Australian National Report
for the 11th WMO/UNEP Ozone Research Managers Meeting
Geneva, 1-3 April 2020

1. OBSERVATIONAL ACTIVITIES

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

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

- The BoM Dobson network consists of stations located at Darwin, Brisbane, Melbourne and Macquarie Island. NOAA also operate a Dobson at Perth supported by BoM staff. Brisbane, Macquarie Island and Melbourne have records dating back to 1957.

Total column ozone is also measured by:

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

NIWA 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 BoM at:

- Broadmeadows (Melbourne)
- Macquarie Island
- Davis station, Antarctica, in conjunction with the Australian Antarctic Division (AAD) and the Chinese Academy of Meteorological Sciences (CAMS)

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). Collaboration with CAMS includes information exchange and research associated with atmospheric chemistry measurements at China's Zhongshan station, near Davis.

- In conjunction with some of these ozonesonde flights, the AAD has 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 will continue taking data until late 2020.
- Coarse vertical resolution profiles from Dobson Umkehr measurements have been made at BoM Dobson network sites dating back to 1962. Umkehr observations are still made at Brisbane, Darwin and Perth. (Stone et al., 2015).
- The FTIR operated by the University of Wollongong also reports course vertical resolution profiles (4 to 5 degress 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 BoM owns and operates two NIWA-designed spectroradiometers at Alice Springs and Broadmeadows (Melbourne).

Measurements of spectral irradiance have been made at Cape Grim by the University of Wollongong since 2000 and archived at WOUDC for 2000 - 2005. The measurements were stopped by a failure of the instrument. 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 commenced measurements in December 2008 and has been operating continuously since then. 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.

1.4 Calibration activities

The BoM 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. 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 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.

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 Cape Grim, Tasmania (funded and managed by the Australian Bureau of Meteorology, with the science program jointly undertaken with CSIRO) and at the CSIRO Oceans and Atmosphere 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, and all 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), which are regulated under the Montreal Protocol following the Kigali Amendment (2016), are also monitored and modelled.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

2.1 Ozone Depleting Substances

Australian research on ozone depleting substances (ODSs) made major contributions to the WMO/UNEP *Scientific Assessment of Ozone Depletion: 2018* (Engel, Rigby *et al*., 2018; Montzka, Velders *et al*., 2018).

Cape Grim ODS data have been included in several reviews of the evolution of ODS measurements and their global and regional emissions since the mid-1970s through to the late-2010s (Fraser *et al*., 2018; Prinn *et al*., 2018; Reimann *et al*., 2018). Cape Grim ODS data have made a significant contribution to the compilation of global greenhouse gas data for the forthcoming *IPCC 6th Assessment Report on Climate Change* (Meinshausen *et al*., 2017).

New research on the global and regional estimates of the abundances and emissions of several ODSs - CFC-11 (CCl_3F), CFC-13 ($CClF_3$), CFC-113a (CCl_3CF_3), CFC-114 ($CClF_2CClF_2$), CFC-114a (CCl_2FCF_3), CFC-115 ($CClF_2CF_3$), HCFC-22 ($CHClF_2$), HCFC-141b (CH_3CCl_2F), HCFC-142b (CH_3CClF_2), HCFC-124 ($CHClFCF_3$), carbon tetrachloride (CCl_4) and chloroform ($CHCl_3$), using data from Asian observatories (China, Japan, S. Korea, Taiwan), from Cape Grim and other global sites, and from aircraft, has been published. Thanks to the Montreal Protocol, the atmospheric abundances of the major CFCs, most HCFCs and CCl_4 have stopped growing or are in decline, whereas CFC-113a, CFC-114, CFC-114a and HCFC-22 are still increasing, but with declining growth rates. These latest results have identified east Asia, in particular China, as the major source region for recent,

renewed emissions of most of these ODSs and their possible impact on the recovery of the stratospheric ozone layer (Adcock *et al*., 2018; Fang *et al*., 2019; Lunt *et al*., 2018; Rigby *et al*., 2019; Simmonds *et al*., 2017, 2018; Stanley *et al*., 2019; Vollmer *et al*., 2018).

Cape Grim and other global data have been used to show that there are several short-lived ODSs ($CHCl_3$, dichloromethane – CH_2Cl_2, perchloroethylene - CCl_2CCl_2, dichloroethane (CH_2ClCH_2Cl) whose contribution to stratospheric chlorine has almost doubled (<2% to approaching 4%) for the period 2000-2017 (Fang *et a*l., 2019; Hossaini *et al*., 2019).

2.2 Ozone & UV

The GAW/IO3C/SPARC activity *Long-term Ozone Trends and Uncertainties in the Stratosphere* (LOTUS) made use of Australian ozone profile data from ozonesondes, FTIR and Umkehr observations (SPARC/IO3C/GAW, 2019), which in turn made a substantial contribution to the 2018 WMO/UNEP Scientific Assessment of Ozone Depletion (Braesicke, P., & Neu, J., 2018). The Australian measurements represent a substantial fraction of the long-term datasets available for southern hemisphere mid-latitudes.

Analyses of Australian ozonesonde data are used in the following areas:

- Investigation of ozone loss processes and variability (e.g. Klekociuk et al., 2018, 2019; Krummel et al., 2018; Tully et al., 2019a,b).
- Long-term monitoring of Antarctic ozone (e.g. under Australian Antarctic Science (AAS) project 4293; https://secure3.aad.gov.au/public/projects/report_project_public.cfm?project_no=4293&season=1516).https://secure3.aad.gov.au/public/projects/report_project_public.cfm?project_no=4293&season=1516).
- Near real-time analyses of ozone in the Southern Hemisphere winter (WMO Antarctic Ozone Bulletins; see http://www.wmo.ch/pages/prog/arep/gaw/ozone/index.html)
- Satellite and instrument validation (e.g. Sofieva 2017).
- Assimilation into global atmospheric composition reanalysis (e.g. Benedictow et al., 2013).

An assessment was made by Greenslade et al. (2017) of the stratospheric intrusion of ozone into the troposphere, making use of ozone sonde data from Davis, Macquarie Island and Melbourne (Broadmeadows).

Measurements at Cape Grim, Tasmania (2000 – 2005) of the UV-B driven photolysis of ozone producing reactive oxygen atoms have been analysed to quantify the impact of the key drivers (ozone, solar zenith angle and cloud) (Wilson 2015).

Antarctic and Arctic ozonesonde data are being used to develop a database of information for the upper troposphere and lower stratosphere region as part of an Action group in the Scientific Committee on Antarctic Research (https://www.scar.org/science/pact/home/).

Course resolution ozone profiles from the University of Wollongong FTIR are now 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 BoM Dobson network and MAX-DOAS instrument is also provided to CAMS via NDACC rapid delivery.

Data from UV spectral measurements at Alice Springs and Melbourne (Broadmeadows) were used by McKenzie et al. (2019) to establish the success of the Montreal Protocol in preventing long-term increases in UV irradiance.

3. THEORY, MODELLING, AND OTHER OZONE RELATED RESEARCH

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

ACCESS-CM2-Chem is based on 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.

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. Subsequent research will focus on timescales to ozone recovery, which both depend on future greenhouse gas and ODS emission pathways.

ACCESS-CM2-Chem model runs on the new 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-UKCA) contributed to CCMI1 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/).

Gillet et al. (2019) has recently studied the relation between interannual variations of Antarctic ozone and surface temperature in spring and summer, while Lim et al. (2019) examined the impact on Australian temperature and rainfall of a weaker Antarctic vortex.

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.

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. A plot of the UV levels for all network sites is available on 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).

The University of Melbourne Earth Sciences' website provides five-minute UV index updates for Melbourne: http://earthsci.unimelb.edu.au/engage/dynamic-earth-updates/weather-station

Ozone analyses and forecasts are used by a number of groups to issue statements on the development of the ozone hole each year.

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 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 Cape Grim can be found on the 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 2016 Australian State of the Environment Report (Klekociuk and Wienecke, 2017).

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 Agriculture, Water & Environment, which 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 2018 Scientific Assessment of Ozone Depletion, with some support from the Department of Agriculture, Water and Environment.

Similarly, the assessment of the Environmental Effects of Ozone Depletion has a significant number of Australian scientists involved.

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.

The BoM/AAD ozonesonde and AAD lidar measurements at Davis station in Antarctica have contributed to the International Polar Year cluster project ORACLE-O3, and the CONCORDIASI and MATCH campaigns.

ARPANSA has an ongoing 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).

The Australian Research Council has funded a 5 year project looking at a number of atmospheric "grand challenges" in the southern hemisphere involving the University of Wollongong, the University of Melbourne and several overseas collaborators. (2016 – 2020, DP160101598).

Short-term summer research intern positions which allow graduate university students to work alongside researchers over periods of several weeks are run annually in conjunction between various universities, the Centre of Excellence for Climate Extremes and research organisations (e.g. CSIRO, AAD, BoM) and are funded by the Department of Agriculture, Water and Environment. Several students have worked on projects directly related to ozone science (e.g. Greenslade et al., 2017).

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 Cape Grim
- The BoM 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 BoM).
- A Region V Dobson intercomparison was held in Melbourne (February 2017), including participants from the Philippines, supported by the Vienna Convention Trust Fund.
- An Asia/Pacific Brewer Workshop was held in Sydney in September 2017, hosted by the BoM, with support from the Vienna Convention Trust Fund and the Canadian Brewer Trust Fund.
- Spectral UV data from Broadmeadows (NIWA) and 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 intend to install UV spectroradiometers at Casey and Davis stations in Antarctica as part of the Australian Antarctic Division collaborative research project (AAS 4115).

Proposals are being discussed for the development of a national atmospheric chemistry network for rapid data delivery for research and operational purposes.

8. NEEDS AND RECOMMENDATIONS

It is recommended that the ORM urge the Parties to continue long-term ozone observations, and request the Parties remind responsible agencies and institutions in their own countries of the importance of continuing long time-series, and also of supporting the global calibration systems of the respective networks.

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.

In light of the unexpected emissions of CFC-11, recommendations on how to improve coverage and quality of measurements of emissions of ozone depleting substances should be considered. This might also extend to consideration if any existing global monitoring networks which have chemical monitoring capabilities could be utilised for this purpose.