Australian National Report
for the 12th WMO/UNEP Ozone Research Managers Meeting
Geneva, Switzerland, 24-26 April 2024

1. OBSERVATIONAL ACTIVITIES

1.1 Column measurements of ozone and other gases/variables relevant to ozone loss.

The Australian Government's Bureau of Meteorology has primary responsibility for monitoring total column ozone.

- The Bureau of Meteorology's Dobson network consists of stations located at Darwin, Brisbane, Melbourne and Macquarie Island. NOAA also operate a Dobson at Perth supported by Bureau of Meteorology staff. Brisbane, Macquarie Island and Melbourne have records dating back to 1957. Brewer spectrophotometers have also now been progressively installed at all five of these sites.

Total column ozone is also measured by:

- A Brewer spectrophotometer operated by the University of Tasmania (financially supported by the Bureau of Meteorology).
- Remote sensing FTIR measurements at Wollongong, operated by the University of Wollongong. These measurements are made as part of the Network for the Detection of Atmospheric Composition Change, NDACC).

NIWA (the New Zealand National Institute of Water and Atmospheric Research) operates a zenith viewing spectrometer at Macquarie Island for NO_2 column and profile information.

1.2 Profile measurements of ozone and other gases/variables relevant to ozone loss

Weekly ozonesonde measurements are taken by the Bureau of Meteorology at:

- Broadmeadows (Melbourne)
- Macquarie Island
- Davis station, Antarctica, in conjunction with the Australian Antarctic Division (AAD).

The ozonesonde program at Davis dates from 2003, Macquarie Island from 1994, and Broadmeadows continues the program originally located in Aspendale (1965-1982) and Laverton (1983-1998). In conjunction with some of these ozonesonde flights, the AAD operated a Rayleigh/Mie/Raman lidar at Davis to measure temperature and aerosol loading in the stratosphere (the lidar operated from 2001-2012). A depolarisation lidar for troposphere-stratosphere measurements, including studies of Polar Stratospheric Clouds, began continuous operations in November 2018, and continued taking data until late 2020.

- Coarse vertical resolution profiles from Dobson Umkehr measurements have been made at Dobson network sites dating back to 1962. Umkehr observations are still made at Brisbane, Darwin and Perth. (Stone et al., 2015). Brewer Umkehr observations are now being made at Darwin, Brisbane, Perth and Melbourne.
- The FTIR operated by the University of Wollongong also reports coarse vertical resolution profiles (4 to 5 degrees of freedom) from the mid-IR spectra, which are provided along with total columns to the NDACC archive.

1.3 UV measurements

1.3.1 Broadband ultraviolet

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) has maintained a network of UV detectors in capital cities around Australia since 1989. In 1996 the instruments were changed over to Solar Light UVB 501 broadband biometers. Kingston, Tasmania was added in 2007, Canberra was added in 2010, and Alice Springs was added in 2011. Biometers have also been collecting data at Macquarie Island since 2001 and the Australian Antarctic stations Mawson, since 2002, and both Davis and Casey since 1996. The biometers are intercompared at Yallambie before placement in the field.

In 2017 ARPANSA began replacing the existing biometers with SiC photodiode UV sensors (sglux ERYCA) at all network sites. There are currently thirteen measurement sites in Australia that have been upgraded to the new sensors: Adelaide, Alice Springs, Brisbane, Canberra, Darwin, Emerald (new site 2019), Gold Coast (new site 2018), Kingston, Melbourne, Newcastle, Perth, Sydney and Townsville. In addition, the biometers at the Australian Antarctic Division (AAD) research stations of Mawson and Macquarie Island have been upgraded to the new UV sensors. Biometer detectors are still in place at the remaining two AAD stations of Casey and Davis.

1.3.2 Spectral ultraviolet

The Bureau of Meteorology owns and operates two NIWA-designed spectroradiometers at Alice Springs and Broadmeadows (Melbourne).

Measurements of spectral irradiance have been made at Kennaook / Cape Grim by the University of Wollongong since 2000 and archived at WOUDC for 2000 - 2005. A new instrument is now operational.

ARPANSA currently uses a Bentham spectroradiometer based at the Melbourne site to simultaneously measure solar UVR and transfer a traceable calibration to the broadband detectors before installation at network sites. This instrument has been operating continuously during daylight hours since it was installed in December 2008. Spectral measurements with traceable calibrations at Antarctic mainland stations commenced in 2010 at Davis and Mawson. In 2011 a Bentham spectral system was installed at Davis with the aim of providing a longer duration series of calibrated spectral measurements. This instrument failed in 2012, but was replaced in 2013 and is still recording UV spectral data. Another Bentham spectral system was installed in Casey in December 2012 and removed in May 2014. In 2023, ARPANSA began trialling a portable CCD array spectroradiometer system for the transfer of calibrations between detectors.

1.4 Calibration activities

The Bureau of Meteorology holds the Region V Dobson standard and operates the Regional Dobson Calibration Centre (RDCC) for the south-west Pacific. The regional standard Dobson is inter-compared regularly with the world standard Dobson, most recently in Boulder in August 2013 and in Melbourne in February 2017 and November 2022. ARPANSA meets the WMO's instrument specifications and characterization as a health advisory agency that provides the daily UV levels. CSIRO/BoM ODS measurements employ calibration standards supplied by the Scripps Institution for Oceanography (USA) and the data are regularly compared to data collected at Kennaook / Cape Grim by NOAA (USA) and University of East Anglia (UK).

In Melbourne in 2013 ARPANSA was involved with an international intercomparison of solar UVR spectral measurements involving the ARPANSA Bentham spectroradiometer intercompared with the BoM owned NIWA-designed spectroradiometer and solar UVR spectroradiometer from Public Health England (PHE) (Gies et al. 2015).

The ARPANSA travelling Bentham spectroradiometer was involved in an intercomparison at NIWA Lauder, New Zealand 29 January to 12 February 2016 with two NIWA spectroradiometers and the travelling reference spectroradiometer QASUME from PMOD/WRC.

A Regional Dobson Intercomparison was held in Melbourne in February 2017, including participation from the Philippines supported by the Vienna Convention Trust Fund for Research and Systematic Observations, as well as Japan, New Zealand and the USA.

The Philippines Dobson (D052) was repaired and calibrated in March 2023.

1.5 Ozone Depleting Substances

Australian activities in ODS research are focused on *in situ* ODS observations at the WMO GAW Global Baseline Station at Kennaook / Cape Grim, Tasmania (funded and managed by the Australian Bureau of Meteorology, with the science program jointly undertaken with CSIRO) and at the CSIRO Environment laboratory at Aspendale, Victoria, analysing air samples from the Cape Grim Air Archive, from the CSIRO Australian and global flask sampling networks and from firn air samples from Antarctica. Australian activities also include ODS modelling (global and regional). ODS observational and modelling research involve collaborations with AGAGE (Advanced Global Atmospheric Gases Experiment) and other colleagues in the USA, Europe (Germany, Norway, Switzerland, UK) and Asia (China, Japan, South Korea).

ODSs monitored and modelled in the Australian program include species from all the major ODS groups – CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons), halons, chlorocarbons, bromocarbons and nitrous oxide. HFCs (hydrofluorocarbons, ODS replacement species), which are regulated under the Montreal Protocol following the Kigali Amendment (2016) and other ODS replacement species (sulfuryl fluoride) are also monitored and modelled.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

2.1 Ozone Depleting Substances

Australian observations of ODSs and their replacement chemicals (HFCs, sulfuryl fluoride) and estimates of their Australian emissions have been reported to the Australian government, in international data archives and made available to the public (Dunse *et al.*, 2019 a,b; 2023 a,b; Fraser *et al*., 2020; Meinshausen *et al*., 2020; Gregory *et al*., 2021; Krummel *et al*., 2021).

Australian data and research on ODSs and HFCs made significant contributions to the IPCC 6th Assessment Report on Climate Change (Dentener *et al*., 2021; Gulev *et al*., 2021) and to the WMO/UNEP Scientific Assessment of Ozone Depletion: 2022 (Laube *et al*., 2022; Liang *et al*., 2022; Velders *et al*., 2022).

Australian ODS data have been incorporated into WMO Bulletins on Greenhouse Gases and ODSs (Matsyutov et al., 2019; Chevallier *et al*., 2023).

Australian scientists have been involved in the interpretation of ODS observations in the upper-troposphere and lower stratosphere (Adcock *et al*., 2020, Lickley *et al*., 2021, Pardo Cantos *et al*., 2022) and the contribution of short-lived ODSs to stratospheric chlorine and bromine (Claxton *et al*., 2020, An *et al*. 2021, 2023).

Trends in Kennaook / Cape Grim ODS and HFC data have been used for verification of trends derived from satellite data (Chen *et al*., 2023).

Australian ODS data have been incorporated in extensive studies of the Antarctic ozone holes 2014-2020 reported to the Australian government and published in the peer-reviewed literature (Klekociuk *et al*., 2019, 2021, 2022; Krummel *et al*., 2019 a,b; 2020, 2021; Tully *et a*l., 2020).

Australian scientists have been involved extensively in communications and research describing and understanding the causes of the rapid increase in CFCs emissions from China in the late-2010s and their rapid decrease in the early 2020s (Krummel *et al*., 2019, 2021; Fahey *et al.*, 2021, Montzka *et al*., 2021; Park *et al*., 2021) and the unexpected increase in global emissions of some minor CFCs and HCFCs (Vollmer *et al*., 2021; Western *et a*l., 2023).

Australian scientists have been involved in describing and understanding an unexpected increase in HCFC emissions from China, possible due to foam applications (Western *et al*., 2022). Kennaook / Cape Grim and other global data show that radiative forcing and equivalent effective chlorine due to HCFCs peaked in 2021 (Western *et al*., 2024).

Australian data from Kennaook / Cape Grim have been used to describe the successful phase-out of methyl bromide in structural and other fumigation uses (Porter and Fraser, 2020) and the transition to sulfuryl fluoride as a replacement fumigant (Gressent et al., 2021). However, there are unaccounted-for methyl bromide emissions from east China (Choi *et al*., 2022; Hu *et al*., 2024).

Australian scientists have been involved in describing ODS emissions from India and South Africa (Say *et al*., 2019, 2020).

Declining trends in Kennaook / Cape Grim methyl chloroform data have been used with other global baseline data to derive long-term global abundances of the important hydroxyl radical (Patra *et al*., 2021). HFC trends have also been used to estimate global hydroxyl levels (Thompson *et al*., 2024).

Kennaook / Cape Grim nitrous oxide data have been used along with data from other baseline sites to significantly improve our understanding of the global nitrous oxide budget (Tian *et al*., 2020, 2024; Harris *et al.*, 2022; Huang *et al*. 2022; Patra *et al*., 2022; Stell *et al*., 2022; Ghosh *et al*., 2023; Worthy *et al*., 2023).

Australian data have been used extensively in describing and understanding the rapid rise of HFCs in the global atmosphere and their resultant emissions globally and regionally (Stanley *et al*., 2020; Manning *et al*., 2021; Takeda *et al*., 2021; Guo *et al*., 2023; Park *et a*l., 2023), including HFC production from feedstock use of HCFCs (Muhle *et al*., 2021).

2.2 Ozone & UV

Ozonesonde data from Broadmeadows and Macquarie Island, and FTIR data from Wollongong, was used in the 2022 WMO/UNEP Scientific Assessment of Ozone Depletion (Hassler & Young, 2022, Table 3A-2). Total ozone data from the Australian Dobson network was also included in the analysis of long-term changes in total ozone through the WOUDC.

Broadmeadows and Macquarie Island ozonesonde data was also used to investigate ozone changes due to COVID-19 restrictions in the global free troposphere (Steinbrecht et al. 2021 , Chang et al. 2022).

Observational data from the Australian radiosonde network was also used extensively to characterise the unprecedented injection of water vapour directly into the stratosphere from the volcanic eruption of Hunga Tonga-Hunga Ha'apai (Vömel, Evans & Tully 2022).

Coarse resolution ozone profiles from the University of Wollongong FTIR are delivered to the Belgium Institute for Space Aeronomy on a monthly basis as part of the follow on EU FP7 programme, the Copernicus Atmosphere Monitoring Service (CAMS). These profiles are used to help validate the CAMS model. Data from the Bureau of Meteorology Dobson network and MAX-DOAS instrument is also provided to CAMS via NDACC rapid delivery.

Ozone profiles from the University of Wollongong FTIR and the Bureau of Meteorology ozonesondes have been used, alongside measurements from other FTIR sites within the NDACC network and co-located ozonesondes, to examine the long-term trends in Southern Hemisphere stratospheric ozone. Using a multiple linear regression model the effect of various dynamical influences was considered and a linear trend value was produced at each site for each measurement technique (Takacs et al.,2023).

Long term observations made by the Hobart Brewer were used to create a climatology of aerosol optical depth at 320 nm showing the effect of biomass burning (Nuñez, M., Serrano, A., & Larson, N. R., 2023).

3. THEORY, MODELLING, AND OTHER OZONE RELATED RESEARCH

The global climate version of the Australian Community Climate and Earth System Simulator (ACCESS) has the capability to resolve stratospheric ozone depletion and recovery, and associated climate impacts. This model, known as ACCESS-CM2-Chem (Dennison & Woodhouse 2023), is available to all academic researchers in Australia, and was used in Australia's contribution to the second phase of the Chemistry-Climate Model Initiative (CCMI-2).

ACCESS-CM2-Chem is a chemistry-enabled version of the ACCESS-CM2 climate model, which is one of Australia's submissions to the Coupled Model Intercomparison Project 6 (CMIP6). This development approach ensures availability to the community and ongoing technical support. The full chemistry configuration of ACCESS-CM2 can run with or without an interactive ocean and can be nudged to meteorological reanalyses to suit the experimental application. A similar development approach for the next version of the ACCESS chemistry model (ACCESS-CM3-Chem) will be followed, exploiting progress and infrastructure in the ramp up to CMIP7.

Evaluation against observations of the ACCESS-CM2-Chem model reveals improved skill in reproducing the stratospheric ozone hole as compared to the previous ACCESS-CCM and ACCESS-UKCA models (Dennison & Woodhouse, 2023). Additionally, analysis has shown that the simulated Southern Annular Mode is sensitive to stratospheric ozone depletion when simulated interactively.

ACCESS-CM2-Chem model runs on the NCI Gadi supercomputer, under projects p66 and q90. Knowledge, data sharing, and collaborative activities are occurring between NIWA, the AAD, the BoM, domestic universities, and international collaborators (e.g. UK Met Office).

Simulations performed with the previous version of the model (ACCESS-CCM) contributed to CCMI-1 and have been archived at the British Atmospheric Data Centre. Studies based on analysis of these model runs are listed in 4.3. (See https://blogs.reading.ac.uk/ccmi/badc-data-access/).

Lim et al 2022 reviewed the impacts of recent Antarctic stratospheric ozone trends on the surface climate, while Oh et al 2022 highlighted the role of stratospheric ozone in Southern Hemisphere sub-seasonal prediction.

4. DISSEMINATION OF RESULTS

4.1 Data reporting

Ozonesonde and Dobson data from all Bureau of Meteorology stations are archived at the World Ozone and UV Data Centre (WOUDC) and widely used in the literature, including for satellite

validation and model comparisons. Ozonesonde and Dobson data are also being progressively archived at NDACC.

Measurements of column amounts from the FTIR system at Wollongong are reported via the Network for Detection of Atmospheric Composition Change (NDACC) database (see http://www.ndsc.ncep.noaa.gov/data/), as are spectral UV data from Alice Springs. Spectral UV data from Broadmeadows are archived at WOUDC.

Kennaook / Cape Grim and AGAGE global ODS data, and N_2O data from the CSIRO global flask monitoring network are regularly archived at the WMO World Data Centre for Greenhouse Gases (WDCGG) in Japan: https://gaw.kishou.go.jp/. https://gaw.kishou.go.jp/. AGAGE data can also be found on the MIT AGAGE website: https://agage.mit.edu/https://agage.mit.edu/

ARPANSA provides UVR data from its broadband detectors in Casey, Davis, Mawson and Macquarie Island to the Australian Antarctic Division Data Centre. https://data.aad.gov.au/metadata/records/ARPANSA_BIO

Broadband UV data collected since 2007 from all other ARPANSA network sites is archived at the Australian Government data portal https://www.data.gov.au/.

4.2 Information to the public

A UV forecast (based on data from the Copernicus Atmospheric Monitoring Service) is issued daily by the Bureau of Meteorology, and provided to the media as part of the weather report, and on the BoM weather app. The forecast is used extensively in Australia's SunSmart promotional and educational campaigns.

ARPANSA provide measured real-time UV levels which are updated every minute. Data and plots of the UV levels for all network sites since 2017 are available to view and download from the ARPANSA web site at: https://www.arpansa.gov.au/our-services/monitoring/ultraviolet-radiation-monitoring/ultraviolet-radiation-index. Historical UV index data since 2007 is also available on the Australian Government data portal at https://www.data.gov.au/. The ARPANSA real-time UV measurement data are also provided as an xml format file for application developers at https://uvdata.arpansa.gov.au/xml/uvvalues.xml. This file is updated approximately once every minute with the most recent UVR levels and is used in many mobile apps (such as the SunSmart app).

During spring of each year, CSIRO provides a weekly update on the status of the ozone hole, based primarily on satellite data from OMPS, OMI and TOMS, which is posted on the Department of Environment and Energy website and publicly available.

Figures showing Kennaook / Cape Grim and global levels of ODSs can be found on the AGAGE website:
https://agage.mit.edu/data/agage-data https://agage.mit.edu/data/agage-data while the levels of N2O at Kennaook / Cape Grim can be found on the Kennaook / Cape Grim greenhouse gases webpage: https://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/Latest-greenhouse-gas-datahttps://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/Latest-greenhouse-gas-data

Information on Antarctic ozone depletion was provided in the 2023 Australian State of the Environment Report (Wienecke, Klekociuk and Welsford, 2023).

General information to the public is also disseminated from time to time in the form of general articles (e.g. Klekociuk and Krummel, The Conversation, 15 September 2017).

4.3 Relevant scientific papers

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5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

Information on Australian activities related to ozone and UV is shared through the *Australian Ozone Science Group,* co-ordinated by the Australian Government Department of Climate Change, Energy Environment and Water. This group has led to greatly increased co-operation and co-ordination between agencies and institutions in both Australia and New Zealand, and is appreciated by all.

A number of Australian scientists contributed as members of the steering committee, lead-authors, co-authors, contributors or reviewers of the WMO/UNEP 2022 Scientific Assessment of Ozone Depletion, with some support from the Department of Climate Change, Energy Environment and Water.

Similarly, the 2022 Assessment Report of the Environmental Effects of Stratospheric Ozone Depletion, UV Radiation and Interactions with Climate Change, had a significant number of Australian scientists involved as members of the panel (5), co-authors (3) and reviewers (5).

The Bureau of Meteorology has ongoing collaboration projects with the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) on UV Index validation against surface measurements and with SunSmart (Cancer Council Australia) on the use of the UV Index to promote sun protection.

ARPANSA had a collaborative project with the Australian Antarctic Division entitled Determination of the ultraviolet radiation environment at the Australian Antarctic Stations using broadband and spectral instrumentation (AAS 4115) that ran from 2012/13 to 2020/21. This program was succeeded by a new project entitled UV Monitoring (AAS 4646) from 2022/23.

Other projects and collaborations are also discussed above in Section 3.

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 10th OZONE RESEARCH MANAGERS MEETING

Progress towards implementing the specific recommendations of the 9th ORM include the following actions:

- Research work has continued regarding the development and validation of Chemistry-Climate models in Australia, recognising the interactions between ozone and climate. The ACCESS-CM2 will contribute to CCMI2.
- Long-term ozone monitoring sites have continued, in particular total ozone and ozonesonde programs at Macquarie Island
- High quality baseline measurements of emerging ODS substitutes such as HFOs are being made by CSIRO at Kennaook / Cape Grim
- The Bureau of Meteorology is conducting intercomparisons of modern instrumentation for ozone measurement alongside the Dobson and Brewer, including a "Pandora", mini-SAOZ and MAX-DOAS.
- Digitisation of historic (1960s and 1970s) Dobson umkehr observations has now been completed (University of Melbourne and Bureau of Meteorology.
- The Bureau of Meteorology is continuing to support Dobson observations in the Philippines, following repair and calibration of the Dobson operated by PAGASA in Manila.
- Dobson D007 previously operated in Singapore is currently under repair by the Bureau of Meteorology.

- Spectral UV data from Broadmeadows (NIWA) and Kennaook / Cape Grim (University of Wollongong) are now archived at WOUDC
- Capacity for inverse modelling to determine regional emissions of ODSs and substitutes has progressed.

7. FUTURE PLANS

Chemistry-climate simulations using the ACCESS model will be archived for the CCMI-2 project.

The historic Umkehr Dobson record is to be reanalysed for the Australian region (BoM – University of Melbourne). The Dobson total ozone record is also being progressively reprocessed as is the ozonesonde dataset according to the international O3S-DQA homogenisation project.

ARPANSA is about to evaluate the effectiveness of using a CCD array spectroradiometer to transfer calibrations to broadband detectors at Casey, Davis and Mawson stations in Antarctica as part of the Australian Antarctic Division collaborative research project (AAS 4646). ARPANSA intends to purchase a second (Gigahertz-Optik BTS2048-UV) CCD array spectroradiometer this financial year for calibration transfers within the Australian UV monitoring network.

8. NEEDS AND RECOMMENDATIONS

It is recommended that the ORM urge the Parties to continue long-term observations of ozone, ozone depleting substances and ultraviolet irradiance, and request the Parties remind responsible agencies and institutions in their own countries of the importance of continuing long time-series, of supporting the global calibration systems of the respective networks, and of allocating sufficient scientific resources to ensure the long-term consistency of datasets.

Continued financial support for the Vienna Convention Trust Fund for Research & Systematic Observations is important to continue the work of building capacity and improving the global ozone observing system.

Space agencies are requested to make more effort to explicitly support the ground-based measurements required for calibration and validation, either by making a financial contribution to their operation or simply by directly communicating with the relevant agencies.

Enhanced geographic coverage of monitoring networks for ODS and their replacements is required.

Continued production of the Brewer spectrophotometer is essential.

End.