Ozone Research Activities in Germany (2017 – 2020)
Report to the 11th WMO/UNEP Ozone Research Managers Meeting

1. OBSERVATIONAL ACTIVITIES

1.1 Column measurements of ozone and other gases/variables relevant to ozone loss.
(e.g., Dobson, Brewer, DOAS, FT-IR, Satellite; also include any measurements of
meteorological parameters that are critical to the interpretation of your ozone and ozone-relevant
data)

1.1.1 Stations (only long-term, ongoing)
A number of German institutes run ground-based long-term observation programs at stations in
Germany, the Arctic and Antarctic, and at some lower latitude stations.

Table 1: Stations with long-term column observations

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Instruments</th>
<th>Gases</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ny Ålesund – AWIPEV,</td>
<td>U. Bremen, AWI</td>
<td>FTIR</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂</td>
<td>1992 – now</td>
</tr>
<tr>
<td>Spitzbergen</td>
<td>U. Bremen</td>
<td>FTIR/SAOZ</td>
<td>O₃, NO₂</td>
<td>1992 – now</td>
</tr>
<tr>
<td>Kiruna, Sweden</td>
<td>KIT</td>
<td>FTIR/DOAS</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂, COS</td>
<td>1996 – now</td>
</tr>
<tr>
<td></td>
<td>MPI-C, U. Heidelberg</td>
<td>FTIR/DOAS</td>
<td>O₃, NO₂</td>
<td>2015 – now</td>
</tr>
<tr>
<td>Bremen</td>
<td>U. Bremen</td>
<td>FTIR/DOAS</td>
<td>Total O₃, HCl, HF, HNO₃, N₂O, NO₂, O₃, NO₂</td>
<td>2002 – now</td>
</tr>
<tr>
<td>Lindenberg / Potsdam</td>
<td>DWD</td>
<td>Dobson, Brewer</td>
<td>Total O₃</td>
<td>1964 – now</td>
</tr>
<tr>
<td>Hohenpeißenberg</td>
<td>DWD</td>
<td>Dobson, Brewer</td>
<td>Total O₃</td>
<td>1968 – now</td>
</tr>
<tr>
<td>Garmisch / Zugspitze</td>
<td>KIT</td>
<td>FTIR</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂, COS</td>
<td>1995 – now</td>
</tr>
<tr>
<td>Izaña, Canary Islands</td>
<td>KIT</td>
<td>FTIR</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂, COS</td>
<td>1999 – now</td>
</tr>
<tr>
<td>Paramaribo, Suriname</td>
<td>U. Bremen, AWI</td>
<td>FTIR</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂</td>
<td>2004 – now</td>
</tr>
<tr>
<td>Palau, West Pacific</td>
<td>AWI</td>
<td>FTIR</td>
<td>Total O₃, HCl, ClONO₂, HF, HNO₃, N₂O, NO₂</td>
<td>2016 - now</td>
</tr>
<tr>
<td>Neumayer, Antarctica</td>
<td>U. Heidelberg</td>
<td>DOAS</td>
<td>Total O₃, NO₂</td>
<td>1999 – now</td>
</tr>
</tbody>
</table>
1.1.2 Satellite Column Data

Germany provides major contributions to European satellite programs, including those targeting the stratospheric ozone layer. Key players are U Bremen (research, processors, processing, especially UV/VIS), DLR (research, processors, processing, data centers), KIT (research, processors, especially thermal IR), as well as EUMETSAT in Darmstadt and a number of companies building satellites and space equipment.

Table 2: Long-term column observations from satellites with large German contribution.

<table>
<thead>
<tr>
<th>Satellite(s)</th>
<th>Organization</th>
<th>Instruments</th>
<th>Gases</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA Sentinel-5P</td>
<td>DLR/ESA, U Bremen</td>
<td>TROPOMI</td>
<td>Total O\textsubscript{3}, SO\textsubscript{2}, HCHO, NO\textsubscript{2}, ..., tropospheric O\textsubscript{3}</td>
<td>2018 – now</td>
</tr>
<tr>
<td>Suomi NPP</td>
<td>U Bremen</td>
<td>OMPS - N</td>
<td>Total O\textsubscript{3}</td>
<td>2012 - now</td>
</tr>
</tbody>
</table>

1.2 Profile measurements of ozone and other gases/variables relevant to ozone loss (e.g., Satellite, OMI, aircraft, ozonesondes, ozone lidar etc; also include any measurements of meteorological parameters that are critical to the interpretation of your ozone and ozone-relevant data)

1.2.1 Stations with profile measurements (only long-term, ongoing)

Table 3: Stations with long-term profile observations

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Instruments</th>
<th>Gases</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ny Ålesund – AWIPEV, Spitzbergen</td>
<td>AWI U Bremen</td>
<td>ECC-Sonde Frostpoint-Sonde Lidar µWave</td>
<td>O\textsubscript{3}, temperature H\textsubscript{2}O aerosol O\textsubscript{3}</td>
<td>1992 – now 2002 - now 1991 - now 2004 - now</td>
</tr>
<tr>
<td>Jülich / Frankfurt</td>
<td>U Frankfurt</td>
<td>Whole air sampler Aircore-Sonde</td>
<td>CFCs, SF\textsubscript{6}, CO\textsubscript{2}, many more</td>
<td>1975 – 2005 2016 - now</td>
</tr>
<tr>
<td>Lindenberg</td>
<td>DWD</td>
<td>B/M-Sonde ECC-Sonde Frostpoint Sonde</td>
<td>O\textsubscript{3}, temperature O\textsubscript{3}, temperature H\textsubscript{2}O</td>
<td>1974 - 1993 1994 – now 1999 - now</td>
</tr>
<tr>
<td>Hohenpeißenberg</td>
<td>DWD</td>
<td>B/M-Sonde Lidar</td>
<td>O\textsubscript{3}, temperature O\textsubscript{3}, temperature</td>
<td>1967 – now 1987 - now</td>
</tr>
<tr>
<td>Garmisch / Zugspitze</td>
<td>KIT</td>
<td>Lidar aerosol</td>
<td></td>
<td>1977 – now</td>
</tr>
<tr>
<td>Palau, West Pacific</td>
<td>AWI</td>
<td>ECC-Sonde Frostpoint Sonde</td>
<td>O\textsubscript{3}, temperature H\textsubscript{2}O</td>
<td>2016 - now</td>
</tr>
<tr>
<td>Neumayer, Antarctica</td>
<td>AWI</td>
<td>ECC-Sonde</td>
<td>O\textsubscript{3}, temperature</td>
<td>1992 – now</td>
</tr>
</tbody>
</table>
1.2.2 Satellite Profilers (non-nadir)

Table 4: Long-term profile observations from satellites with large German contribution.

<table>
<thead>
<tr>
<th>Satellite(s)</th>
<th>Organization</th>
<th>Instruments</th>
<th>Gases</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA ENVISAT</td>
<td>U Bremen</td>
<td>SCIAMACHY (UV-VIS Limb)</td>
<td>O₃, SO₂, NO₂, H₂O, BrO, OClO</td>
<td>2003 - 2012</td>
</tr>
<tr>
<td>ESA ENVISAT</td>
<td>KIT</td>
<td>MIPAS (IR Limb)</td>
<td>O₃, F₁₁, F₁₂, F₂₂, CCl₄, ClO, CINO₃, BrONO₂, SO₂, OCS, H₂SO₄, N₂O, NO₂, NO, N₂O₅, HNO₃, HNO₄, HOCI, H₂O, CH₄, CO, NH₃, SF₆, Temperature, aerosol, PSCs</td>
<td>2003 - 2012</td>
</tr>
<tr>
<td>Suomi NPP</td>
<td>U Bremen</td>
<td>OMPS-L</td>
<td>O₃ and aerosol</td>
<td>2012 - present</td>
</tr>
</tbody>
</table>

Table 5: Long-term tropospheric ozone from satellites with large German contribution.

<table>
<thead>
<tr>
<th>Satellite(s)</th>
<th>Organization</th>
<th>Instruments</th>
<th>Gases</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA ENVISAT</td>
<td>U Bremen</td>
<td>SCIAMACHY (UV-VIS Limb)</td>
<td>Tropospheric O₃, NO₂</td>
<td>2003 - 2012</td>
</tr>
<tr>
<td>Suomi NPP</td>
<td>U Bremen</td>
<td>OMPS-L + -N</td>
<td>Tropospheric O₃</td>
<td>2012 - present</td>
</tr>
<tr>
<td>METOP-A,B,C</td>
<td>DLR/EUMETSAT</td>
<td>GOME-2A,B,C</td>
<td>tropospheric O₃, NO₂, …</td>
<td>2007 – now</td>
</tr>
</tbody>
</table>

1.2.3 Profile measurements from airplanes

German institutions are major contributors to the European research infrastructure IAGOS (In-Service Aircraft for a Global Observing System, [https://www.iagos.org/](https://www.iagos.org/)). Flying on commercial airliners, IAGOS provides a comprehensive set of routine trace-gas and aerosol measurements in the upper troposphere and lower stratosphere. Involved German institutions are

- Lufthansa (aircraft & operation), Lufthansa Technik (engineering)
- Enviscope (engineering), Safran (engineering)
- FZ Jülich (IAGOS-CORE: H₂O, NOₓ, NO₃, IAGOS-CARIBIC: aerosol)
- MPI-Biogeochemistry (IAGOS-CORE: CO₂, CH₄, CO, IAGOS-CARIBIC: CO₂, CH₄)
- KIT (IAGOS-CARIBIC: O₃, H₂O, cloud H₂O, ~5 VOCs, …)
- MPI-C (IAGOS-CARIBIC: CO, CO₂, CH₄, N₂O, SF₆, NMHCs, soot, aerosol composition)
- TROPOS (IAGOS-CARIBIC: aerosol size distribution / number concentration)
- DLR (IAGOS-CARIBIC: NOₓ, NO₃)
- U Heidelberg (IAGOS CARIBIC, HALO, Balloon: O₃, BrO, IO, OClO, total Brₓ, NO₂, HONO, CH₂O, C₂H₂O₂, C₃H₆O₂, …)
- U Frankfurt (IAGOS CARIBIC, HALO: Halocarbons)

For dedicated research campaigns, Germany operates the "High Altitude and Long Range Research Aircraft" ([HALO, https://www.halo.dlr.de](https://www.halo.dlr.de)), a Gulfstream G550 research aircraft adapted for atmospheric research and earth observation. HALO offers technical infrastructure for
very diversified scientific payloads, including lidars, 1 and 2-D IR and UV/VIS spectrometers, halocarbon measurements (GhOST-MS, Gaschromatograph for Observational Studies using Tracers - Mass Spectrometer), as well as standard trace-gas and aerosol instrumentation. HALO is operated by a consortium of German research centers (DLR, KIT, FZ Jülich, MPG, TROPOS Leipzig, GFZ Potsdam) and the DFG (Deutsche Forschungsgemeinschaft, representing German universities). HALO consortium members are the main scientific users of the aircraft, but, in principle, HALO is open to other users as well. See Section 5 for a list of recent HALO campaigns.

1.2.4 Balloon measurements

While the current focus of atmospheric measurement campaigns is on the HALO research aircraft, a number of German institutes have instruments for flying on large stratospheric balloons. Examples are the MIPAS-Balloon IR emission spectrometer (KIT, providing data on many species), UV/VIS/NIR Differential Optical Absorption Spectrometers (U Heidelberg, providing profiles of H$_2$O, O$_3$, NO$_2$, HONO, BrO, IO, OClO, CH$_3$O, C$_2$H$_5$O$_2$ ...), whole-air samplers (U Frankfurt, whole air sampling for halocarbons, SF$_6$, CO$_2$, age-of-air and other species). U Frankfurt is also flying Air-Core samplers on small balloons on a reasonably regular schedule.

1.3 UV measurements
(e.g., broadband, narrowband, Spectroradiometers, etc)

UV measurements in Germany are coordinated by the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS). Currently, 27 stations, distributed over Germany, take routine measurements. Half of the sites use spectroradiometers (double monochromators and diode array radiometers with BTS technology), the other half use broadband filter radiometers only. See https://www.bfs.de/uv-aktuell for data and more information.

1.4 Calibration activities

1.4.1 World Calibration Centre for Ozone Sondes
Since 1995, FZ Jülich hosts the World Calibration Centre for Ozone Sondes (WCCOS). WCCOS is part of the quality assurance for balloon borne ozone sondes in WMO GAW. WCCOS provides an experimental chamber simulating the atmosphere as a balloon ascends from the surface to the stratosphere. These Jülich Ozone Sonde Intercomparison Experiments (JOSIE) have evaluated and substantially improved the performance of ozone sondes, most recently in a cooperation with the largely tropical SHADOZ network in 2017/18. WCCOS also leads the “Ozone Sonde Data Quality Assessment (O3S-DQA)” activity with the primary goals of homogenizing selected long-term ozone sonde data sets. In addition, the ongoing Assessment of Standard Operating Procedures (ASOPOS) will provide revised and more strict Standard Operating Procedures (SOP’s) to reduce uncertainties of ozone sounding records, from currently 10-20 % down to the 5 % level.

1.4.2 Regional Dobson Calibration Centre
Since 1999, DWD, in cooperation with Czech CHMI, is hosting the WMO RA VI Regional Dobson Calibration Centre (RDCC-E). Connected to the World Dobson Calibration Center (NOAA Boulder), and other regional Dobson Calibration Centers, RDCC-E provides calibration, maintenance, refurbishment and training for about 20 Dobson spectrometers/ stations in Europe and neighboring regions (including the British Antarctic Dobsons). RDCC-E hosts calibration campaigns at least once a year. In 2019, RDCC-E also supported the African Regional Dobson Calibration Center during a campaign in Irene, South Africa.
2. RESULTS FROM OBSERVATIONS AND ANALYSIS
(e.g., trend analyses, UV doses (annual, monthly etc.), UV maps)

![Figure 1: Top panel: Observed annual mean total ozone columns at Hohenpeißenberg, Germany (black dots), and reconstruction of the observed time series by multiple linear regression (grey circles). The colored lines in top panel and lower panels give the ozone variations attributed to different influence factors in the regression.](image)

As one example, Fig. 1 shows the observed evolution of total ozone at a German station, along with results from a multilinear regression, which attributes the observed variations and long-term trends to a number of influencing factors. The observed data are consistent with long-term ozone decline due to increasing ozone depleting substances (ODSs) from 1968 until the late 1990s, and a beginning slow recovery of ozone since the late 1990s. The observed rates of change in both periods (red line in Fig. 1) are consistent with the evolution of ODSs or stratospheric halogen loading (e.g. given by Equivalent Effective Stratospheric Chlorine = EESC). Note also that the long-term behavior of total ozone above Germany is very similar to the general behavior at Northern mid-latitudes, and even very similar to near global total ozone.
Similar trend analyses, also using satellite data, are carried out by a number of German groups, e.g. at Bremen University, KIT, DLR and FU-Berlin.

To our knowledge there have not been any recent studies looking at changes in UV doses, largely because UV over Germany is influenced by many more factors than stratospheric ozone alone. Thus, ozone- or ODS-related long-term UV changes are generally small and hard to detect over Germany. It is, however, noteworthy that due to the still quite enhanced ODS levels, large polar ozone depletion can occur in the Arctic spring, e.g. in years like 2011 or 2016. In such years, ozone poor air can reach Germany, and in combination with clear weather and a high tropopause, can result in substantially enhanced UV doses from March to May or June. Usually UV-warnings will be issued in such cases, see also 4.2 below. Apart from BfS, the University of Hannover is an important center for UV research in Germany.

For more information on German ozone data analysis and ozone research see the list of publication topics and publications in Section 4.3.

3. THEORY, MODELLING, AND OTHER OZONE RELATED RESEARCH
(e.g., 3-D CTM modelling, data assimilation, use of satellite data, UV effect studies)

A number of German groups use a range of models, including chemistry transport (CTM) and chemistry-climate models (CCMs), to simulate and understand changes and trends of stratospheric ozone, and to predict the future evolution of the ozone layer. German activities are well interfaced to international programs like the SPARC/IGAC Chemistry-Climate-Modelling Initiative (CCMI), which has been co-led by DLR.

ECHAM-MESSY (=EMAC), an improved CCM has been established by a consortium from DLR, MPI for Chemistry, the University in Mainz, MPI for Meteorology in Hamburg, FU Berlin, and KIT. EMAC has simulated decadal trends from the 1960s to 2100. These results have contributed significantly to WMO/UNEP Scientific Assessments of Ozone. Using EMAC, DLR also published the first study on effects of recent illegal ODS emission on the future ozone layer (Dameris et al., 2019). At MPI for Chemistry a version of EMAC with interactive stratospheric and tropospheric aerosol, including volcanic effects, has contributed to the SPARC-Initiative SSIRC. The working group Atmospheric Dynamics at the Institut für Meteorologie of Freie Universität Berlin (head: Prof. Dr. Ulrike Langematz) also uses EMAC, as well as observations, to study the effects of changes in anthropogenic emissions of ozone depleting substances (ODSs) and green-house gases (GHGs) on stratospheric ozone.

AWI is developing and employing the ATLAS CTM, e.g. for modeling polar ozone depletion and transport pathways from the troposphere to the stratosphere. AWI is also developing SWIFT, a fast but accurate ozone chemistry scheme intended for use in Earth System and Climate Models (e.g. for IPCC).

FZ-Jülich regularly performs simulations of polar ozone depletion and its interaction with other processes like vertical NO\textsubscript{y} redistribution using the Lagrangian CTM CLaMS, also used extensively for various aircraft campaigns (e.g. POLSTRACC, StratoClim).

DLR runs the SACADA 4D-Var chemistry data assimilation system which provides consistent and continuous daily global stratospheric analyses since July 2013 based on Microwave Limb Sounder (MLS) profile data of O3, HNO3, H2O, N2O and HCl. Recently, results were used for calculating the global erythemal UV-radiation for 2019.
At KIT, chemistry-climate interactions and ozone relevant VOC distributions in the UTLS region are simulated with the ICON-ART model (Weimer et al., 2017; Schröter et al., 2018). In the future, ICON, developed by DWD and MPI-M, and used for weather forecasting by DWD, will deliver UV forecasts (via KIT’s ART module).

UV studies by the Leibniz University of Hannover (Prof. Dr. Seckmeyer) show that UV radiation is reduced by more than 60% in urban areas, where a large fraction of the population lives. Hannover has also explained the significant increase in skin cancer rate with altitude (by as much as 30% per 100 m altitude) through modeling of UV exposure.

4. DISSEMINATION OF RESULTS

4.1 Data reporting
(e.g., submission of data to the WOUDC and other data centres)

Routine ozone layer data are submitted to the WOUDC, to NDACC and to the NILU data center (e.g. MATCH campaigns). In addition, DLR hosts the World Data Center for Remote Sensing of the Atmosphere, and provides operational processing and data delivery for total ozone columns and other traces gases from European satellites. Results and data are also available from most institutes (see Section 9 for websites).

4.2 Information to the public
(e.g., UV forecasts)

BfS and DWD provide the public with UV-information including warnings and daily forecasts of the UV-index. UV-forecasts for clear sky and cloudy conditions are available for free on a global scale (http://kunden.dwd.de/uvi/) and nationally (http://www.uv-index.de, http://www.bfs.de/DE/themen/opt/uv/uv-index/prognose/prognose_node.html).

A wealth of general information and educational material on atmospheric constituents and the ozone layer is available from German institutes (see Section 9 for websites).

4.3 Relevant scientific papers (2017 to 2019)

Ozone Depleting Substances and Very Short Lived Substances


Fiehn, A., Quack, B., Stemmler, I., Ziska, F., and Krüger, K.: Importance of seasonally resolved oceanic emissions for bromoform...
Data sets and trends


Polar Ozone


Tritscher, I., Groß, J. U., Spang, R., Pitts, M. C., Poole, L. R., Müller, R., and Riese, M.: Lagrangian simulation of ice particles and resulting dehydration in the polar winter stratosphere, Atmos. Chem. Phys., 19, 543-563, 10.5194/acp-19-543-2019, 2019.


Asian Monsoon and Tibetan Plateau


Upper Troposphere – Lower Stratosphere and Tropical Tropopause Layer


Modelling and Climate Change


New Instruments & Retrievals


Stratospheric Aerosol & Geo-Engineering

Germany is collaborating in the large European Infrastructure Projects, especially In-service Aircraft for a Global Observing System (IAGOS), Integrated Carbon Observation System (ICOS), Aerosol, Clouds and Trace gas Research Infra-Structure (ACTRIS), Integrated access to balloon-borne platforms for innovative research and technology (HEMERA), the Copernicus Climate Change Service (C3S), and in the Copernicus Atmospheric Monitoring System (CAMS).

Germany is actively involved in the European satellite projects AC-SAF from EUMETSAT and Sentinel-5P from ESA.

The SPARC-OCTAV activity (Observations and Trends And Variability) uses a multiplatform approach to determine trends in the UTLS. To reduce the influence of dynamical variability, all observations (balloon, aircraft, satellite) are put on a coordinate system relative to the tropopause and to the jet-streams, using consistent reanalysis data and tropopause metrics.
SPARC-OCTAV is co-lead by U-Mainz, NASA-JPL, and NOAA Boulder, and is supported by WMO’s GAW program.

Large national projects have centered around the HALO research aircraft:

- HALO 2019 SouthTRACC, Transport, Dynamics and Chemistry in the SH UTLS
- HALO 2018 CAFE, "Chemistry of the atmosphere: African Field Experiment", Atmospheric oxidation capacity over the tropical and South Atlantic Ocean
- HALO 2018 EMeRGe "Effect of Megacities on the Transport and Transformation of Pollutants on the Regional to Global Scales"
- HALO 2017 WISE, "Wave-driven ISentropic Exchange", Dynamics & chemistry of mid-latitude upper troposphere / lower stratosphere

A number of German research projects are financed by BMBF within the Role of the Middle Atmosphere in Climate (ROMIC and ROMIC II) initiative.

BfS is supporting Leibniz University of Hannover for a feasibility study on microscale modelling of UV exposure in urban environments for skin cancer prevention.

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 10th OZONE RESEARCH MANAGERS MEETING
(e.g., specifics on progress towards such implementation, difficulties encountered, near-term plans, etc.)

Germany has followed many of the recommendations of the 10th ORM by

- continuing systematic long-term observations and maintaining their quality
- funding and carrying out extensive research on ozone layer processes, ozone layer recovery and climate change, as evidenced by Section 4.3
- continuing QA/QC tasks and capacity building, e.g., through JOSIE ozone sonde chamber experiments, as well as RDCC calibration campaigns in Germany, Spain, and South Africa
- contributing to the Vienna Convention Trust Fund
- regular data submission to the international data centers
- participation in internationally coordinated modelling activities like the Chemistry-Climate Modelling Initiative (CCMI)
- contributing substantial man-power and expertise to the 2018 WMO/UNEP ozone assessment.

7. FUTURE PLANS
(e.g., new stations, upcoming projects, instrument development)

Germany plays a leading role in the upcoming ESA / EUMETSAT satellite missions Sentinel-4 and Sentinel-5. It will continue contributing to EU initiatives, especially the Copernicus Climate Change Service (C3S), the Copernicus Atmospheric Monitoring System (CAMS), and to European Research Infrastructures, especially In-service Aircraft for a Global Observing System (IAGOS), Integrated Carbon Observation System (ICOS), and Aerosol, Clouds and Trace gas Research Infra-Structure (ACTRIS).
U Bremen and DLR are contributing to the generation of long-term consolidated ozone time series under the ESA Ozone-Climate Change Initiative in Germany.


8. NEEDS AND RECOMMENDATIONS

- Monitoring the expected recovery process of the ozone layer remains essential for the next decades. It requires continuing high-quality measurements of total ozone, ozone profiles and other key constituents and atmospheric parameters (e.g. stratospheric temperature).

- To achieve the required accuracy, multiple redundant satellite and ground-based observations have to be maintained. Comprehensive quality assurance and quality control activities have to be continued (standard operating procedures, calibration centres, inter-comparison exercises, best possible absorption cross sections, …).

- The scarcity of future limb sounding satellite instruments remains a great concern. Vertically resolved profiles, not only of ozone, but also other key constituents, are essential for monitoring and attributing future ozone changes, under recovery from man-made halogen loading, but also under the influence of a changing climate.

- The complex interactions of climate change, ozone recovery, UV-radiation and changes in the atmospheric large-scale circulation remain uncertain, as does the future evolution of anthropogenic emissions. High quality, long-term data sets and continued modelling efforts are key prerequisites for understanding the observed past and predicting the future.

- Not all processes controlling the future of the ozone layer are fully understood, or properly modelled. Dedicated measurement campaigns, e.g. from special balloons and research aircraft, and accompanying model simulations and model improvement remain important to improve our process understanding and, ultimately, our predictive capabilities.

9. INSTITUTIONS

AWI, Alfred Wegener Institut für Polarforschung, https://www.awi.de/
BfS, Bundesamt für Strahlenschutz, https://www.bfs.de/
DWD, Deutscher Wetterdienst, www.dwd.de/ozon
FU Berlin, Institut für Meteorologie Freie Universität Berlin, https://www.geo.fu-berlin.de/met
KIT, Institut für Meteorologie und Klimaforschung, Karlsruhe Institute of Technology, http://www.imk.kit.edu/
MPI-BGC, Max Planck Institut für Biogeochemie, https://www.bgc-jena.mpg.de
MPI-C, Max Planck Institut für Chemie, https://www.mpic.de/
MPI-M, Max Planck Institut für Meteorologie, [https://www.mpimet.mpg.de/startseite/](https://www.mpimet.mpg.de/startseite/)

U Bremen, Institut für Umweltphysik Universität Bremen, [https://www.iup.uni-bremen.de/deu/](https://www.iup.uni-bremen.de/deu/)

U Frankfurt, Institut für Atmosphäre und Umwelt Universität Frankfurt, [https://www.uni-frankfurt.de/41121398/Institut_f%C3%BCr_Atmosph%C3%A4re_und_Umwelt](https://www.uni-frankfurt.de/41121398/Institut_f%C3%BCr_Atmosph%C3%A4re_und_Umwelt)

U Hannover, Institut für Meteorologie und Klimatologie, [https://www.muk.uni-hannover.de/244.html?&L=1](https://www.muk.uni-hannover.de/244.html?&L=1)

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