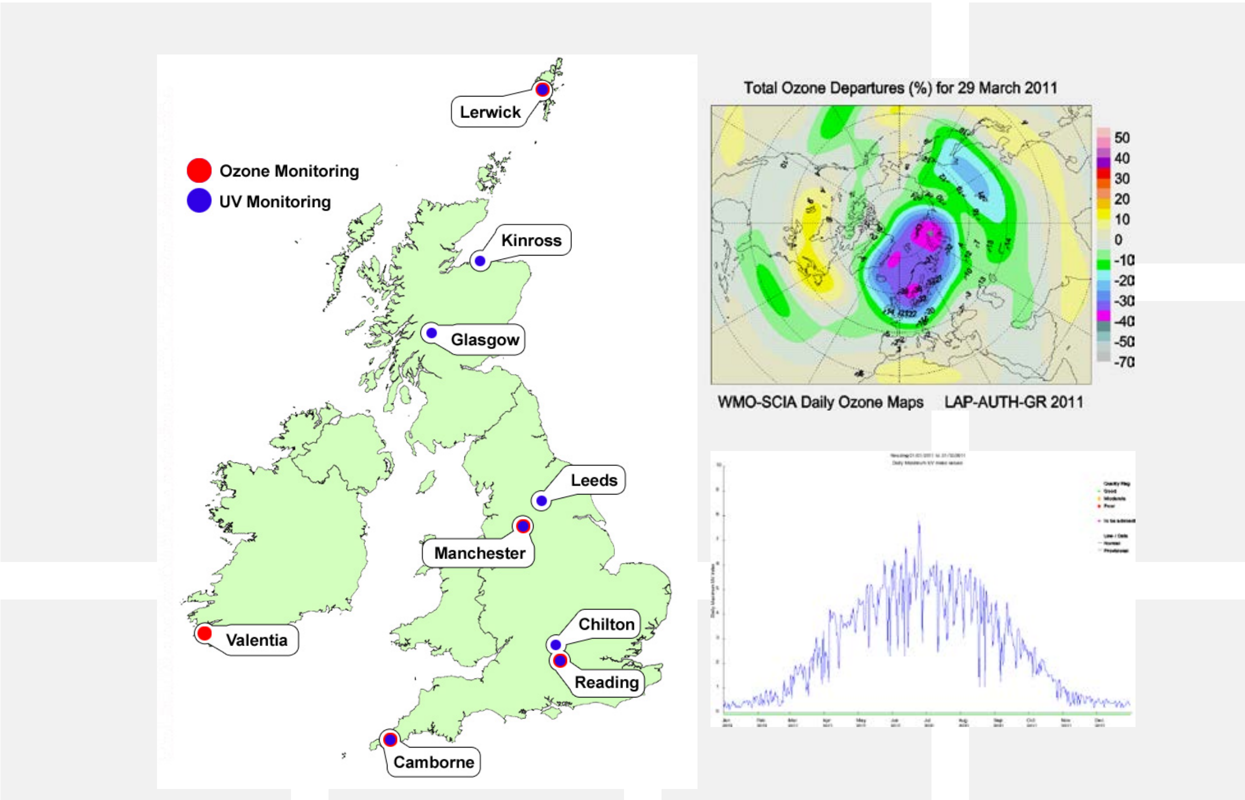
Baseline Measurement and Analysis of UK Ozone and UV

Annual 2013 Report



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Executive summary

As part of the UK commitment to the Vienna Convention to Protect the Ozone Layer, the Department for Environment, Food and Rural Affairs (Defra) has supported the ground-based monitoring of column ozone at two UK sites over many years. Ozone measurements are made on a daily basis at Lerwick by the Met Office using Dobson ozone spectrophotometers, with an historical record going back to 1957 at this location. The Department has also supported the University of Manchester in making automated Brewer ozone measurements at Reading since 2003, and spectrally resolved UV measurements at Reading since 1993. The UV radiation measurements are primarily made to assess human exposure and are more local in their relevance given the sensitivity to factors such as tropospheric air pollution, cloud cover, etc.

In the present contract, awarded to a project team led by Ricardo-AEA, the Ozone and UV monitoring activities are combined under one programme with the following commitments in place:

- **Continuation of the Dobson Ozone Monitoring Programme at Lerwick:** There is an overwhelming case to continue the ozone measurements made at Lerwick because of the proximity of this station to the Arctic polar vortex region where significant ozone depletion has been observed, and its long-term historical data record. It provides one of the key worldwide data sets.
- **Continuation of UV Measurements at Reading:** The Reading dataset, which started in 1993, provides the longest time series of such measurements in the UK. The Reading measurements are considered to be an essential part of any future UK monitoring programme.
- **Brewer Ozone monitoring at Reading:** The state-of-the-art ozone monitoring at Reading using a Brewer spectrophotometer is co-located with the existing UV spectrometer. This allows high frequency automated measurements, which, when combined with the UV data, provide additional insight into the factors controlling column ozone and surface UV levels. Reading acts as the southern UK monitoring site, providing representative data for an area of high population density.

The current contract commenced on 16th October 2010 and will be completed on 15th October 2015. The project team comprises Ricardo-AEA, the University of Manchester, the Unversity of Reading, Imperial College and the Met Office. This annual report covers the project activities for the period 1st October 2012 – 30th September 2013 and describes the work carried on the data processing, reporting and analysis of the measurements made.

The key activities and results during the reporting period were:

- **The Reading and Lerwick sites remained fully operational.** High quality, reliable results were made with a Dobson spectrophotometer at Lerwick, and with the automated Brewer ozone spectrometer and UV spectrometer at Reading. Staff at the Met Office Lerwick Observatory and the University of Manchester respectively carried out initial data checks, ensuring conformance with WMO best practice. Data transfer systems have been developed to enable Ricardo-AEA to carry out the quality assurance and reporting of ozone data from Lerwick and both ozone and UV data from Reading.
- **The on-going reporting** of the daily-averaged ozone values determined at the Reading and Lerwick sites, and the Reading Spectral UV data, continued to a number of different organisations, including world data centres. The reporting of the ozone measurements fulfils part of the UK commitments under the Vienna Convention.

- **Trend Analysis of the Measurements** suggests that the long-term decline in column ozone over the UK has not yet been reversed.
  The long-term (since 1978) autumn decline at Lerwick is statistically significant for single and multiple regression. This is difficult to explain since it implies enhanced ozone loss prior to the cold season of polar stratospheric cloud formation. However, principal component analysis confirms that the most likely cause of the autumn trend is tropospheric circulation changes.
  Trend analysis of the short Reading time series shows an annual mean increase which is not statistically significant.

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1 Introduction

The Department for Environment, Food and Rural Affairs (Defra) has let a contract for the Baseline Measurement and Analysis of UK Ozone and UV to a project team led by Ricardo-AEA. The other members of the project team are the Met Office, the University of Manchester, the University of Reading and Imperial College. Each has specific individual responsibilities for the monitoring, reporting or analysis of stratospheric ozone and UV as illustrated in Figure 1 below.

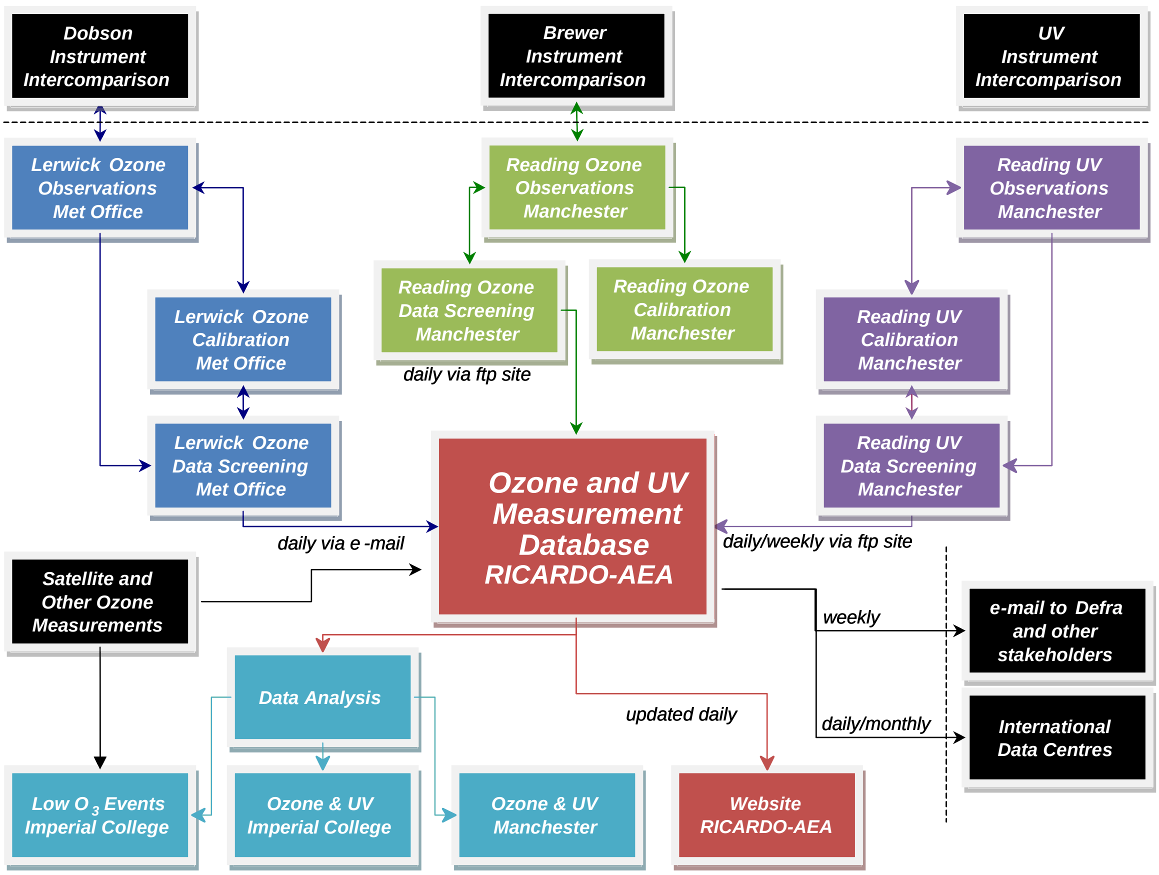


Figure 1 Project team roles

The current contract runs from the 16th October 2010 to 30th September 2015. This annual report covers the period 1st October 2012 to 30th September 2013

2 Project Aims and Objectives

2.1 Background

The current monitoring programme runs from the 16th October 2010 to 30th September 2015. It has recently been independently reviewed[1] and continues operation with:

- Daily measurements of total column ozone at Lerwick using Dobson spectrophotometers (1957-present)
- Automated measurements of total column ozone at Reading using a Brewer instrument (2003-present)
- Spectral UV measurements at Reading (1993-present, co-located with the Brewer instrument).

The locations of these and the other measurement sites for ozone and UV in the UK and the Republic of Ireland are shown in Figure 2, taken from the website for the monitoring programme[2].

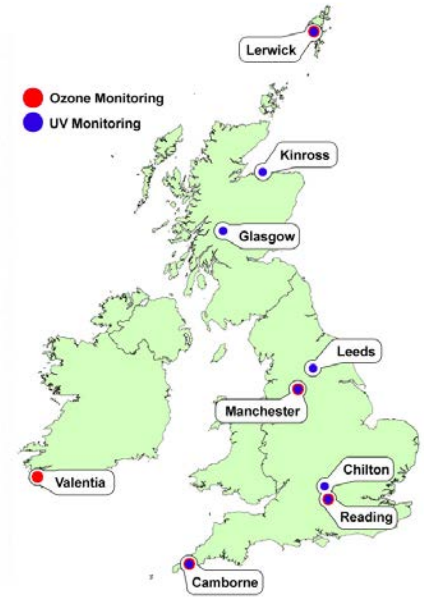


Figure 2 Location of Defra and Other Ozone and UV Monitoring Sites.

The contract is held by a project team led by Ricardo-AEA. The project team also includes the Met Office, the University of Manchester, the University of Reading and Imperial College.

The main driver for the monitoring programme is the 1985 Vienna Convention on the Protection of the Ozone Layer. The Vienna Convention obliges parties (including the UK) to undertake various activities, including *inter alia* monitoring, data dissemination and information exchange, in accordance with their capabilities and the means at their disposal.

[1] Hayman G.D. & Monks P. Review of the monitoring programme: Baseline Measurement and Analysis of UK Ozone and UV. Available from the Defra website, at http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=433&FromSearch=Y&Publisher=1&SearchText=review of the monitoring&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

[2] http://ozone-uv.defra.gov.uk/

3 Data Measurement, Processing & Reporting

The Met Office determines column ozone amounts at Lerwick using a Dobson ozone spectrophotometer. The University of Manchester makes ozone measurements at Reading using a Brewer spectrophotometer, together with spectral UV measurements using a Bentham spectroradiometer. The University of Reading provides local support for the Reading monitoring activities. In accordance with WMO recommended best practise, the instrument operators carry out the initial data processing and quality checks, before forwarding the results to Ricardo-AEA for collation, analysis and final reporting.

3.1 Dobson Ozone Measurements

3.1.1 Site Operations at Lerwick

Bi-annual visits have been made to Lerwick to inspect the instruments, perform maintenance tasks, update ISO9000 documentation, train staff and if possible conduct intercomparisons.

During the September visit a noisy motor drive was rectified on Dobson 32. Also the Q1 lever on the spare instrument Dobson 41 was found to sag in the A wavelength position by 0.3 º. Any errors introduced would be insignificant and this fault has therefore been scheduled to be fixed at the next visit. due to the amount of work already planned during the September 2012 trip.

During the April 2013 visit the Met Office found the Q leaver was only drooping by an insignificant 0.1 Q and only at the A wavelength. As Dobson 41 is the spare instrument and is due for calibration at Hohenpeissenberg June 2014 the Met Office decided that this would be the time to correct the issue.

3.1.1.1 Standard and Mercury Lamp Tests

Standard and Mercury lamp tests have continued throughout the period with both instruments performing satisfactorily.

3.1.1.2 Dobson 35 Operational availability

Since the last annual update Dobson 35 has remained on loan to the South African Weather Service. It is currently fully operational as the Irene Operational unit standing in for Dobson 89 which required maintenance due to the optical wedge belt breaking. Minor maintenance has been carried out on the Dobson 35 Q1-lever due to it seizing up in March but that is now functioning correctly. It is hoped that Dobson 89 will be reinstalled shortly as the Dobson 35 shutter motor has become erratic and a replacement is in the process of being sourced or the motor rewired.

The data are being prepared to be submitted to WOUDC in place of 89 for 2013.

It is still hoped to install Dobson 35 at the Cape Point Facility however renovations are proving difficult and it will be a while longer until they are complete.

It is hoped that South African Weather Service will be hosting the African Dobson Inter comparison during 2014 in which Dobson 35 will also participate.

3.1.2 Polynomial Reassessment Measurements

A revised Dobson observation schedule has been written for Lerwick to supplement the existing measurements so that, in due course, the existing cloudy polynomials can be updated, after enough data has been gathered. Focussed sun measurements have continued to be made where conditions have allowed according to the revised schedule. These are basically direct sun measurements with the ground quartz plate diffuser removed which provides a smaller but brighter image of the sun inside the instrument, thus enabling the instrument to be used at lower sun angles. This enables more time coincident direct sun and zenith measurements to be made as direct sun measurements cannot normally be made at such a low sun angle as zenith measurements.

It should be noted that the focussed sun measurements are not as easy to make as direct sun. Because more light enters the instrument care is required to not overload the photomultiplier. These measurements are also noisier than direct sun measurements and will not therefore be used to provide the routine ozone value for the day.

3.1.3 Informal Intercomparisons conducted at Lerwick

During 2013 there were several limited intercomparisons conducted at Lerwick site visits by David Moore (Met Office). The results were excellent and are illustrated in Table 1

Date	Dobson (41-32) DSAD (%)	Dobson (41-32) DSCD (%)	Dobson 41 DSAD Ozone values (DU)
23rd Apr 2012	0.0%	-	395
27th Sept 2012	-0.2%	-	286
28th Sept 2012	-0.3%	+0.6%	284
5th Apr 2013	-0.9%	-1.9%	423
9th Oct 2013	-0.9%	-1.0%	321

Table 1 Intercomparison results at Lerwick between instruments #041 and #032

3.1.4 Dobson Observation room

During September 2013 the Met Office Lerwick staff carried out a staged move into the new Dobson observation room. The carefully designed and highly specified room in the building underwent a series of simulated Dobson measurements. This verified that the room was fit for purpose for both the range of measurement types and sun angles experienced through the year. The old building has now been demolished and removed.

3.1.5 Measurement Summary

Figure 3 and Figure 4 show the comparison of daily Lerwick column ozone values with measurements from the OMI satellite-based instrument during this reporting period. There appears to be generally good agreement between ground-based measurements at Lerwick and the OMI satellite data.

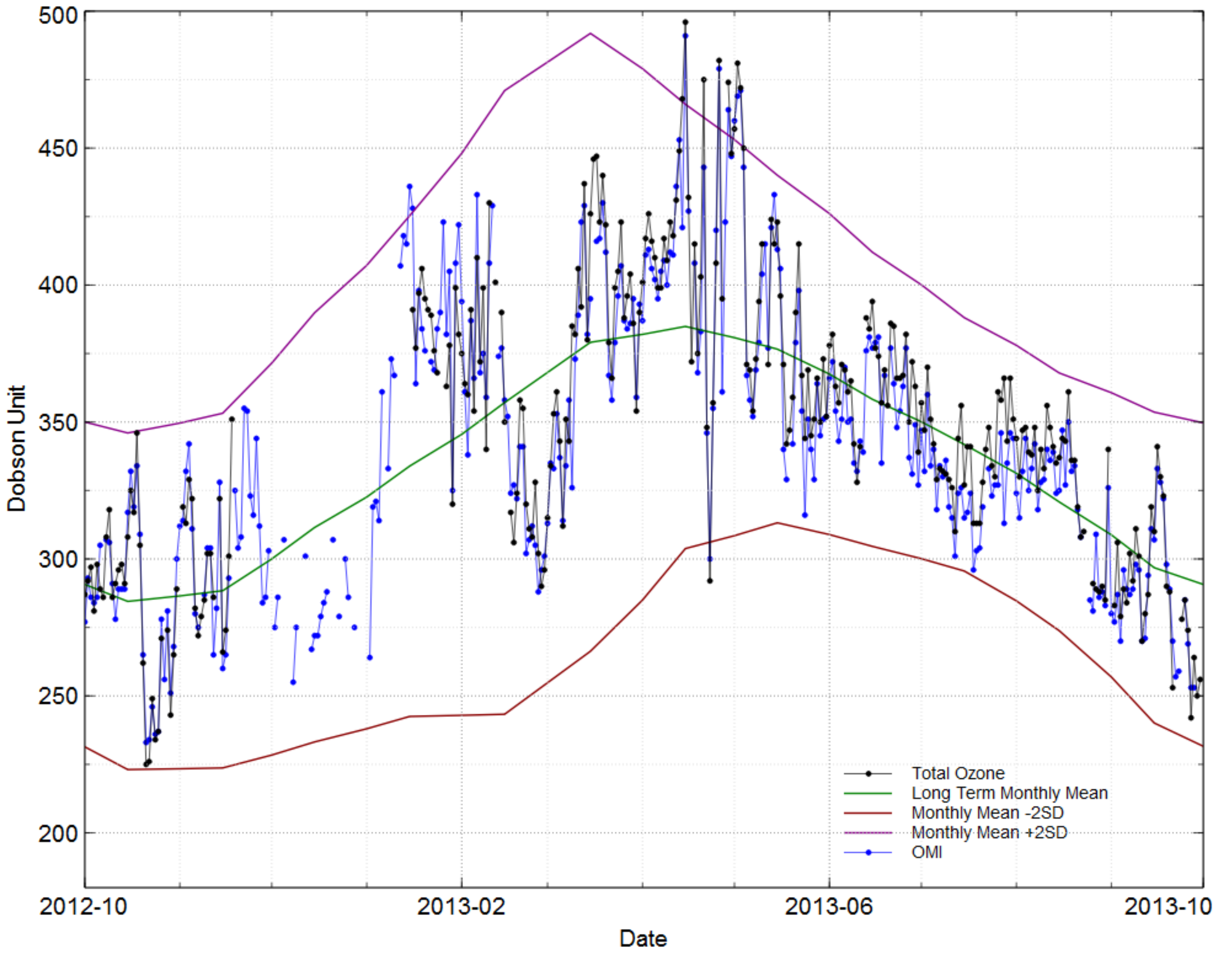


Figure 3 - Lerwick vs OMI October 2012 to September 2013

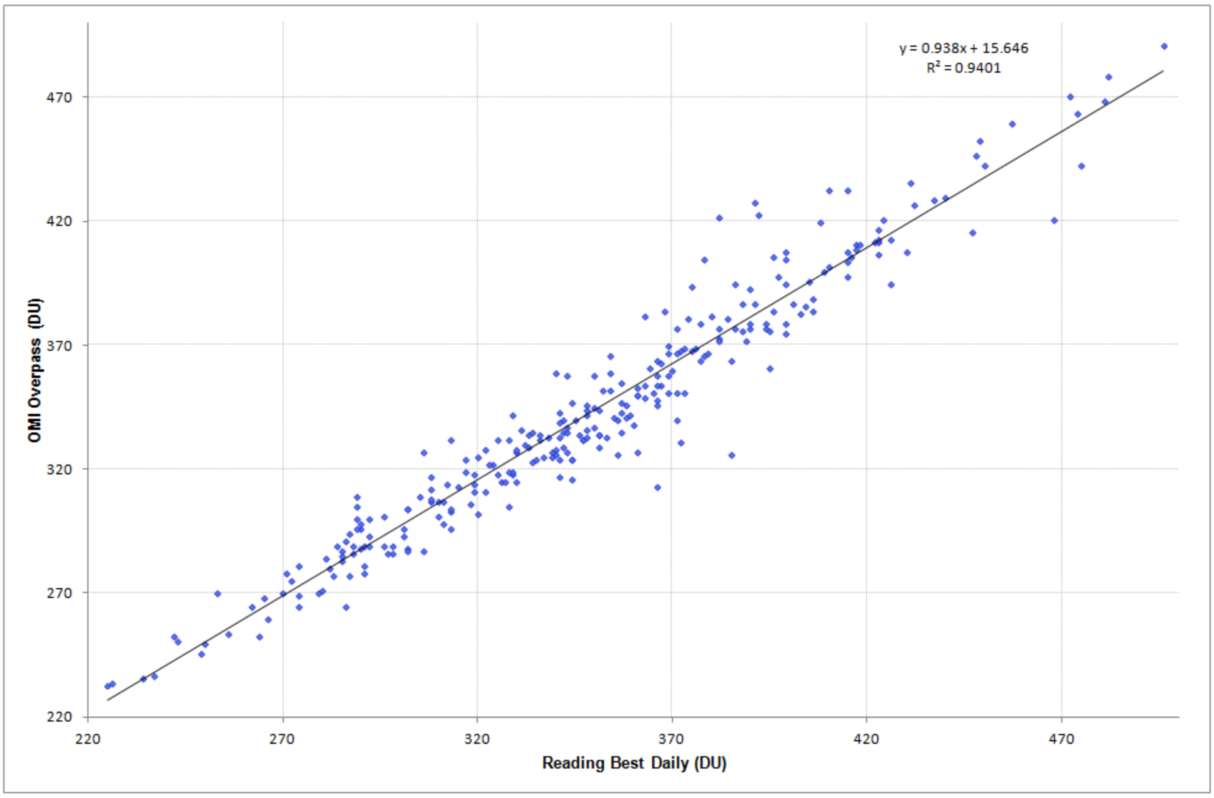


Figure 4 - Lerwick Best Daily vs OMI Overpass 01/10/2012 - 30/09/2013

3.2 Reading Ozone and UV Measurements

3.2.1 Ozone Measurements Brewer

Ozone measurements at Reading have continued largely unperturbed during the reporting period. However there have been a few days since May 2013 where the schedule has stopped unexpectedly. In most cases the schedule was restarted within a few hours. The cause, as during a similar event at the end of 2012, was suspected to be an internal issue with the Brewer data acquisition software. In particular it was suspected that there is an underlying incompatibility with running the data acquisition software on Windows 7. As part of the biennial RBCC-E intercomparison in El Arenosillo, Spain further investigations were made but no definite cause was found. As at the end of September there have been no pauses in the schedule for several weeks.

In preparation for the intercalibration exercise Brewer #075 began running an adapted schedule from late May 2013 until it was packed up ready for shipment on 6th June 2013. The calibration check on arrival at El Arenosillo revealed that Brewer #75 had been exceptionally stable since the calibration in 2011. Although we have yet to receive the calibration report, we do not expect to be notified of any major issues. The instrument returned from calibration and was re-installed at its rooftop location on 25th June 2013 and has continued to record data according to its normal monitoring schedule since that date.

For both Reading and Manchester instruments, the reprocessed data is now marked at v4.1 for WOUDC purposes, indicating that a new calibration has been applied, but that there have been no major changes in reprocessing or analysis method. The raw bfiles for both instruments during the period that each is sited in Reading have been submitted as usual to the WOUDC by the University of Manchester team. Once a calibration report has been received the new calibration values will be applied to the data.

At the 2011 project meeting, it was recognised that Brewer vertical profile umkehr measurements would be an important addition to the monitoring program. During the 2012 project meeting the University of Manchester was given the go-ahead to implement umkehr measurements into the schedule. A new schedule was written and installed on the instrument during December with the majority of the umkehr measurements scheduled for the highest solar zenith angles. This ensures that there is minimal effect on the daily average of total ozone column. (The number of attempted measurements in the ozocor and ozoavg files, however, has altered as this includes additionally measurements carried out at high airmass values that do not contribute to the daily average.) These profile measurements are now being processed on a monthly basis using a third party application, filtered for good ozone profiles, and the resulting data files are then uploaded onto the Manchester-hosted database, as is carried out for Brewer #172 in Manchester. The raw Umkehr data is included in the ‘b-files’ which are routinely submitted to WOUDC. An example profile from the last reporting period is shown in Figure 5

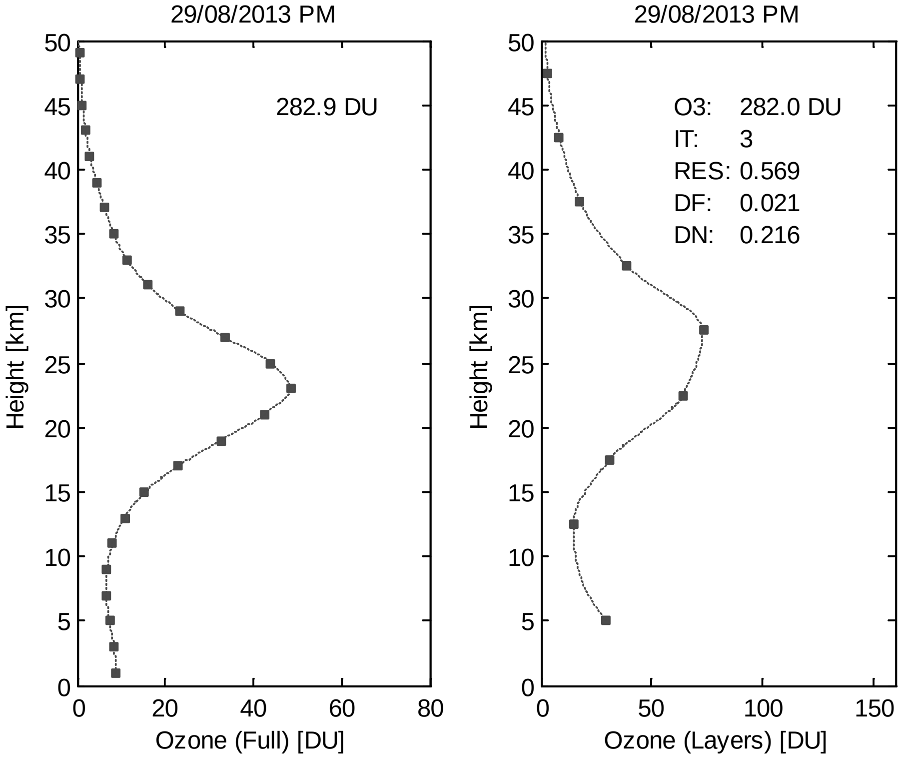


Figure 5: Example umkehr profile obtained from Brewer #075. Right hand plot shows the amount of ozone measured at each of eight layers plotted against nominal layer height; left hand plot shows interpolated ozone densities as a function of height.

Figure 6 and Figure 7 show the comparison of the daily Reading column ozone values with measurements from the OMI satellite instrument. The two sets of measurements are generally in good qualitative and quantitative agreement.

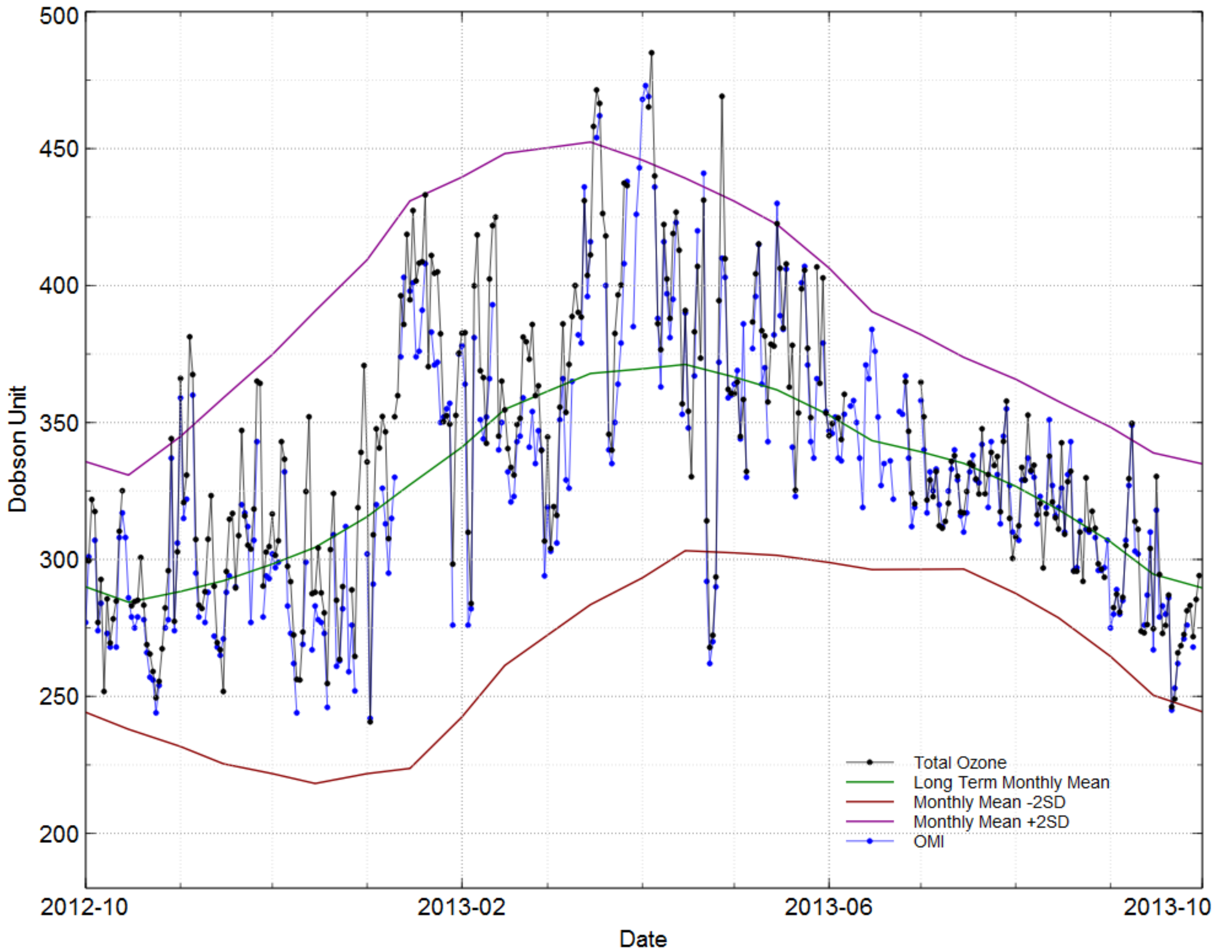


Figure 6 - Reading vs. OMI, October2012 to September 2013.

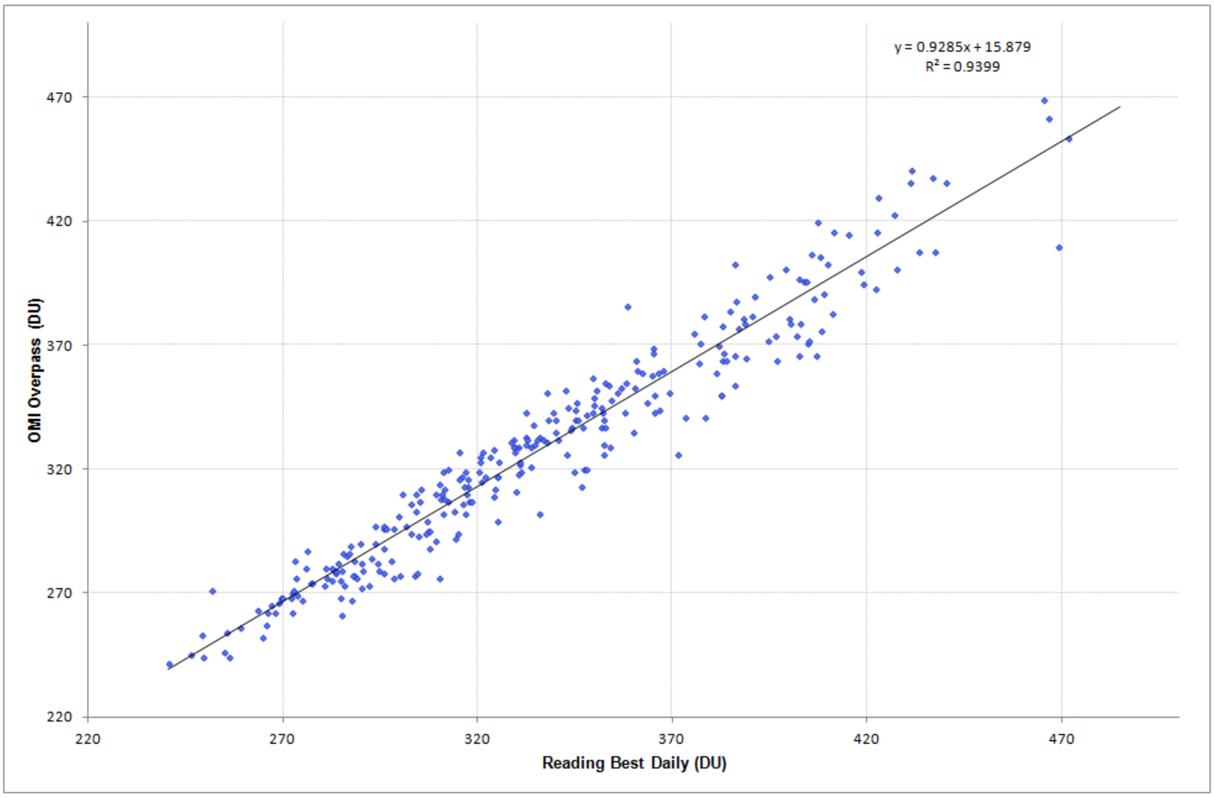


Figure 7 - Lerwick Best Daily vs OMI Overpass 01/10/2012 - 30/09/2013

3.2.2 Reading UV

Spectral UV measurements have continued during this last annual reporting period with few interruptions. The majority of those occurring before the start of the reporting period were associated with the construction of the new Reading Atmospheric Observatory. At the end of September 2012 the project team was informed that the new observatory building was ready for the relocation of the Bentham DM150 spectroradiometer and on 11th October the instrument was transferred to its new location. At the same time a new replacement air circulation system was installed to minimise humidity within the dome. The majority of interruptions to the schedule after the instrument's transfer to the new Atmospheric Observatory occurring during 2013 were associated with (often minor) power outages. In order to minimise any further loss of data a universal power supply was sourced and installed at the measurement site.

As planned at the end of June 2012 the World Standard UV instrument 'QASUME' arrived on site from Davos, Switzerland for a five day long intercomparison. Initial results indicate that our measurements have been stable with respect to QASUME at the few-percent level since the last intercomparison in 2003 - although there are a number of issues to address such as an observed diurnal variation. This intercomparison was conducted in far from ideal conditions since the refurbishment work at the Reading University site had run on far longer than we had originally been notified and was a source of disruption and random noise on the power supply. For this reason we cannot consider our instrument to have been in a typical operating mode. Much of the time during the intercomparison was spent recording data that was assimilated into our normal time series, so that, save for a short gap during installation, the campaign spectra have now been processed and included into our time series. The final report from this campaign was received in late 2012 from the World Radiation Centre and has been forwarded to Ricardo-AEA and Defra as requested. The minor issues with wavelength calibration have now been addressed and the investigation into the diurnal variation is on-going. It is strongly suggested that the intercomparison is repeated in about three years.

During the last annual reporting period the fraction of yellow (fair) level_1 quality flags has been very low, as shown in Figure 8 and Figure 9, with green flags being produced almost all of the time during the period, showing the high quality of the resulting data series. A small number of days (approx. 5) have exhibited slightly lower percentages of green (good) level_1 flags and these were associated with rapidly changing sky conditions (particularly around days 129 and 215 during summer 2013). It is thought that the shicRIVM software that is used to assess data quality can occasionally misinterpret unexpected changes in the spectral shape as an instrumental issue. As the flags reverted to their normal level once conditions became less changeable, this hypothesis seems to be borne out. As normal where changes over the 2% threshold have been noted during recent calibration checks, corrections have been made to the instrument response before spectral measurements were resumed (Figure 10). It will be noted that calibration checks have been closer or below the 2% threshold over the last few months, since construction work at the site has been completed.

On 19th July, the quartz dome was accidentally damaged during a calibration check. It was replaced with a new one on 22nd July but during the interval, the instrument was calibrated to run without a dome so that effects on data were kept to a minimum.

The University of Manchester continues to produce WOUDC and EUVDB format files during the nightly processing routines, from the level_1 spectral UV dataset, filtering these for quality flags. These files reside on the o3uvdata.seaes.manchester.ac.uk ftp database. At the end of each month these files are sent to the World Ozone and UV Data Centre (WOUDC) and European Ultraviolet Database (EUVDB) for use by the wider scientific community. This processing is still considered as state of the art, although WMO have now approved the inclusion of UV-index into WOUDC files. University of Manchester staff are currently awaiting details of the specified format from WOUDC. However due to ongoing developments at Environment Canada who host the WOUDC we expect there to be a considerable delay before this task can be completed. When possible the change will also be applied to the historic data series, before resubmission.

The Finnish Meteorological Institute who host EUVDB are have yet to resolve their technical difficulties with part of submission process, which incurs a slight delay before data is manually added into the database. The processing of data by the Manchester team ensures that the dataset is identical to that submitted to the WOUDC as EUVDB format files are produced during the nightly processing routines from the same underlying files.

In addition University of Manchester staff have been investigating transferring the ozone and UV database to the University's nascent Remote Data Storage solution (a 'cloud-based' remote drive intended for research groups at the university). It is hoped that this system would make the UoM database more resilient. It is planned that off-site access will still be via the current ftp server system such that any transfer would be seamless for other members of the consortium. Once responses have been received from UoM IT services regarding the continuity and robustness a decision will be made on whether to transfer the database to the RDS.

At the end of the reporting period we have also been liaising with PHE who run the UK network of UV broadband meters and are experiencing some inconsistencies with their internal calibration. Although their monitoring falls outside of our contract, in an effort to provide comparable data across the UK, we have invited them to our calibration laboratory to ascertain the cause of the issue.

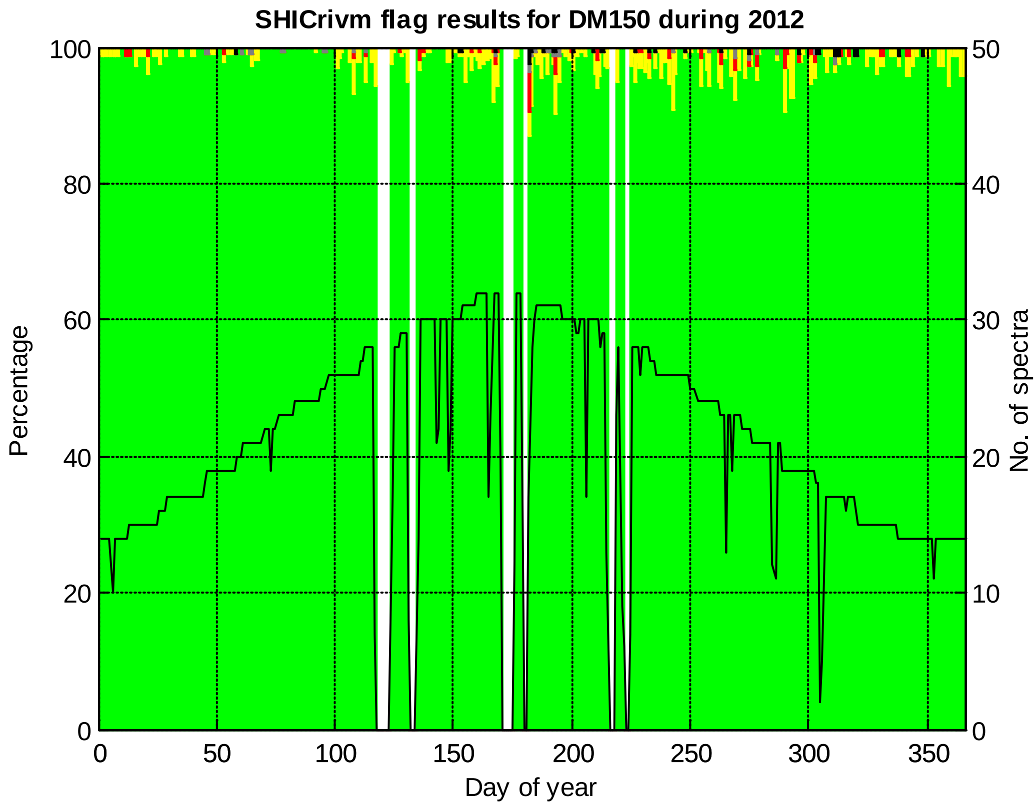


Figure 8: 2013 level_1 quality flags produced by the ShicRIVM processing software.

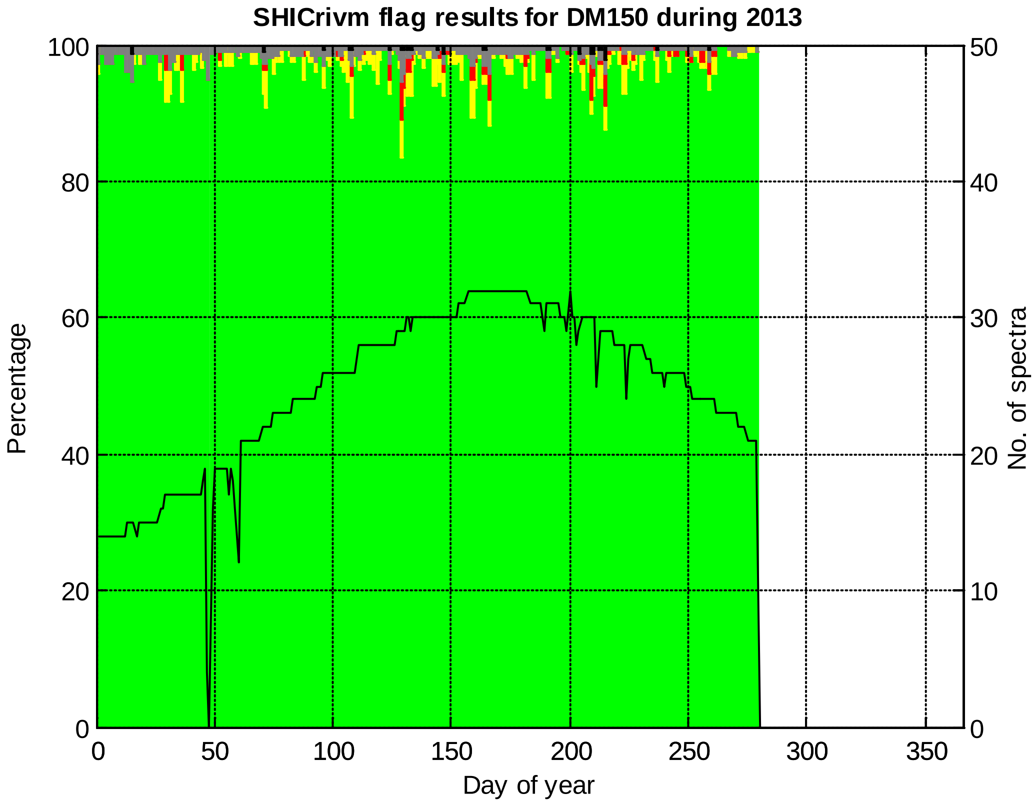


Figure 9: 2013 level_1 quality flags produced by the ShicRIVM processing software.

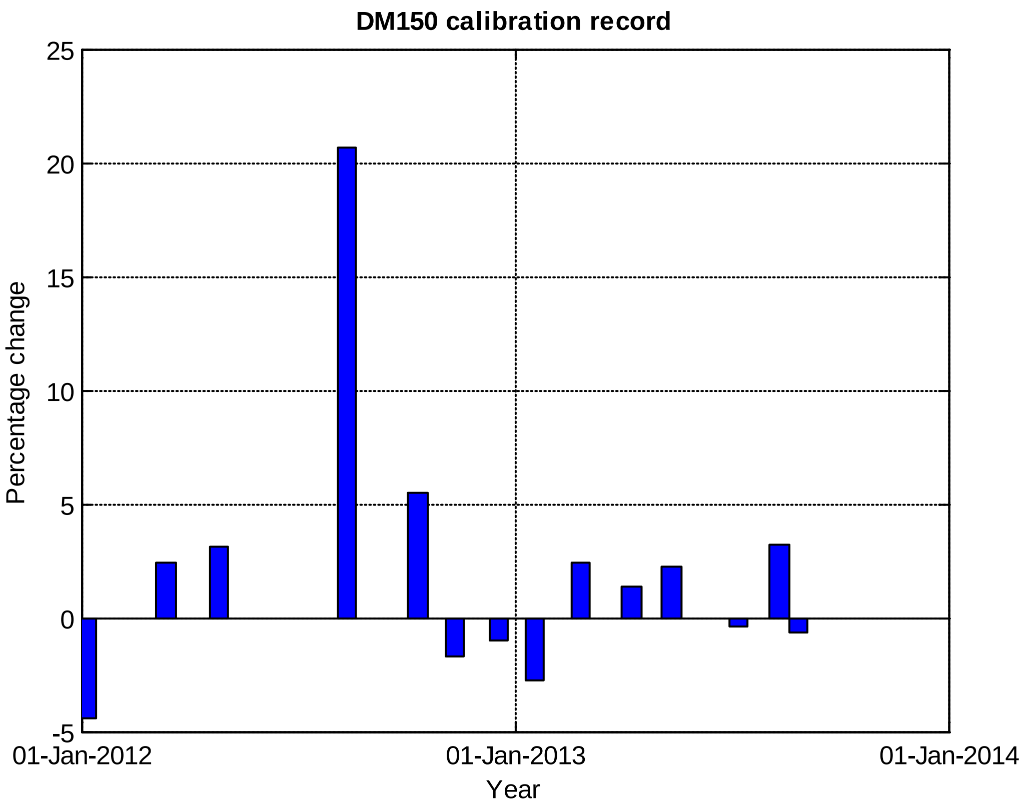


Figure 10: DM150 irradiance calibration record.

3.2.3 UV Index

Software developed by Ricardo-AEA automatically processes the spectral data from the DM150 UV instrument at Reading and converts them to a simple UV index comparable with the results from the PHE broadband UV monitoring network. The measurement data and plots of the daily UV index and of the maximum daily UV index throughout the year are available on the website one day in arrears for public information.

The daily maximum UV index values are plotted with quality flags, as an ongoing annual graph. The daily maximum UV index graphs for Reading for 2012 can be found here http://ozone-uv.defra.gov.uk/uv/data_search.php

3.3 Manchester Measurements

The University of Manchester also makes column ozone measurements at Manchester using a Brewer instrument (#172), in parallel with the reading measurements with Brewer #075. The analysis contains individual measurements made at air masses up to 6.0, as well as the usual standard lamp corrections. The version 4.1 reprocessed data, including checks against the satellite record, from Brewer #172 are being submitted to WOUDC on a monthly basis together with the raw bfiles, i.e. on the same basis as both the single monochromator instruments, Brewers #075 and #126.

Ozone data from Brewer #172 located in Manchester continues to be submitted on a goodwill basis to the Defra project team alongside the daily updates for Brewer #075. The analysis contains individual measurements made at air masses up to 6.0, as well as the usual standard lamp corrections. Reprocessed data files, including checks against the satellite record, from Brewer #172 are being submitted to WOUDC on a monthly basis together with the raw bfiles, i.e. on the same basis as both the single monochromator instruments, Brewers #075 and, and when necessary, #126.

The operating schedule for Brewer #172 was altered in preparation for calibration during late May 2013, and the instrument was packed up ready for shipment to the RBCC-E site in Spain on 5th June 2013. It was returned from a successful calibration exercise and was reinstalled at Manchester on 26th June 2013. As with Brewer #075, once the calibration report has been received and reviewed, the necessary adjustments will be made to the time series. Additionally Brewer #172 is being used by Dr Andrew Smedley as the baseline for a new instrument being developed and tested as part of the EMRP SolarUV project. This instrument is a dual channel solid state instrument fitted with both direct and global optics and it is intended that it can produce both spectral data across the UV and visible bands, together with DOAS retrieved products including ozone.

Umkehr ozone profiling measurements have been run by Brewer #172 as part of the daily schedule of measurements since 2008. During the period we have continued to process these on a monthly basis using a third party application, filter for good ozone profiles, and upload the resulting data files onto the Manchester-hosted database.

3.4 Manchester FTP

The FTP server has continued to be reliable providing data to the project team.

3.5 Ozone Data Reporting

A summary of daily Dobson and Brewer ozone data is reported on a weekly basis by email to the project partners and a number of other interested organisations and individuals.

The data are also delivered daily to the University of Thessaloniki for the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) near real-time ozone mapping programme. Interpolated maps are disseminated by return to all the participants. The mapped results can also be viewed from the web page: http://exp-studies.tor.ec.gc.ca/e/ozone/Curr_allmap.htm.

Final data are reported monthly (after Ricardo-AEA's monthly QC checks and any follow-up actions) to the WOUDC data archive. The QC checks involve:

- Comparison of all relevant datasets against each other for consistency.
- Follow-up with data providers any data points which are apparent outliers.
- Regression analysis between ground-based and satellite data to determine whether the relationship is improving or deteriorating.
- Comparison with climatology to assess whether levels are normal for the time of year.

Climatology updated by Ricardo-AEA now includes 2012 data. The Reading site now uses its own climatology rather than that transferred from the closed Camborne site.

All reports were delivered successfully during this period of the contract.

4 Data Analysis

4.1 Summary

During the period of the contract the ozone columns at Reading and Lerwick followed their normal seasonal progression. The 2012 annual means at both sites were similar to values recorded in the last 20 years.

4.2 A new statistical model

4.2.1 EOF Analysis

In the 2012 report we presented an attempt at introducing an empirical orthogonal function (EOF) analysis. On daily time scales the column ozone is strongly influenced by troposphere weather systems. The long term role of weather changes on ozone trends is only now beginning to be examined. We have examined the role of the geopotential height at 500 hPa proxy. On a daily basis this dynamical proxy is known to be anti-correlated with column ozone i.e. large heights or anti-cyclones also tend to depress the ozone column by lifting the tropopause. This is a well understood physical connection and the ozone column by itself should have negligible impact on the height. In previous work we have shown that other proxies such as the geopotential height at 200 hPa, the solar cycle (10.7 cm solar flux time series) and the Quasi Biennial Oscillation (QBO) signal do not materially improve the statistical model. Last year we studied the role of the 500 hPa proxy by EOF analysis.

Since the introduction of EOF analysis in atmospheric science by Lorenz, this simple yet effective method has been used extensively in atmospheric, oceanic, and climatic research (e.g. Hannachi et al. 2007). The essence of EOF analysis is to identify and extract the spatiotemporal modes that are ordered in terms of their representations of data variance. Because a small number of leading modes usually account for most of the total variance, EOF analysis enables one to pick out the dominant and sometimes physically meaningful modes of variability while greatly reducing the data space. By construction, the spatial patterns (EOFs) and the temporal coefficients [principal components (PCs)] of these modes are both orthogonal. Such orthogonality has the advantage of isolating uncorrelated modes, but sometimes it also leads to complexity of spatial structures and difficulty in physical interpretations; thus, it may cause misunderstanding and confusion.

Figure 11, Figure 12, Figure 13 and Figure 14 show the first and second EOFs of the seasonal mean 500 hPa field. Together these two components account for 72 % (DJF), 62 % (MAM), 61% (JJA), and 61% (SON). It can be seen that the basic spatial pattern is very similar between the seasons. The first principal pattern is a single lobe whose centre shifts seasonally south into the winter. The second pattern is of a dipole nature splitting northern and southern Europe. The second component in the summer is anomalous with a rotated dipole pattern.

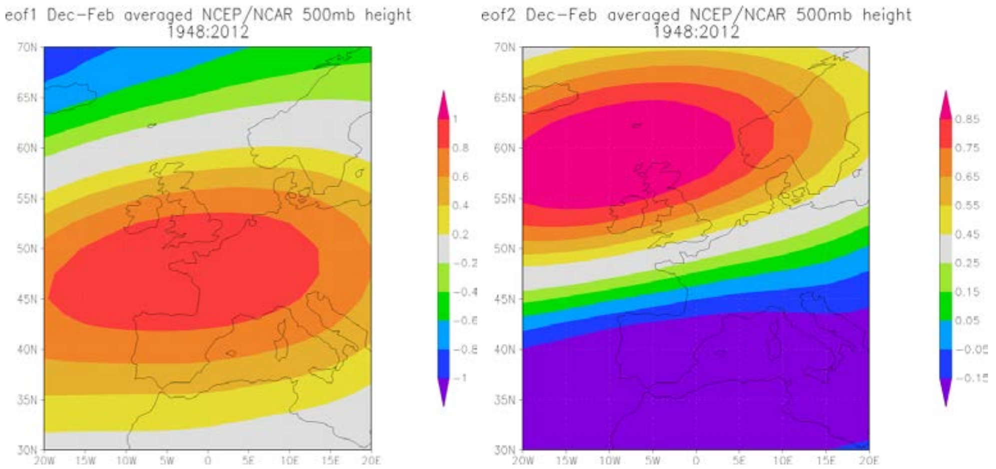


Figure 11 - Winter (DJF) principal components 1 and 2 from the NCEP re-analysis (1948-2012).

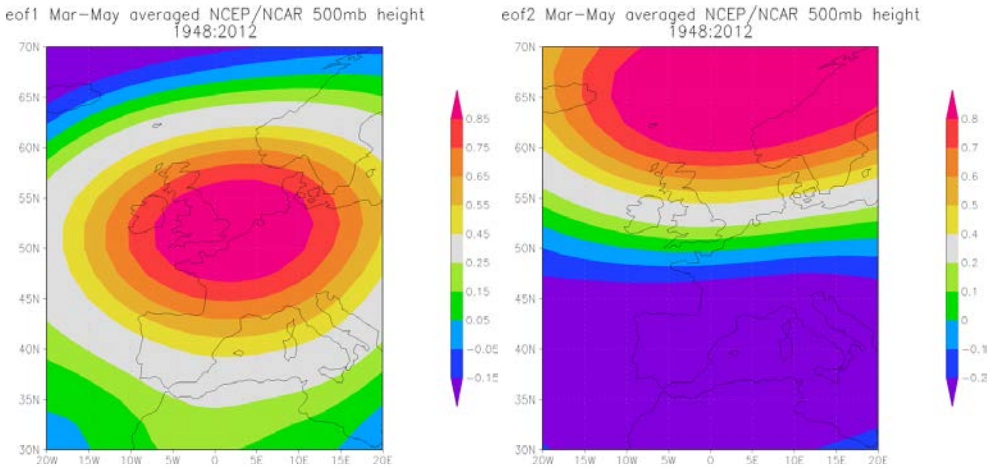


Figure 12 - Spring (MAM) principal components 1 and 2 from the NCEP re-analysis (1948-2012).

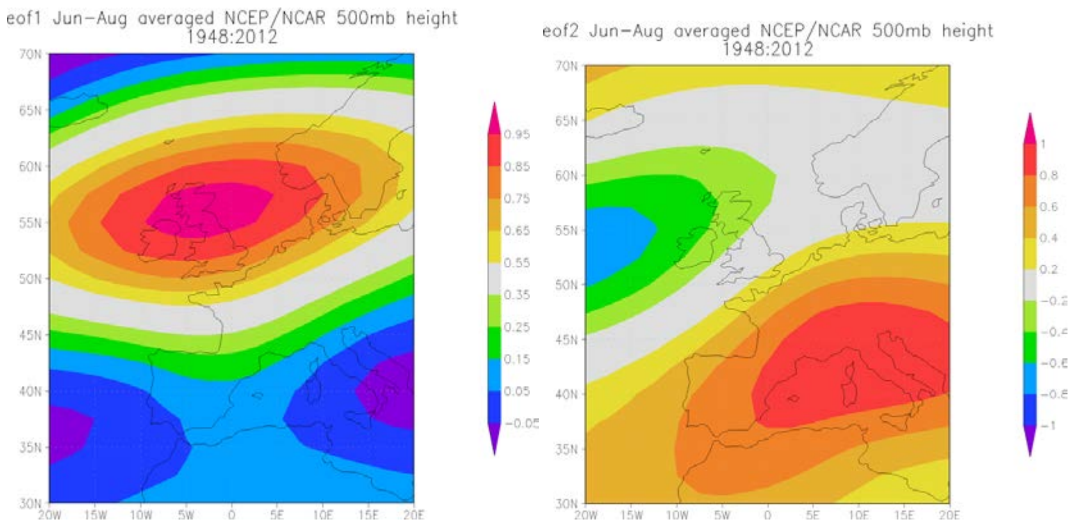


Figure 13 - Summer (JJA) principal components 1 and 2 from the NCEP re-analysis (1948-2012).

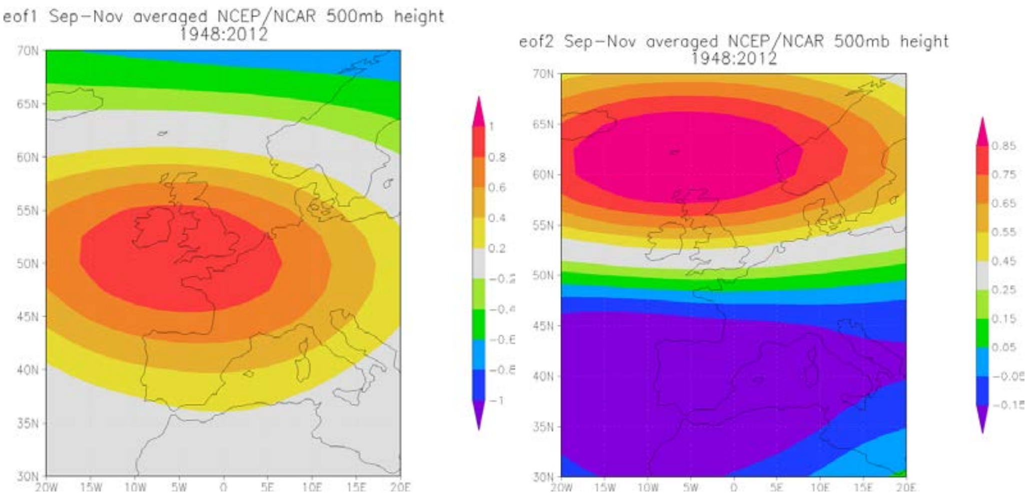


Figure 14 - Autumn (SON) principal components 1 and 2 from the NCEP re-analysis (1948-2012).

Each pattern has a principle component time series which can be correlated with the column ozone measurements at Lerwick and Reading. Table 2 shows this correlation for the components and for comparison the correlation with the local geopotential height. It can be seen that for Reading the principal component analysis outperforms the local geopotential in all seasons. It is thus a very promising substitute proxy in future multiple regression analysis. The analysis for the longer Lerwick time series also shows mostly good correlation; however, for autumn and winter it is the second component that most closely correlates with ozone. In winter for Lerwick and summer in Reading the correlations are low (and not significant) for both proxies. The cause for this could be data gaps in winter at Lerwick and dominance of horizontal advection as an explanation for ozone variability in the summer at Reading. For Lerwick the principal component time series shows some promise to replace the local geopotential height measure. It is encouraging that both Lerwick and Reading data sets can now be explained by a single analysis (time series).

	Lerwick		Reading	
	PC (1 or 2)	GP	PC (1 or 2)	GP
DJF (to 2012)	0.02 (2)	0.01	0.70 (1)	0.59
MAM (to 2012)	0.32 (1)	0.35	0.25 (1)	0.22
JJA (to 2012)	0.25 (1)	0.31	0.04 (1)	0.01
SON (to 2011)	0.36 (2)	0.38	0.84 (1)	0.77

Table 2 Correlation coefficient, R^2, between the column ozone at Lerwick (1978-2012) and Reading (2003-2012) and the first and second principal component time series (1 and 2) as well as the local 500 hPa geopotential height (GP).

4.2.2 Trend Analysis

The next stage is to recalculate the linear trends using the principal component in the multiple regression analysis. It was decided to use the first principal component in all cases and the second principal component for autumn as well. The analysis has been carried out for Lerwick since 1978 and Reading since 2003 and both to August 2013. Table 3 shows the results comparing the principal components and local geopotential height proxies in the multiple regression.

For Lerwick, for the annual trend the principal component shows a slightly higher trend than with local geopotential. Both methods agree within the uncertainties and the significance does not change. The biggest difference is seen for the autumn. With first principal component the autumn trend is increased and this increase is more than the standard errors of both methods. However, it was shown that the second principal component has higher correlation. For the second component the trend is reduced and no longer significant. The second component is centred closer to Lerwick and thus more representative of the dynamics in the region. The principal component analysis filters out much noisy variability accounting for only about 25% of the variance. Based on this analysis the autumn trend can be attributed to the tropospheric dynamical changes. In the spring the first principal component also reduces the trend so that it becomes no longer significant. In the winter and summer the trends change little and remain not significant.

For Reading the differences between the principal component and the local geopotential height are not significant for annual means or the seasons. All of the multiple regression trends have no statistical significance.

In conclusion the multiple regressions with the principal components give different trends. In some cases (e.g. for autumn at Lerwick) the differences are significant between the methods, but mostly there is no statistical difference in the methods. The principal component analysis should be added to the trend analysis to test for the robustness of trends.

	Annual (to 2012);	**Autumn (SON) (to 2012);**	**Winter[3] (DJF) (to 2013);**	**Spring (MAM) (to 2013);**	**Summer (JJA) (to 2013);**
Lerwick -PC1	**-0.55** +/- 0.19	**-0.54** +/- 0.19 PC2: -0.30 +/- 0.18	**-**0.21+/- 0.50	-0.40 +/- 0.24	**-**0.15 +/**-** 0.13
Lerwick- GP	**-0.50**+/- 0.19	**-0.39** +/- 0.16	-0.18 +/- 0.51;	-**0.57**+/**-** 0.22	-0.16 +/- 0.12
Reading -PC1	-0.28 +/ 0.91;	-0.11 +/- 0.62;	-0.39 +/- 1.25	+0.21 +/- 1.10;	+0.39 +/- 0.63
Reading -GP	-0.53 +/- 1.16	-0.03 +/- 0.80	-1.03 +/- 1.48	+0.42 +/- 1.11	+0.30 +/- 0.64

Table 3 Column ozone trend in DU per year with standard errors. Numbers in bold are significant at the 95% confidence level (P<0.05) PC1: multiple regression with first principal component; PC2: multiple regression with second principal component; GP: multiple regression with local geopotential height. Lerwick since 1978 and Reading since 2003 and both to August 2013.

4.3 Routine Trends Analysis

In trend analysis to date we have chosen only the 500 hPa geopotential height rather than the sometimes used 200 hPa to make sure that the proxy is truly tropospheric and not partly influenced by stratospheric temperatures which are influenced by stratospheric ozone. We have performed two types of trend analysis for Lerwick and Reading over the reporting year:

[3] Winter (DJF) season includes December of preceding year e.g. Winter 2013 is December 2012 to February 2013.

1. A simple regression of the column ozone from the start of record for Reading in 2003 and since the start of the satellite observations for Lerwick in 1978.

2. A multiple regression where we include the monthly 500 hPa geopotential height over the site from NCEP re-analysis as a tropospheric dynamical proxy.

These analyses are automated using the “R” statistical software so that they can be performed as simply as possible from the ozone and meteorological databases. We are of course aware that long-term trends will not vary greatly from quarter-to-quarter (e.g. the changes in the Lerwick seasonal trends from 2011 to 2013 in Table 4) but this analysis quickly highlights any interesting anomalies or features in the data such as the change in significance of the autumn trend for Lerwick from multiple regression.

4.3.1 Lerwick

Analysis by simple linear regression of annual means shows that since the early 1980s ozone has been decreasing ~2% per decade over Lerwick (Table 4, Figure 15). This long-term trend is declining as ozone has stabilised since the 1990s. Trends are sensitive to the chosen time frame and we have chosen the beginning of the global 30 year satellite period as suitable starting year. There is as yet no evidence of significant ozone recovery. The long-term (since 1978) autumn decline is significant for single and multiple regression. It is difficult to explain enhanced ozone loss prior to the cold season of polar stratospheric cloud formation. However, the principal component analysis (see 4.2.2) confirms that the most likely cause of the autumn trend is tropospheric circulation changes.

Since 1990 the Lerwick annual mean trend has been upward but this is not significant (at the 95% confidence interval). The seasonal evolution is shown in Figure 14. There is an apparent turn-around in the spring (March/April/May) ozone column over this location. From the 1970’s until around 1990 there was a very strong downward trend, which has now levelled off. However, there is no statistically significant recovery since the late 1990s, when stratospheric chlorine loading is thought to have peaked.

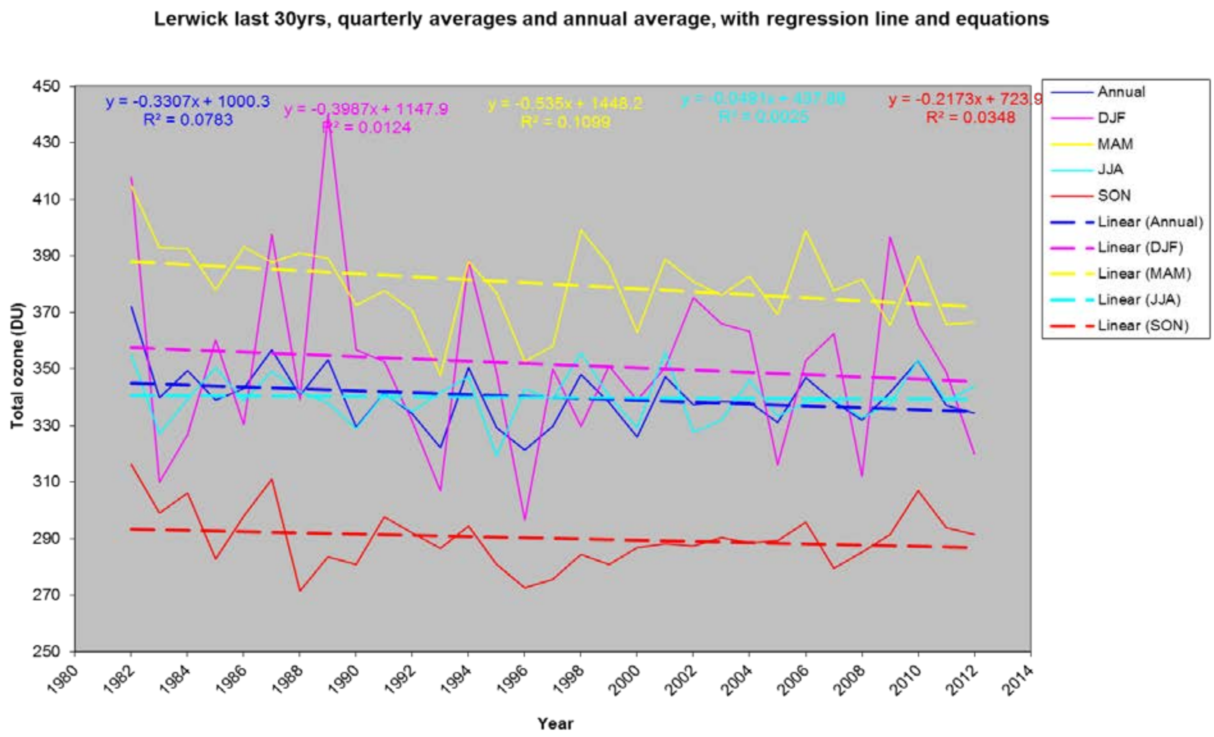


Figure 15 Long-term trends since 1982 in annual and seasonal ozone column over Lerwick

4.3.2 Reading

At Reading there is an annual increase of ozone since 2003 but this is not significant. Seasonal trends are also not significantly different from zero at the 95% confidence interval. The data record is relatively short so that trends are very sensitive to record length and possibly tropospheric circulation trends.

4.3.3 Trends including 2012, single and multiple regression

Table 4 shows the results of the analysis to date including quarterly updates from the year 2013 where available (winter, spring and summer trends have been updated), as well as the trends as they stood at the other years for comparison (italicised to distinguish them clearly from the current values for the trend).

	Annual **(to 2012)** ***(to 2011)*;** ***(to 2010)***	**Autumn (SON)** **(to 2012)** ***(to 2011)*;** ***(to 2010)***	**Winter[4] (DJF)** **(2012-2013)** ***(2011-2012)*;** ***(2010-2011)***	**Spring (MAM)** **(to 2013)** ***(to 2012)*;** ***(to 2011)***	**Summer (JJA)** **(to 2013)** ***(to 2012)*;** ***(to 2011)***
Lerwick -SR	**-0.59**+/-0.18 ***-0.60*** *+/- 0.19* ***-0.62*** *+/- 0.20*	**-0.51**+/-0.19 ***-0.55*** *+/-* 0.20; ***-0.61*** *+/- 0.21*	-0.21+/-0.50 *-0.28+/- 0.52;* *-0.13+/- 0.55*	**-0.75**+/-0.27 **-0.88** +/- 0.27; ***-0.87*** *+/- 0.28*	-0.16 +/-0.14 -0.19 +/-0.15; *-0.23 +/-0.16*
Lerwick- MR	**-0.50**+/- 0.19 ***-0.49****+/- 0.20;* ***-0.52****+/- 0.21*	**-0.39**+/0.16 *0.33***+/-***0.18;* ***-0.40+/-****0.18*	-0.18+/-0.51 *-0.25+/-0.54;* *-0.09+/-0.56*	**-0.57**+/- 0.22 ***-0.66+/-*** *0.24;* ***-0.67****+/- 0.25*	-0.16+/-0.12 -0.22+/-0.12; -0.23+/-0.13
Reading -SR	+0.59+/-1.16 *+1.43+/-1.32;* *+2.97+/-1.19*	+1.05+/-1.26 *+0.99+/-1.58;* *+2.19+/-1.70*	+0.90+/-2.12 *+0.34+/-2.57;* *+3.55+/-2.12*	+0.57+/-1.28 *-0.30+/-1.44;* *-0.10+/-1.87*	*+0.49+/-0.61* *+1.00+/-0.65;* *+0.75+/-0.81*
Reading -MR	-0.53+/-1.16 *+0.29+/-1.24;* *+2.10+/-1.94*	-0.03+/-0.80 *+0.50+/-0.83;* *+0.49+/-1.15*	-1.03+/-1.48 *-1.14+/-1.76;* *+1.38+/-1.58*	+0.42+/-1.11 *+0.19+/-1.41;* *+0.48+/-1.80*	+0.30+/-0.64 *+1.06+/-0.91;* *+0.80+/-1.07*

Table 4 Column ozone trend in DU per year with standard errors. Numbers in bold are significant at the 95% confidence level (P<0.05) SR: single regression; MR: multiple regression. Lerwick since 1978 and Reading since 2003 and both to August 2013.

4.3.4 Camborne / Reading

In this contract we have attempted to create a simple synthetic Camborne/Reading time series. Creating synthetic time series is fraught with difficulties and results should be regarded with caution. According to satellite observations the inter-annual correlation of the annual mean ozone at Camborne and Reading should be very high (correlation coefficient greater than 0.95). The annual mean ozone of the two stations should therefore track each other very well. In 2003 both sites were run simultaneously for a complete year and it was found that Reading column ozone was 0.7% larger than the column ozone at Camborne. This is within the uncertainty of both instruments. However to be conservative Reading annual means were scaled down by 0.7% for the synthetic time series. The synthetic annual mean Camborne/Reading (1990-2012) upward trend of 0.5 DU/yr is significant (p=0.05). For

[4] Winter (DJF) season includes December of preceding year e.g. Winter 2013 is December 2012 to February 2013.

2012 the annual mean ozone at Reading and at Lerwick were similar to values recorded in the last 20 years and can been seen in Figure 16.

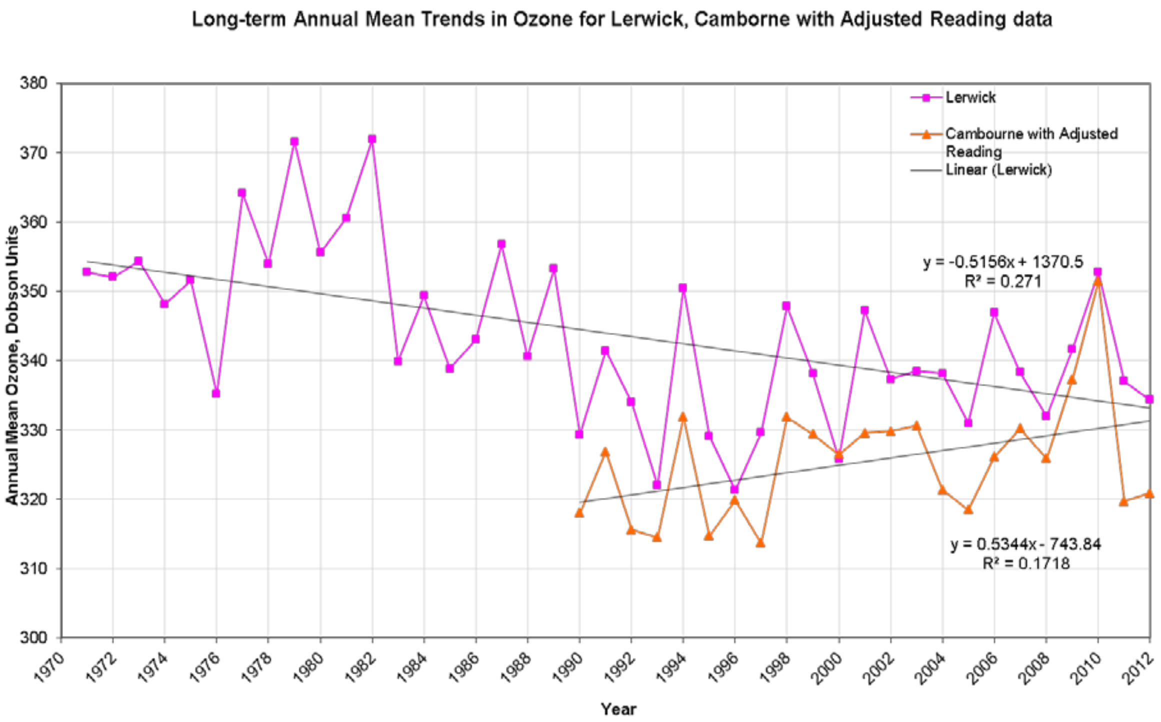
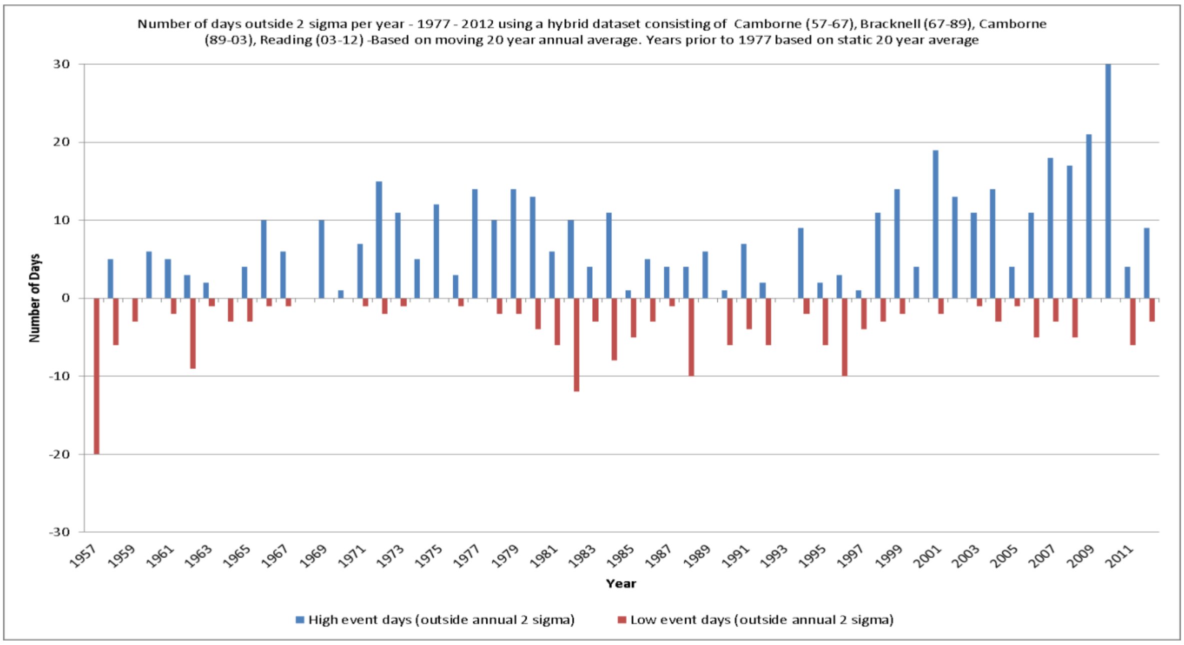


Figure 16 The annual mean of daily ozone column over Lerwick and combined Cambourne/Reading (Lerwick includes incomplete winter days).

4.4 High and Low Ozone Events

High and low ozone events have been determined as 2 standard deviation anomalies relative to a 20 year moving average. Figure 17 shows the long-term evolution of high and low events at Reading and Lerwick. There appear to be long-term decadal cycles of the ratio of high and low ozone events (Figure 18). We have not identified a cause for this but it is consistent with shifting patterns of tropospheric indicators, such as the North Atlantic Oscillation (NAO), which also remain unexplained. The cycles are out of phase. In the current phase we are experiencing relatively more high/low events in Reading and Lerwick. 2012 was a year of typical number high and low events compared to the 20 year moving average. This methodology is different in the current quarterly reports of low events which use a monthly climatology. The monthly climatology is perhaps more representative as it captures true anomalies even in a more variable part of the year. However, the long-term cycles of high/low events discussed here are unlikely to be affected by this difference in methodology.



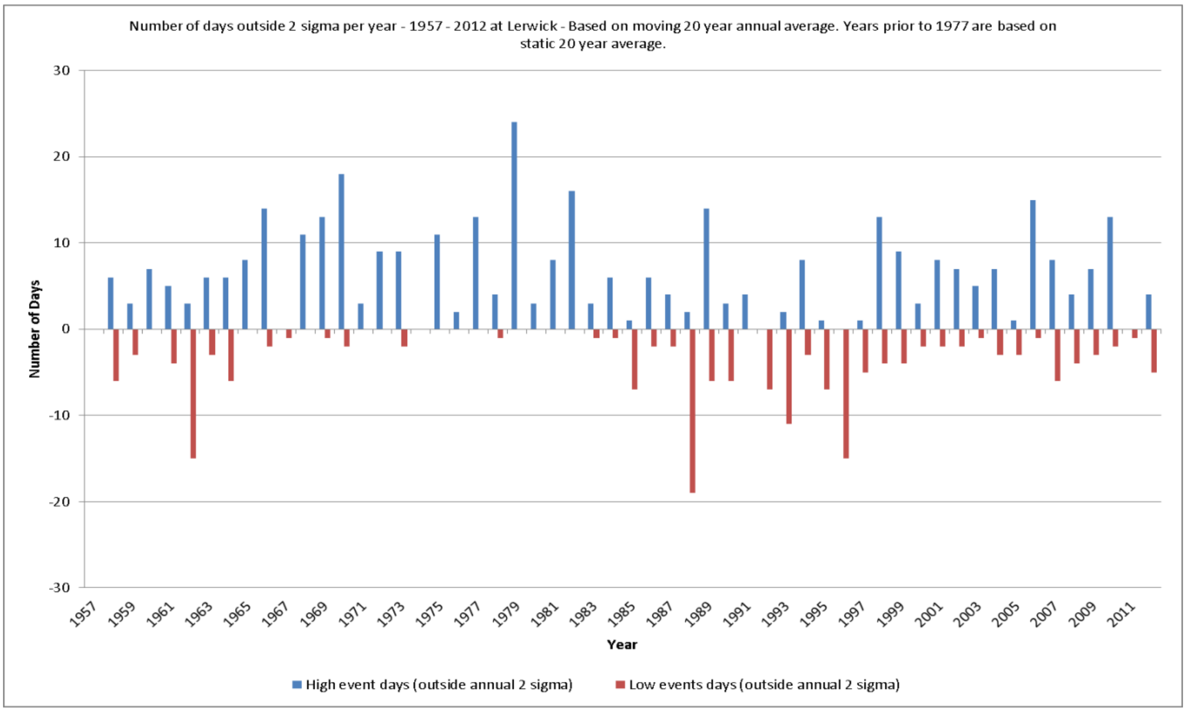


Figure 17 Time series of high and low ozone events at Reading (top) and Lerwick (bottom). The Reading data is a synthesis including other nearby stations.

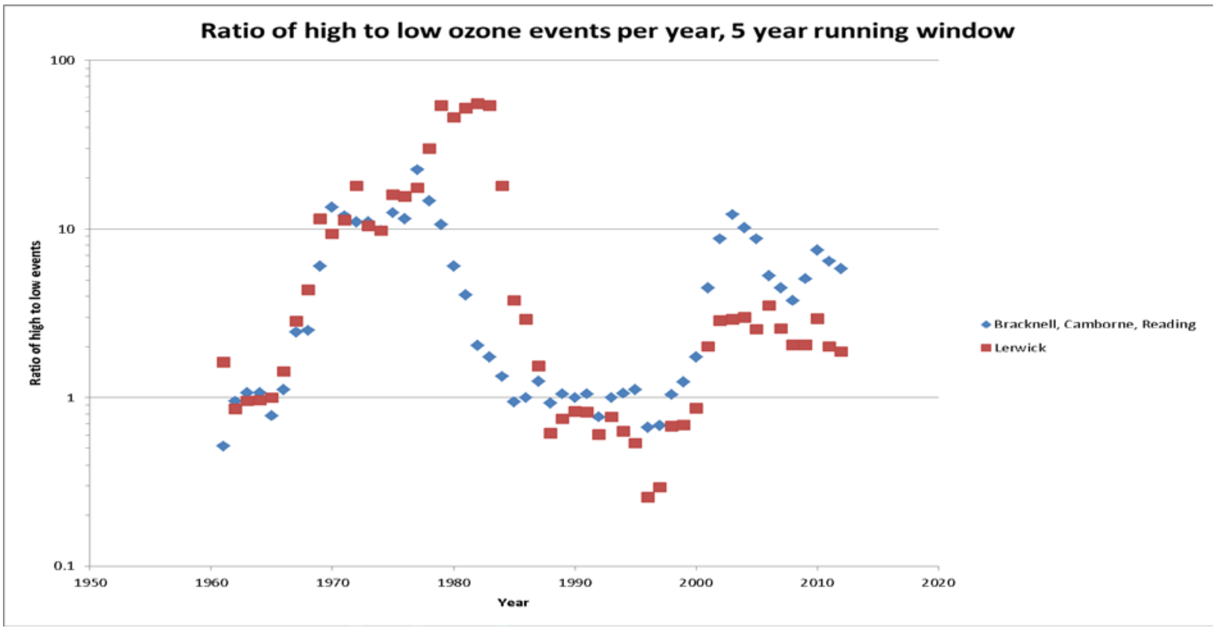


Figure 18 The ratio of the number of high and low ozone events per year when applying a 5 year moving average.

4.5 Conclusions and Future work

We have identified principle component (PC) analysis as a promising route to improve the geopotential trend analysis. This appears more promising than the two alternatives identified in the 2011 report. It is not attractive to use QBO solely for summer regression because the physical basis is not identified. The attraction of the PCs is that they give a plausible way to identify the major modes of variability and not be concerned with the high frequency noise which can distort relationships and trends. It is also attractive to just use one pattern (the first principal component) to explain variation in both Reading and Lerwick. Using this analysis the seasonal declines at Lerwick are no longer significant. However, it requires the use of the second principal component for the autumn analysis and it is not clear why autumn is special. In the next year it is proposed to identify the physical basis of the choice of the second component for autumn only. This will give more confidence if they are to replace the current multiple regression methodology.

4.6 References:

Hannachi, A., Jolliffe, I. T., and Stephenson, D. B. Empirical orthogonal functions and related techniques in atmospheric science: A review. INTERNATIONAL JOURNAL OF CLIMATOLOGY, Vol: 27, Iss: 9, 1119-1152, 2007. DOI: 10.1002/joc.1499.

5 Project Information & Dissemination

5.1 Web Site

The project homepage is illustrated in Figure 19 below and accessible via the following address http://ozone-uv.defra.gov.uk/ .

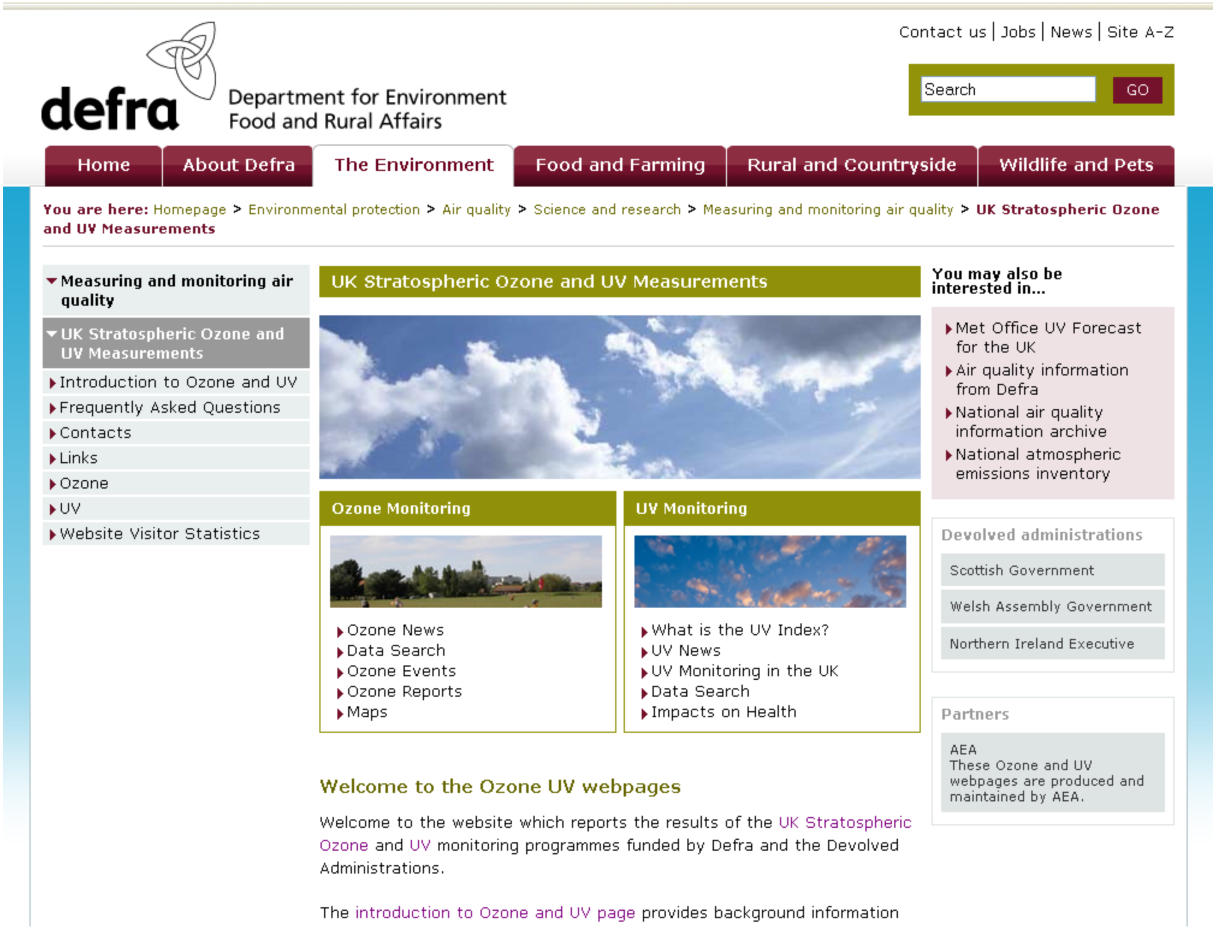


Figure 19 - The project website homepage.

Traffic continues to be redirected from the old project web url (http://www.ozone-uv.co.uk/). The live statistics can be accessed from the link section off the main project page and can be viewed directly at http://ozone-uv.defra.gov.uk/cgi-bin/usage.pl.

The following data are currently updated daily during normal working hours and made available for download from the website:

- **Dobson ozone data from Lerwick (plus historic data from Camborne)**
- **Brewer ozone data from Reading.**
- **Graphs of Manchester Brewer ozone data.**
- **Spectral UV data from Reading.**

The news section continues to be periodically updated as and when suitable articles are identified. Recent articles added include the following:

- Low Ozone Update – where the measured daily ozone has been more than two standard deviations below the long term historical monthly mean on the 23rd and 24th April 2013.

Further publicity for the website may still be helpful in order to increase its usage and it was discussed at the last project team meeting the possibility of providing links from the Met Office website to increase project exposure.

5.1.1 Integration with UK-AIR

During this reporting period Defra a new navigation and integration map for UK-AIR that includes the current Ozone UV project website. Initial discussions have been conducted by the development team and it has been proposed that the ozone-uv website sits in an area called "Research" where the main search tools will reside. The FAQ's will be combined into a central area titled "About Air Pollution" and the news sections with be part of the main "UK-AIR news". Some information pages will be merged and condensed into a central page to aid navigation.

5.1.2 Website Usage Overview

Under the new contract a brief summary of the website usage was requested to be included in the quarterly reports. Table 5 data has been taken from the AWSTATS software which monitors the site usage, and is broken down on a month by month basis (See footnotes for any clarification of what each data represents).

Year	Month	Unique visitors[5]	Number of visits[6]	Pages[7]	Hits[8]	Bandwidth[9]
2012	September	566	974	4688	11788	527.24MB
2012	October	590	1082	4710	12542	502.01 MB
2012	November	523	1089	4715	12523	928.69 MB
2012	December	356	633	2661	7186	272.06 MB
2013	January	488	1104	5513	13131	869.96 MB
2013	February	472	924	5823	13538	519.59 MB
2013	March	570	1091	6578	15413	692.09 MB
2013	April	598	1123	4960	16027	660.30 MB
2013	May	537	1003	2517	11680	513.63 MB
2013	June	577	938	2404	11129	507.01 MB
2013	July	624	1142	2244	13613	531.85 MB
2013	August	443	827	2383	10243	674.29 MB
2013	September	494	845	1853	10879	447.58 MB
Summary		6,838	12775	51049	159692	7646 MB

[5] **Unique Visitor:** A unique visitor is a person or computer (host) that has made at least 1 hit on 1 page of your web site during the current period shown by the report. If this user makes several visits during this period, it is counted only once.
[6] **Visits:** Number of visits made by all visitors. Think "session" here, say a unique IP accesses a page, and then requests three other pages within an hour. All of the "pages" are included in the visit, therefore you should expect multiple pages per visit and multiple visits per unique visitor
[7] **Pages:** The number of "pages" viewed by visitors. Pages are usually HTML, PHP or ASP files, not images or other files requested as a result of loading a "Page".
[8] **Hits**: Any files requested from the server (including files that are "Pages").
[9] **Bandwidth:** Total number of bytes for pages, images and files downloaded by web browsing.

Table 5 AWSTATS data for http://ozone-uv.defra.gov.uk/ Ozone AWSTATS

5.2 Literature Review

During the period of the project Defra requested a review on papers focusing on column ozone or UV measurements and a short non-technical summary to be provided on each paper together with its policy significance. During this period eleven relevant papers were reviewed and their findings are summarised in the project quarterly reports

- Hossaini, R.; Chipperfield, M. P.; Dhomse, S.; et al. Modelling future changes to the stratospheric source gas injection of biogenic bromocarbons, GEOPHYSICAL RESEARCH LETTERS, Vol: 39, No: L20813, DOI: 10.1029/2012GL053401, 2012
- Hess, P. G.; Zbinden, R. Stratospheric impact on tropospheric ozone variability and trends: 1990-2009. ATMOSPHERIC CHEMISTRY AND PHYSICS,Volume: 13, Issue: 2,Pages: 649-674, DOI: 10.5194/acp-13-649-2013, 2013.
- Gonzalez, P. L. M., Polvani L. M., Lorenzo M., Seager, R., Correa, G. J. P.. J. Climate Dynamics. Stratospheric ozone depletion: a key driver of recent precipitation trends in South Eastern South America. dx.doi.org/10.1007/s00382-013-1777-x, May 2013.
- Bekki, S., A. Rap, V. Poulain, S. Dhomse, M. Marchand, F. Lefevre, P. M. Forster, S. Szopa, and M. P. Chipperfield (2013), Climate impact of stratospheric ozone recovery, Geophys. Res. Lett., 40, 2796–2800, doi:10.1002/grl.50358.

6 Other Project Activities

6.1.1.1 Project Meetings

The annual Project Review meeting was held on the 25th October 2012

6.1.1.2 Other Meetings

There have been a number of international conferences and meetings over the project duration which have helped to raise the profile of UK Ozone and UV monitoring activities. Selected synopses and a list of posters presented, follow:

6.1.1.3 European Brewer Spectrophotometers COST action

On 29th April 2013, the kick off meeting for the COST Action ES1207 'A European Brewer Network – EUBREWNET', took place attended by John Rimmer who was voted to Action Chair. Work plan and budget plan for the first grant period were defined. John Rimmer was also appointed grant holder.

6.1.1.4 WMO 'Absorption Cross Sections of Ozone (ACSO)'

In June 2013, John Rimmer attended the WMO 'Absorption Cross Sections of Ozone (ACSO)' meeting and part of the WMO SAG-Ozone meeting in Geneva. The ACSO meeting was convened since an improved set of ozone cross sections had been produced by the University of Bremen. These cross sections have been measured at 11 different temperatures and cover a wide spectral range from UV to visible. The adoption of these cross sections would have a small effect on the Brewer measurements but, significantly, if temperature correction is applied to Dobson data, the seasonal variation between Dobson and Brewer data is all but eliminated. Other results presented led to the conclusion that these new cross sections should be applied but only after full consistency checks. This work is on-going. At the SAG-Ozone meeting there were discussions about the lack of a positive response from Environment Canada over the creation of a memorandum of understanding which had been discussed by all parties at the Quadrennial Ozone Symposium in Toronto August 2012. However, a recent appointment to the SAG-Ozone representing WOUDC indicated a strong willingness to work with the community on data submissions.

6.1.1.5 Kipp and Zonen

During this year, John Rimmer has met with Foeke Kuik and Keith Wilson of Kipp and Zonen, the manufacturer of the Brewer Spectrophotometer on a number of occasions. This is part of an on-going synergy between Kipp and Zonen and the University of Manchester Ozone and UV Group which, since the withdrawal of scientific support for the Brewer from Environment Canada, is important for the long term strategy of the UK program. The meetings have focussed on a collaboration to develop a new instrument using solid state technology based on an initial idea by John Rimmer. Kipp and Zonen are providing funds to purchase components and materials for a PhD project aimed at producing a working prototype.

In addition, a sub-group within the Photon Science Institute at University of Manchester is proposing to host a conference funded by the University of Manchester Research Institute (UMRI) on the development of a range of gas sensors based on optical detection. This will certainly be of interest in many other areas under the remit of Defra such as air quality, agriculture etc.

6.1.1.6 COST Action ES1207 – EUBREWNET

On 26th and 27th September, the COST Action ES1207 – EUBREWNET held its first scientific meeting in Manchester, hosted by the UoM Ozone and UV group. Presentations are available as links on the meeting agenda to be found at http://rbcce.aemet.es/cost1207/mc-and-wg-meeting-in-manchester-on-26th-and-27th-september-preliminary-agenda/. The meeting was considered a success and further working group meetings are planned for January 2014. The Action now has the support of ESA and has international partners NOAA, York University Toronto, International Ozone Services and WMO. There have also been possibilities raised for the affiliation of the network with NDACC.

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