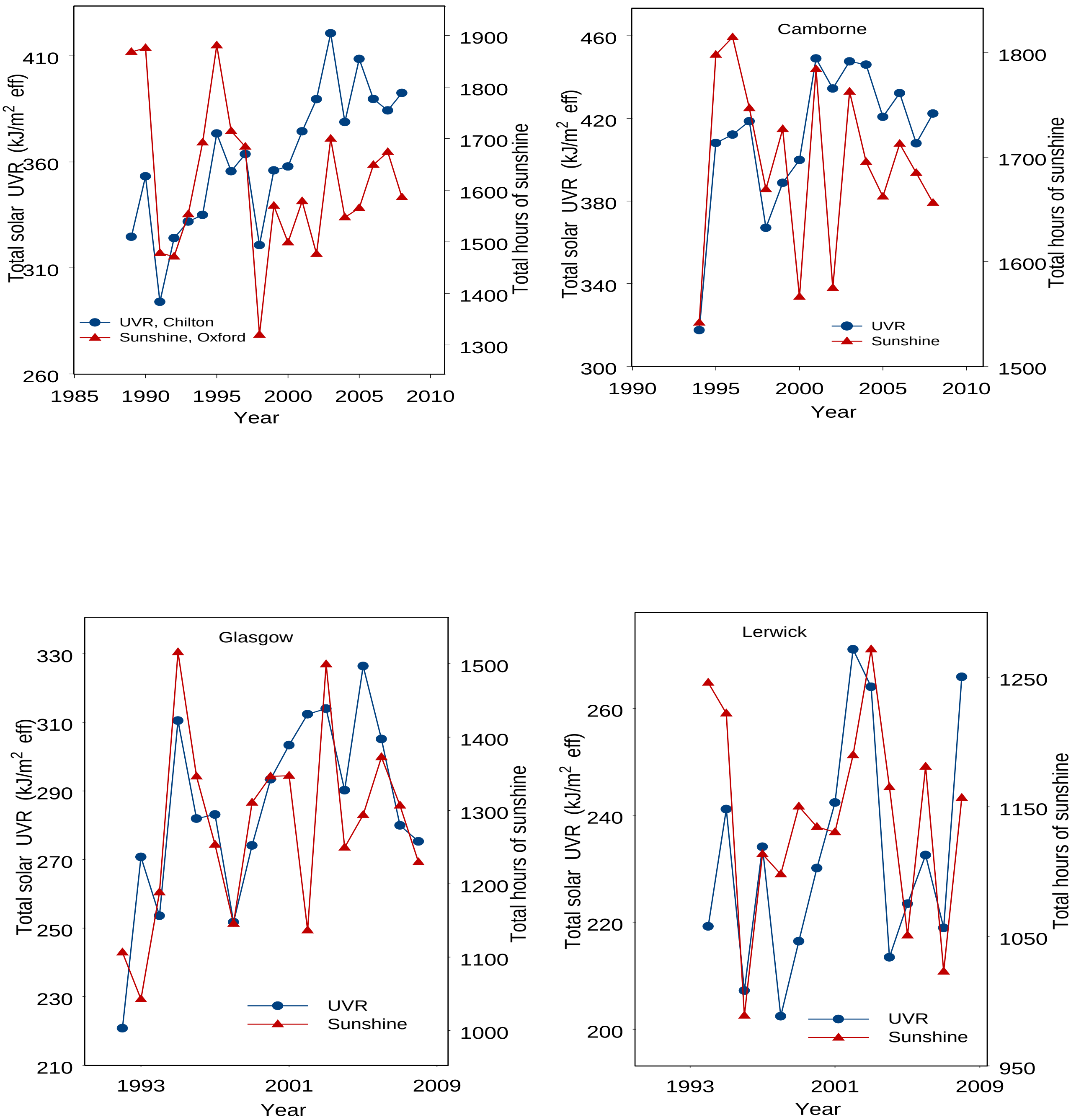
http://www.metoffice.gov.uk/climate/uk/stationdata/.

A linear regression analysis of total hours of sunshine indicates that the overall trend covering the period 1983-2008 for Camborne and Oxford has shown a statistically insignificant upward linear trend, P=0.34 and P=0.58 respectively and a borderline significance for Lerwick (P=0.05) and Glasgow (P=0.07). In contrast, the UVR_{eff} values for Chilton (near Oxford), Camborne and Glasgow, the linear trend covering the period 1989-2008 and 1994-2008 respectively have been upward at a statistically significant level (see section 3.1), but for Lerwick the linear trend was not statistically significant.

Figure 15 shows the relationship between sunshine hours and UVR_{eff} values at Camborne and Oxford in England and Glasgow and Lerwick in Scotland. All four figures illustrate clear peaks in 1995 and 2003 and a sharp fall in 1998 for both total hours of sunshine and UVR_{eff}.

A t-test was employed in order to check the statistical significance of a correlation between these values. When UVR_{eff} values were compared to sunshine hours at Camborne (Fig.15), the correlation was positive, but the t-test result was not statistically significant (P=0.08). UVR_{eff} values at Chilton were compared to sunshine hours in Oxford, and the correlation was positive, again the t-test result was not statistically significant (P=0.45). However, when the UVR_{eff} values were compared with total hours of sunshine at Glasgow and the Lerwick site (Fig.15), the correlation was positive and the t-test result was statistically significant for Glasgow (P=0.01) and for Lerwick (0.04).

Figure 15: Total annual erythemally weighted UVR$_{eff}$ and total annual sunshine hours at Camborne (1994-2008), Glasgow (1992-2008) and Lerwick (1994-2008 and UVR$_{eff}$ values for Chilton (1989-2008) versus total sunshine hours at Oxford (1989-2008).



4 DISCUSSION AND CONCLUSIONS

The new results for the years of 2006, 2007 and 2008 of a continuing survey of solar radiation levels at the HPA establishments at Chilton, Leeds and Glasgow, and over a shorter period at the sites at Camborne, Kinloss and Lerwick, have confirmed the general trends observed during the previous measurement periods.

Our previous result revealed a statistically significant upward linear trend between 1989 and 2005 in total UVR_{eff} and UVA measurements over England and West Central Scotland (Pearson et al 2006). Again, we have repeated the same analysis in order to investigate the long term changes in Solar UV radiation reaching the ground in UK by using new 2006, 2007 and 2008 data and those available previously from 1989 to 2005. The analysis has demonstrated that there are clear increasing linear trends in UVR_{eff} at four sites (Camborne, Chilton, Leeds and Glasgow) and UVA radiation at three sites (Chilton, Leeds and Glasgow). A peak was observed in 1995 and 2003 for UVR_{eff} values recorded at these sites due to hot summers for these years. A clear peak was also observed in 2001 for solar UVA, this may be explained by an overall reduction in cloudiness in UK during this year. The analysis of total erythemally effective ultraviolet radiation (UVR_{eff}) and UVA values has shown statistically significant evidence that are consistent with there being a small but significant increase trend between 1989 and 2008 in the annual integrated radiant exposures in these sites. Overall, the increase in UK for the UVR_{eff} data suggest a mean rate of 0.23 kJ/m ^{2} eff./year (95% CI: 0.01-0.45, P=0.04) or 1.68% increase per year and for the UVA data a mean rate of 0.15 MJ/m ^{2} (95% CI: 0.05-0.25, P=0.003.) or 1.36% increase per year. Although significant evidence exists for upward trends for both UVR_{eff} and UVA radiation in England and West Central Scotland, more recently it appears that the trends may be decreasing, but it is too early to draw any conclusion. In order to understand the long-term changes in surface UVR_{eff}, a longer time period of solar UVR_{eff} measurements is needed.

We have also looked at whether this long-term behaviour of the measured UVR_{eff} irradiances can be explained by known geophysical factors, e.g. ozone depletion or sunshine hours. Overall it has been found that ozone concentration has indicated a statistically significant decreasing linear trend with a rate of about 2% between 1989 and 2008 in the UK, which could be due to natural variation, while there has been an increase of 1.4% in UVR_{eff} over the same period. An increase in peak UVR_{eff} in response to decreasing ozone has been detected at the Camborne and Lerwick sites, but the correlation between annual total UVR_{eff} and stratospheric ozone level for these sites was not statistically significant between 1994 and 2008. For the sunshine hours, an increase in peak UVR_{eff} in response to increasing sunshine hours has been observed. A statistically significant linear association has been found between UVR_{eff} and sunshine hours at the Glasgow and Lerwick sites in Scotland, but the association was not statistically significant at the Camborne and Chilton sites in England. There appear to be a lack of clear evidence of any underlying dependence of ozone concentration and sunshine hours on changes in UVR_{eff} in GB. This may be caused by the lack of accurate long term UV radiation measurements and factors involved in affecting such measurements.

The amount of UV radiation reaching the Earth's surface depends on the total ozone and other identified factors such as cloudiness, aerosols, air pollution and climate. The level of UV radiation can undergo large and rapid changes at any location under these specific situations. However, due to the variability in changes of these factors it will be very difficult to quantify the most influential factor/ factors which cause larger solar UVR changes. The UV radiation data in GB are still too variable and short-term to understand whether these changes continue or not. This may be because cloud is so changeable from day-to-day and year-to-year. Hence, it is very important to continue careful monitoring of solar UVR and the variables that affect UVR at the surface in GB.

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APPENDIX A Detectors and quantities measured

The HPA Solar Radiation Measurement System (SRMS) measures solar radiation, incident onto a horizontal plane, across three wavelength regions. To do this, each SRMS unit incorporates three commercially-acquired detectors.

The quantities measured are all derived from the *irradiance* incident at the point of measurement. Irradiance is the rate at which energy (within the specified wavelength region) arrives at the measurement location, per unit area. Its units are W m^{-2}. Irradiance data may be spectrally weighted across the wavelength region of interest to account for spectral variations in effectiveness at causing some biological endpoint, such as erythema. Spectrally weighted irradiance data are referred to as *effective irradiances*. The units are still W m^{-2}, but this is sometimes written as W m^{-2}(eff).

The three quantities measured by the SRMS units are *UVA irradiance* (315-400 nm), *erythemally effective irradiance* (250 – 400 nm) and *illuminance*. Illuminance is based on the photopically effective irradiance (380 – 770 nm) multiplied by a luminous efficacy factor of 683 lm w^{-1}, and has units of lux.

Two of the incorporated detectors are manufactured by Irradian ltd (formerly Macam Photometrics). The Irradian detectors each comprise a silicon photodiode with spectral response-shaping optical filters and a cosine angular response correction diffuser. The Irradian detectors are models SD-14ACos (which measures UVA irradiance) and SD-14LCos, which measures illuminance.

Measurements of erythemally effective irradiance are made using detectors supplied by the Solar Light Company. All of the SRMSs initially deployed incorporated an RB-500 detector. This uses a blocking filter to reject unwanted wavelengths, a phosphor to shift the ultraviolet radiation into the visible region and a vacuum photodiode to measure the resulting visible radiation. By the end of the period of this report, all of the first generation SRMSs had been replaced by new units in which an RB-501 substituted for the older RB-500. The RB-501 uses a GaAsP photodiode and is held at a constant internal temperature to avoid changes in sensitivity due to ambient temperature.

For the purposes of the statistical analysis described in this report, the UVA and erythemally effective irradiance data measured during each day have been used to calculate the UVA/erythemally effective *radiant exposure* for that day. Radiant exposure is calculated from irradiance data by multiplying irradiance by exposure time. The units of radiant exposure are J m^{-2}. Radiant exposure data for successive days may be summed to calculate the radiant exposure over longer periods, as required.

APPENDIX B Durbin-Watson statistics

The Durbin-Watson statistics is a well known method of testing if autocorrelation is a problem undermining the model's inferential suitability (*e.g.,* assessing the confidence in the predicted value of a dependent variable). The test statistic of the Durbin-Watson procedure is *d* and is calculated as follows:

$$d = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}$$

Recall that e_t represents the observed error term (*i.e.,* residuals) or $(Y_t - \hat{Y}_t) = Y_t - a - bX_t$. It can be shown that the value of *d* will be between zero and four; zero corresponding to perfect positive autocorrelation and four to perfect negative autocorrelation. If the error terms, e_t and e_{t-1}, are uncorrelated, the expected value of *d* is 2. The further *d* is below 2 the stronger the evidence for the existence of positive autocorrelation and *vice versa*. The critical values of *d* for a given level of significance, sample size and number of independent variables are tabulated as pairs of values: D_L and D_U (Table A1). If the test statistic, *d* falls between these two values the test is inconclusive. The formal test of positive autocorrelation is as follows:

$H_o : \rho = 0$ (no autocorrelation)
$H_1 : \rho > 0$ (positive autocorrelation)

If $d < D_L$ reject H_o, while if $d > D_U$ do not reject H_o.

Table B1: Critical values for Durbin-Watson test: 5% and 1% significance level

Number of observation	Significance level	k=2		k=3	
		D_L (Lower level)	D_U (Upper level)	D_L (Lower level)	D_U (Upper level)
13	5%	1.01	1.34	0.86	1.56
	1%	0.74	1.04	0.61	1.26
15	5%	1.08	1.36	0.95	1.54
	1%	0.81	1.07	0.70	1.25
17	5%	1.13	1.38	1.02	1.54
	1%	0.87	1.10	0.77	1.26
19	5%	1.18	1.40	1.07	1.54
	1%	0.93	1.13	0.83	1.26
20	5%	1.20	1.41	1.10	1.54
	1%	0.95	1.15	0.86	1.27

k= Number of independent variables including intercept.