Final Publishable JRP Summary for JRP ENV59 ATMOZ
Traceability for atmospheric total column ozone

Background

Ozone in the earth's upper atmosphere absorbs ultraviolet radiation, preventing most of it reaching the ground. This is important because ultraviolet radiation can harm life on earth, and for example lead to skin cancer. Since the 1980s, it has been known that human-produced chlorofluorocarbons (CFCs) have led to recurring losses of total ozone in the Antarctic (the ozone hole), and these have also been recently observed in the Arctic, while in middle-latitudes, moderate ozone depletion has been observed.

The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty signed in 1994 designed to protect the ozone layer by phasing out the production of substances that are responsible for ozone depletion, and it has been successful in reducing the emission of ozone-depleting substances.

However, monitoring of the recovery of the ozone layer requires accurate long-term observations with reliable and well understood instruments and the development of future instrumentation.

This project characterised key reference and network instruments for the traceability of ozone retrievals (or measurements), developed new instruments and devices for in-field characterisation of the existing network instruments and new ozone monitoring instruments, and generated new datasets for ozone absorption cross sections and extra-terrestrial solar reference spectrum.

Need for the project

Atmospheric ozone has been defined an Essential Climate Variable in the Global Climate Observing System (GCOS) of the World Meteorological Organisation (WMO). This means that it is considered to critically contribute to the characterisation of the earth's climate. Careful long-term monitoring of the global ozone layer from the ground and from space is crucial in verifying the successful implementation of the Montreal Protocol, and its anticipated eventual recovery to pre-1970s levels.

CFCs were once widely used in insulating foam and aerosol spray-cans. Once released, they gradually spread through the atmosphere, eventually reaching the ozone layer which lies within the stratosphere around 25 km above the ground. Once there, they destroy the ozone. CFCs have now been almost completely replaced by chemicals that do not cause this damage.

Nevertheless, recovery of the ozone layer has not been observed so far, and model projections have shown that the recovery will not take place before the middle of the 21st century. There is a need for instruments giving measurements that enable us to reliably monitor and record the predicted worldwide recovery of the ozone layer.

Total column ozone measurements are reported as being equal to the amount of ozone contained in a vertical column, with base 1 cm^2, at standard temperature and pressure conditions (STP). The most reliable total column ozone measurements are made with a worldwide network of UV spectroradiometers, allowing the determination of the differential absorption (absorption at two distinct wavelengths) of ozone from direct solar irradiance measurements. Two instrument types, the Dobson and the Brewer spectrophotometers, are used worldwide for extensive continuous ground-based measurements. The Dobson spectrophotometer network has the most extensive dataset, starting in the 1920s, while the Brewer spectrophotometer started measurements in the late 1970s. Measurements of total column ozone for each network-type is self-consistent within ±0.5%. However, when measurements made by the two different instruments are compared, they differ by up to 3%. Prior to this project, these discrepancies ruled out a merging of both datasets and an eventual replacement of one instrument with another type.

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The current approach is to define common parameters to use, so that total ozone retrievals remain consistent within each network. Furthermore, the discrepancies between different instrument types prevent the phase-out or replacement of the ageing Dobson spectrophotometer with newer instruments since it would represent a break in the long time-series of ozone measurements, and so make it more difficult to detect ozone recovery.

There is, therefore, an urgent need for an improved characterisation and calibration of the Dobson and the Brewer instruments, including the reference instruments for each network. This will have an impact on the whole global observing network by providing improved ozone measurements with known uncertainties, and will assist the development of a replacement for the traditional Dobson spectroradiometer, which requires time consuming manual operation and is no longer being manufactured.

This project builds on some of the methodologies and devices developed in project *ENV03 Traceability for surface spectral solar UV*.

Scientific and technical objectives

Objective 1: Characterisation of Dobson and Brewer reference instruments in order to ensure a consistency between the individual network instruments and within the two networks:

- Characterising the spectral bandwidth and wavelength of the World Reference and European Reference Dobson spectrophotometers (and 2 standard network instruments) in the range 300 nm to 350 nm.
- Characterising the spectral bandwidth, wavelength, out-of-range stray light and temperature of several Brewer spectrophotometers.

Objective 2: Develop new devices for measurement and characterisation of the Dobson, Brewer and full spectrum instruments such as array spectroradiometers with following devices:

- A field-suitable tuneable radiation source (TuPS) in the UV range for the bandwidth and wavelength characterisation of Dobson spectrophotometers with a wavelength uncertainty of 0.05 nm.
- A field-suitable wavelength ruler to characterise and calibrate the wavelength of Brewer and array spectroradiometer instruments.
- A field-suitable UV-LED light source to track the stability of array spectroradiometers.
- A dedicated high-resolution array spectroradiometer system (ERMIS) for direct spectral solar UV irradiance measurements in the range 300 nm to at least 350 nm.

Objective 3: Generation of new reference data sets:

- Improved ozone absorption cross-section data in the Huggins-band, with known uncertainties.
- A benchmark high resolution extra-terrestrial solar spectrum in the wavelength range 310 nm to 350 nm with known uncertainties.

Objective 4: Overall uncertainty budget of ozone retrieval:

- Develop uncertainty models for correlated quantities with application to the total column ozone retrieval for Brewer, Dobson and full-spectrum instruments.
- Determine a comprehensive uncertainty budget for Dobson, Brewer, and array spectroradiometers.

Objective 5: Ozone intercomparison campaign

- Organise and participate at two international field campaigns with the characterised reference Brewer and Dobson spectrophotometers in addition to newly available array spectroradiometer systems (Pandora, Phaethon, Ermis) in order to validate and assess the total column ozone retrieval and respective uncertainties.

Results and conclusions

Objective 1: Characterisation of Dobson and Brewer reference instruments

Dobson: This objective, to characterise the Dobson reference and network instruments, in order to ensure consistency between the network instruments and the two networks, was fully achieved. Bandwidths were measured for the Dobson instruments. The newly characterised Dobson instruments showed an improved agreement with the reference Brewer instruments during the Izaña field measurements in the Canary Islands. Tuneable laser facilities and a double monochromator setup at PTB and CMI respectively were used to characterise three reference Dobson instruments from the global ozone measuring network, producing equivalent results. Additional network instruments from the operational network were first characterised by the tuneable laser facilities. A portable tuneable radiation source was developed for in-field characterisation of the Dobson spectrophotometers. This new device showed equivalent results to those obtained by the methods in the laboratory, and was successfully applied to in-field characterisation of 14 Dobson spectroradiometers of the global ozone network during two field calibration campaigns.

Brewer: In order to ensure a traceable laboratory characterisation of the Brewer instruments, the reference RBCC-E (Regional Brewer Calibration Center for Europe) Brewer from the Spanish Meteorological Agency at Izaña and the travelling reference Brewer #158 from the manufacturer Kipp & Zonen, were characterised for temperature dependency, wavelength and bandwidth. Two Brewer MKII instruments, from the Finnish Meteorological Institute and Deutscher Wetterdienst, were characterised for stray-light properties, using dedicated setups and instrumentation from the National Metrology Institutes, such as climate chamber and tuneable laser facilities. The results confirmed the existing understanding and correction needed for the temperature dependence of Brewer instruments in order to reduce the uncertainty of ozone retrieval. The importance of reducing the effect of stray-light in single Brewer instruments was also confirmed.

Summary: The objective was fully achieved: The measured bandwidth of the Dobson instruments led to an improved consistency between these instruments and the reference Brewer spectrophotometer from RBCC-E. The characterisation of the Brewer reference instruments led to verification of consistency of bandwidths used, the operational temperature corrections and stray-light corrections for single Brewers that need to be applied at large ozone slant-path columns.

Objective 2: Development of new devices for characterisation and measurements

Prototype devices for calibrating and characterising ozone monitoring instruments in the field were constructed and successfully tested in the intercomparison. These were:

- for wavelength calibration of array spectroradiometers,
- a tuneable portable radiation source for wavelength and bandpass measurements of Dobsons
- a new high-precision spectroradiometer for direct spectral irradiance measurements
- a UV-LED-based reference source to track the stability of array spectroradiometers

The results showed that the wavelength scale can be calibrated in the field with the new device with an uncertainty of 0.05 nm, the stability can be tracked based on a UV LED light source and that direct solar spectra can be measured with high precision and with high spectral resolution. In addition, a new array-based instrument from the manufacturer Gigahertz-Optik (project collaborator) was tested during the intercomparison and it was found that it is suitable for ozone retrieval measurements.

Summary: The objective of developing field instruments for characterising and validating network instruments globally was fully achieved and successfully tested during intercomparisons. The newly developed high-precision and low-noise spectroradiometer was shown to be suitable as a future reference instrument for ozone retrieval using the full spectrum in the UV band.

Objective 3: Improved ozone absorption cross-section and extra-terrestrial spectrum

For traceable ozone retrieval, improved datasets of the ozone absorption cross-sections and the extra-terrestrial spectrum with known uncertainty are needed.

New cross-sections: The measurements for new ozone absorption cross-sections were successfully completed. The new cross sections were measured in the laboratory of UniHB and covers temperatures from 193 K to 293 K in 10 K steps. A preliminary analysis confirmed that these cross-sections provide total column ozone retrievals with improved consistency across the temperature range. An in-depth evaluation comprising satellite and ground-based retrievals will be the task of the international ozone community.

New extra-terrestrial spectrum: During the first ATMOZ field campaign at the Izaña Atmospheric Research Center at AEMET, Tenerife, Spain a new high-resolution extra-terrestrial spectrum (called QASUMEFTS) in the range of 300 nm to 500 nm was generated using the Langley plot technique (a method for determining the sun's irradiance at the top of the atmosphere with ground based instrumentation). The new solar spectrum is based on measurements from the portable world reference spectroradiometer for UV radiation QASUME from the World Calibration Center for UV radiation at Davos, and measurements from a newly developed high-resolution Fourier Transform Spectroradiometer. The new extra-terrestrial solar spectrum was validated and compared with published spectra measured in space. The QASUMEFTS solar spectrum represents a benchmark dataset with uncertainties lower than anything previously published. The metrological traceability of the measurements to SI is assured by an unbroken chain of calibrations leading to the primary spectral irradiance standard at PTB.

Summary: The objective of developing a new benchmark dataset for ozone absorption cross section and extraterrestrial spectrum for homogenised total ozone column retrieval is fully achieved. The new dataset is suitable as a new standard dataset for global total column ozone measurement.

Objective 4: Overall uncertainty budget of ozone retrieval

In order to assess the overall uncertainty budget for retrieving total column ozone, three different simulation approaches were investigated and applied to measurements from the field work in Izaña. From these, two methods were selected and used as basis for two software algorithms: first the double ratio technique used for the Brewers and the Dobsons (which look at select wavelengths in the UV part of the solar spectrum), and second the full spectrum retrieval. The overall uncertainty budgets revealed that the Brewers and Dobsons are generally able to measure total column ozone with an uncertainty of 1% - 2%, while the uncertainty from the full spectrum retrieval is around 1%, due to the higher information content of the full spectrum.

Summary: The overall uncertainty of around 1% - 2% for the global ozone monitoring network was validated with state of the art uncertainty calculation methods. The software developed is now available and can be applied to estimate the uncertainty of the global ozone monitoring network.

Objective 5: Ozone intercomparison campaign

The objective of the campaign was to compare the total ozone measurements of the participating instruments, to obtain a ground based high-resolution UV range extraterrestrial spectrum and to apply the new techniques and devices to characterise the end-users instruments in the field.

Direct solar spectra used to estimate the overall uncertainty of TOC retrieval of different instruments were measured at the first ATMOZ field campaign between 12 and 25 September 2016 at the Izaña Atmospheric Observatory, Canary Island Spain. The high mountain measurement site (2373 m a.s.l) is above a subtropical inversion layer ensuring a stable atmosphere. Additionally, ancillary data, such as atmospheric soundings, pressure, aerosol optical depths etc. are collected nearby the station.

Summary: The intercomparison showed clearly that the overall objective of traceable total ozone column measurements and a homogenisation of the different ozone monitoring networks and its reference instruments was achieved within the project.

Actual and potential impact

Dissemination

Sixteen publications were published or submitted, and 25 contributions to conferences were made (13 oral and 12 poster presentations). The conferences included International Conference on Space Optics, Quadrennial Ozone Symposium, NEWRAD, and the International Conference on Meteorology, Climatology and Atmospheric Physics.

Presentations given at a number of ATMOZ forums and workshops can be downloaded from the project website (http://projects.pmodwrc.ch/atmoz/index.php/publications).

The WMO Regional Dobson Calibration Center for Europe, run by the Meteorological Observatory Hohenpeissenberg of Germany's National Meteorological Service DWD, invited the consortium to give a presentation about TuPS (Tunable Portable UV radiation Source) for characterisation of Dobsons

The work of the project was included in a published book *Perspectives on Atmospheric Sciences*, chapter title *Total Ozone Retrieval from the Phaeton DOAS System*.

12 articles were published in peer reviewed journals, including *Atmospheric Measurement Techniques*, *Atmosphere-Ocean*, *Metrologia* and *Atmospheric Environment*.

Early impact

- The project intercomparisons showed that a homogenisation of the total column ozone monitoring network can be achieved using traceable measurements developed in the project. Operators of Brewer and Dobson spectrophotometers benefitted from the knowledge of the project partners regarding the devices, methods and uncertainty estimations by a better understanding of the instrument parameters responsible for the total column ozone retrieval.

- The metrology-based assessment of the overall uncertainty in monitoring ozone from the ground supports current activities of the international ozone community to provide statistically sound methodologies for assessing the datasets used for the detection of a possible recovery of the ozone layer.

- The development and characterisation of novel cost-effective spectroradiometer systems paves the way for including these instruments in the global ozone monitoring network, enabling an eventual replacement (after parallel assessment measurements over several years) of the traditional Dobson spectroradiometers. The evaluation of the overall uncertainty budget shows that these full-spectrum instruments have the capability to reduce the uncertainty of total column ozone measurement.

- The WMO Regional Dobson Calibration Center for Europe used the TuPS, with CMI assistance, for the characterisation of six Dobsons spectrometers of the Global Ozone Network. These were from the UK Met. Office, Arm Hydromet in Armenia, International Ozone Commission and the British Antarctic Survey.

- INTA, the Spanish Space Agency, used the TuPS with CMI assistance for characterisation of five Dobsons spectrometers of the Global Ozone Network. These were from Spain, Greece, South Africa, Egypt, Uganda.

- The collaborator Gigahertz-optik GmbH used project outputs to improve and adapt an existing instrument in order to use it for total column ozone retrieval.

- CMI will offer the new portable spectral characterisation device and in-situ field characterisations for the Dobson end-user community also after the lifetime of the project.

Contribution to standards

Eighteen presentations about the work of the project were given to standards bodies including WMO Scientific Advisory Group for Ozone, Northern Ozone Group, BIPM Consultative committee for Photometry and Radiometry, CIE Division 2 Measurement of Light and Radiation.

The new datasets for ozone absorption cross-section and extraterrestrial spectrum with known uncertainties are available to be used to bring together results from the worldwide ozone monitoring network constituting of Dobsons, Brewers and full-spectrum instruments. The standard use of the new datasets and its implications on total column retrieval will be discussed in the WMO Scientific Advisory Group for Ozone.

Future potential impact

The step-change improvement in the calibration and characterisation of Dobson and Brewer instruments and the network instruments has provided the global observation network with improved ozone measurements with known uncertainties.

The development of novel spectroradiometer systems employing new techniques paves the way for including these instruments in the global ozone monitoring network, with a view to eventually replacing the traditional Dobson instruments, of which around 80 are currently deployed worldwide.

The result of this project is a step forward towards the implementation of the Montreal protocol and provides significant social benefits to the whole population with respect to solar UV induced skin deceases such as melanoma skin cancers.

List of Publications

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