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

Name	Organization	Instruments	Gases	Years
Ny Ålesund – AWIPEV, Spitzbergen	U. Bremen, AWI U. Bremen	FTIR DOAS/SAOZ	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2 O_3, NO_2,	1992 – now 1992 – now
Kiruna, Sweden	KIT MPI-C, U. Heidelberg	FTIR DOAS	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2, COS O_3, NO_2	1996 – now 2015 – now
Bremen	U. Bremen	FTIR DOAS	Total O_3, HCl, HF, HNO_3, N_2O, NO_2 O_3 ;NO_2	2002 – now
Lindenberg / Potsdam	DWD	Dobson, Brewer	Total O_3	1964 – now
Hohenpeißenberg	DWD	Dobson, Brewer	Total O_3	1968 – now
Garmisch / Zugspitze	KIT	FTIR	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2, COS	1995 – now
Izaña, Canary Islands	KIT	FTIR	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2, COS	1999 – now
Paramaribo, Suriname	U. Bremen, AWI	FTIR	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2	2004 – now
Palau, West Pacific	AWI	FTIR	Total O_3, HCl, $ClONO_2$, HF, HNO_3, N_2O, NO_2	2016 - now
Neumayer, Antarctica	U. Heidelberg	DOAS	Total O_3, NO_2	1999 – now

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.

Satellite(s)	Organization	Instruments	Gases	Years
ESA ERS-2 ENVISAT METOP-A,B,C	U Bremen, DLR DLR/EUMETSAT AC-SAF	GOME SCIAMACHY GOME-2A,B,C	Total O_3, SO_2, NO_2, BrO, OClO, …, tropospheric O_3	1996 – 2002 2003 - 2012 2007 – now
ESA Sentinel-5P	DLR/ESA, U Bremen	TROPOMI	Total O_3, SO_2, HCHO, NO_2, …, tropospheric O_3	2018 – now
Suomi NPP	U Bremen	OMPS - N	Total O_3	2012 - now

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

Name	Organization	Instruments	Gases	Years
Ny Ålesund – AWIPEV, Spitzbergen	AWI U Bremen	ECC-Sonde Frostpoint-Sonde Lidar µWave	O_3, temperature H_2O aerosol O_3	1992 – now 2002 - now 1991 - now 2004 - now
Jülich / Frankfurt	U Frankfurt	Whole air sampler Aircore-Sonde	CFCs, SF_6, CO_2, many more	1975 – 2005 2016 - now
Lindenberg	DWD	B/M-Sonde ECC-Sonde Frostpoint Sonde	O_3, temperature O_3, temperature H_2O	1974 - 1993 1994 – now 1999 - now
Hohenpeißenberg	DWD	B/M-Sonde Lidar	O_3, temperature O_3, temperature	1967 – now 1987 - now
Garmisch / Zugspitze	KIT	Lidar	aerosol	1977 – now
Palau, West Pacific	AWI	ECC-Sonde Frostpoint Sonde	O_3, temperature H_2O	2016 - now
Neumayer, Antarctica	AWI	ECC-Sonde	O_3, temperature	1992 – now

1.2.2 Satellite Profilers (non-nadir)

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

Satellite(s)	Organization	Instruments	Gases	Years
ESA ENVISAT	U Bremen	SCIAMACHY (UV-VIS Limb)	O_3, SO_2, NO_2, H_2O, BrO, OClO	2003 - 2012
ESA ENVISAT	KIT	MIPAS (IR Limb)	O_3, F11, F12, F22, CCl_4, ClO, $ClONO_2$, $BrONO_2$, SO_2, OCS, H_2SO_4, N_2O, NO_2, NO, N_2O_5, HNO_3, HNO_4, HOCl, H_2O, CH_4, CO, NH_3, SF_6, Temperature, aerosol, PSCs	2003 - 2012
Suomi NPP	U Bremen	OMPS-L	O_3 and aerosol	2012 - present

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

Satellite(s)	Organization	Instruments	Gases	Years
ESA ENVISAT	U Bremen	SCIAMACHY (UV-VIS Limb)	Tropospheric O_3, NO_2,	2003 - 2012
Suomi NPP	U Bremen	OMPS -L + -N	Tropospheric O_3	2012 - present
METOP-A,B,C	DLR/EUMETSAT AC-SAF	GOME-2A,B,C	tropospheric O_3, NO_2, …	2007 – now

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/). 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: H_2O, NO_x, NO_y, IAGOS-CARIBIC: aerosol)
- MPI-Biogeochemistry (IAGOS-CORE: CO_2, CH_4, CO, IAGOS-CARIBIC: CO_2, CH_4)
- KIT (IAGOS-CARIBIC: O_3, H_2O, cloud H_2O, ~5 VOCs, …)
- MPI-C (IAGOS-CARIBIC: CO, CO_2, CH_4, N_2O, SF_6, NMHCs, soot, aerosol composition)
- TROPOS (IAGOS-CARIBIC: aerosol size distribution / number concentration)
- DLR (IAGOS-CARIBIC: NO_x, NO_y)
- U Heidelberg (IAGOS CARIBIC, HALO, Balloon: O_3, BrO, IO, OClO, total Br_y, NO_2, HONO, CH_2O, $C_2H_2O_2$, $C_3H_4O_2$, …)
- 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), 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_2O, O_3, NO_2, HONO, BrO, IO, OClO, CH_2O, $C_2H_2O_2$ ...), 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)

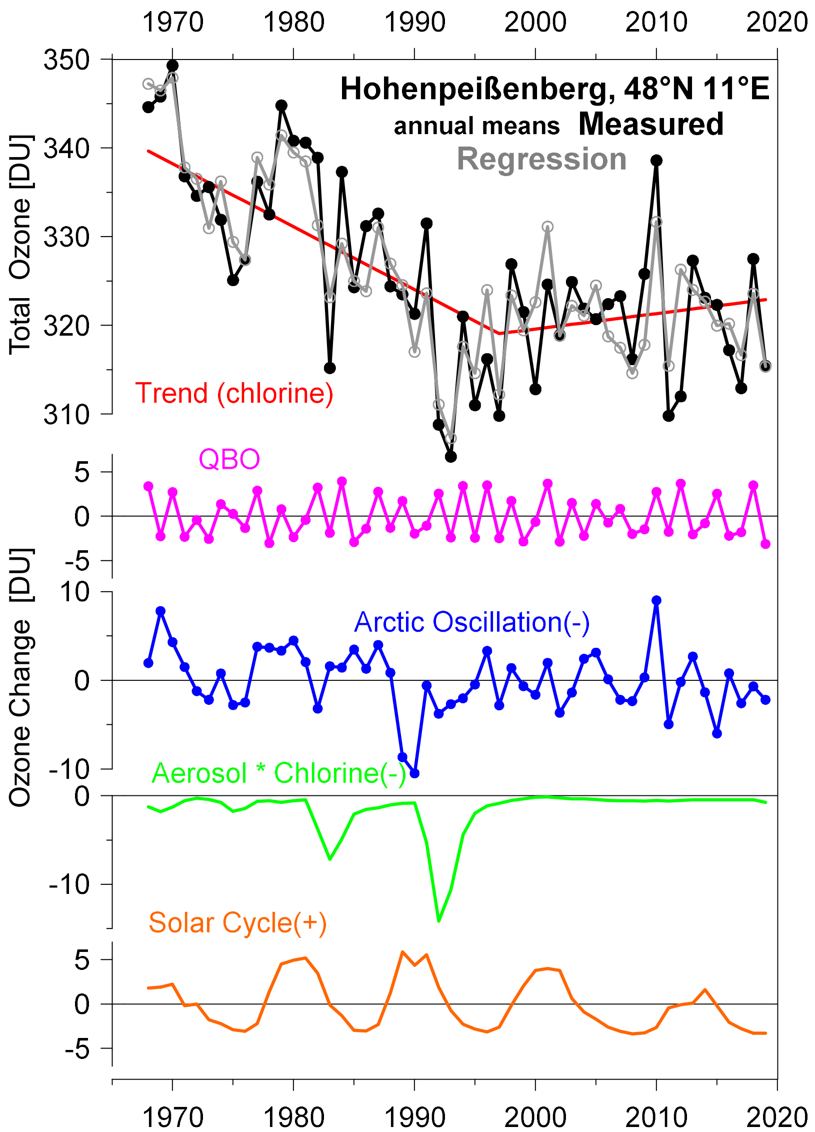

Figure 1: Top panel: Observed annual mean total ozone columns at Hohenpeißenberg, Germany (black dots), and reconstruction of the observed time series by multiple linear regression (grey circles). The colored lines in top panel and lower panels give the ozone variations attributed to different influence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

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_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.
U 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

Adams, C., Bourassa, A. E., McLinden, C. A., Sioris, C. E., von Clarmann, T., Funke, B., Rieger, L. A., and Degenstein, D. A.: Effect of volcanic aerosol on stratospheric NO2 and N2O5 from 2002–2014 as measured by Odin-OSIRIS and Envisat-MIPAS, Atmos. Chem. Phys., 17, 8063–8080, 10.5194/acp-17-8063-2017, 2017.
Bahlmann, E., Keppler, F., Wittmer, J., Greule, M., Schöler, H. F., Seifert, R., and Zetzsch, C.: Evidence for a major missing source in the global chloromethane budget from stable carbon isotopes, Atmos. Chem. Phys., 19, 1703-1719, 10.5194/acp-19-1703-2019, 2019.
Dameris, M., Jöckel, P., and Nützel, M.: Possible implications of enhanced chlorofluorocarbon-11 concentrations on ozone, Atmos. Chem. Phys., 19, 13759-13771, 10.5194/acp-19-13759-2019, 2019.
Eckert, E., von Clarmann, T., Laeng, A., Stiller, G. P., Funke, B., Glatthor, N., Grabowski, U., Kellmann, S., Kiefer, M., Linden, A., Babenhauserheide, A., Wetzel, G., Boone, C., Engel, A., Harrison, J. J., Sheese, P. E., Walker, K. A., and Bernath, P. F.: MIPAS IMK/IAA carbon tetrachloride (CCl4) retrieval and first comparison with other instruments, Atmos. Meas. Tech., 10, 2727–2743, 10.5194/amt-10-2727-2017, 2017.Engel, A., Bönisch, H., Ostermöller, J., Chipperfield, M. P., Dhomse, S., and Jöckel, P.: A refined method for calculating equivalent effective stratospheric chlorine, Atmos. Chem. Phys., 18, 601-619, 10.5194/acp-18-601-2018, 2018.
Falk, S., Sinnhuber, B. M., Krysztofiak, G., Jöckel, P., Graf, P., and Lennartz, S. T.: Brominated VSLS and their influence on ozone under a changing climate, Atmos. Chem. Phys., 17, 11313-11329, 10.5194/acp-17-11313-2017, 2017.
Fiehn, A., Quack, B., Hepach, H., Fuhlbrügge, S., Tegtmeier, S., Toohey, M., Atlas, E., and Krüger, K.: Delivery of halogenated very short-lived substances from the west Indian Ocean to the stratosphere during the Asian summer monsoon, Atmos. Chem. Phys., 17, 6723-6741, 10.5194/acp-17-6723-2017, 2017.
Fiehn, A., Quack, B., Marandino, C. A., and Krüger, K.: Transport Variability of Very Short Lived Substances from the West Indian Ocean to the Stratosphere, J. Geophys. Res., 123, 5720-5738, 10.1029/2017JD027563, 2018.
Fiehn, A., Quack, B., Stemmler, I., Ziska, F., and Krüger, K.: Importance of seasonally resolved oceanic emissions for bromoform

delivery from the tropical Indian Ocean and west Pacific to the stratosphere, Atmos. Chem. Phys., 18, 11973-11990, 10.5194/acp-18-11973-2018, 2018.
Höpfner, M., Deshler, T., Pitts, M., Poole, L., Spang, R., Stiller, G., and von Clarmann, T.: The MIPAS/Envisat climatology (2002–2012) of polar stratospheric cloud volume density profiles, Atmos. Meas. Tech., 11, 5901–5923, 0.5194/amt-11-5901-2018, 2018.
Kolusu, S. R., Schlünzen, K. H., Grawe, D., and Seifert, R.: Determination of chloromethane and dichloromethane in a tropical terrestrial mangrove forest in Brazil by measurements and modelling, Atmos. Env., 173, 185-197, 10.1016/j.atmosenv.2017.10.057, 2018.
Leedham Elvidge, E., Bönisch, H., Brenninkmeijer, C. A. M., Engel, A., Fraser, P. J., Gallacher, E., Langenfelds, R., Mühle, J., Oram, D. E., Ray, E. A., Ridley, A. R., Röckmann, T., Sturges, W. T., Weiss, R. F., and Laube, J. C.: Evaluation of stratospheric age of air from CF4, C2F6, C3F8, CHF3, HFC-125, HFC-227ea and SF6; Implications for the calculations of halocarbon lifetimes, fractional release factors and ozone depletion potentials, Atmos. Chem. Phys., 18, 3369-3385, 10.5194/acp-18-3369-2018, 2018.
Maas, J., Tegtmeier, S., Quack, B., Biastoch, A., Durgadoo, J. V., Rühs, S., Gollasch, S., and David, M.: Simulating the spread of disinfection by-products and anthropogenic bromoform emissions from ballast water discharge in Southeast Asia, Ocean Science, 15, 891-904, 10.5194/os-15-891-2019, 2019.
Ostermöller, J., Bönisch, H., Jöckel, P., and Engel, A.: A new time-independent formulation of fractional release, Atmos. Chem. Phys., 17, 3788-3797, 10.5194/acp-17-3785-2017, 2017.
Sheese, P.E., K. A. Walker, C. D. Boone, P. F. Bernath, L. Froidevaux, B. Funke, P. Raspollini, T. von Clarmann, ACE-FTS ozone, water vapour, nitrous oxide, nitric acid, and carbon monoxide profile comparisons with MIPAS and MLS, J. Quant. Spectrosc. and Radiat. Transfer, 186, 63-80, 10.1016/j.jqsrt.2016.06.026, 2017.
Thorenz, U. R., Baker, A. K., Leedham Elvidge, E. C., Sauvage, C., Riede, H., van Velthoven, P. F. J., Hermann, M., Weigelt, A., Oram, D. E., Brenninkmeijer, C. A. M., Zahn, A., and Williams, J.: Investigating African trace gas sources, vertical transport, and oxidation using IAGOS-CARIBIC measurements between Germany and South Africa between 2009 and 2011, Atmos. Env., 158, 11-26, 10.1016/j.atmosenv.2017.03.021, 2017.
Valeri, M., Barbara, F., Boone, C., Ceccherini, S., Gai, M., Maucher, G., Raspollini, P., Ridolfi, M., Sgheri, L., Wetzel, G., and Zoppetti, N.: CCl4 distribution derived from MIPAS ESA v7 data: Intercomparisons, trend, and lifetime estimation, Atmos. Chem. Phys., 17, 10143-10162, 10.5194/acp-17-10143-2017, 2017.
von Clarmann, T. and Johansson, S.: Chlorine nitrate in the atmosphere, Atmos. Chem. Phys., 18, 15363–15386, 10.5194/acp-18-15363-2018, 2018.
Werner, B., Stutz, J., Spolaor, M., Scalone, L., Raecke, R., Festa, J., Fedele Colosimo, S., Cheung, R., Tsai, C., Hossaini, R., Chipperfield, M. P., Taverna, G. S., Feng, W., Elkins, J. W., Fahey, D. W., Gao, R. S., Hintsa, E. J., Thornberry, T. D., Lee Moore, F., Navarro, M. A., Atlas, E., Daube, B. C., Pittman, J., Wofsy, S., and Pfeilsticker, K.: Probing the subtropical lowermost stratosphere and the tropical upper troposphere and tropopause layer for inorganic bromine, Atmos. Chem. Phys., 17, 1161-1186, 10.5194/acp-17-1161-2017, 2017.
Ziska, F., Quack, B., Tegtmeier, S., Stemmler, I., and Krüger, K.: Future emissions of marine halogenated very-short lived substances under climate change, J. Atmos. Chem., 74, 245-260, 10.1007/s10874-016-9355-3, 2017.

Data sets and trends

Arosio, C., Rozanov, A., Malinina, E., Weber, M., and Burrows, P. J.: Merging of ozone profiles from SCIAMACHY, OMPS and SAGE II observations to study stratospheric ozone changes, Atmos. Meas. Tech., 12, 2423-2444, 10.5194/amt-12-2423-2019, 2019.
Bernet, L., von Clarmann, T., Godin-Beekmann, S., Ancellet, G., Maillard Barras, E., Stübi, R., Steinbrecht, W., Kämpfer, N., and Hocke, K.: Ground-based ozone profiles over central Europe: incorporating anomalous observations into the analysis of stratospheric ozone trends, Atmos. Chem. Phys., 19, 4289–4309, 10.5194/acp-19-4289-2019, 2019.
Coldewey-Egbers, M., Loyola, D., Labow, G., and Frith, S.: Comparison of GTO-ECV and Adjusted-MERRA total ozone columns from the last two decades and assessment of interannual variability, Atmos. Meas. Tech. Discuss., in review, 2019.Galytska, E., Rozanov, A., Chipperfield, M. P., Dhomse, S. S., Weber, M., Arosio, C., Feng, W., and Burrows, J. P.: Dynamically controlled ozone decline in the tropical mid-stratosphere observed by SCIAMACHY, Atmos. Chem. Phys., 19, 767-783, 10.5194/acp-19-767-2019, 2019.
De Mazière M., Thompson A.M., Kurylo M.J., Wild J., Bernhard G., Blumenstock T., Braathen G., Hannigan J., Lambert J., Leblanc T., McGee T.J., Nedoluha G., Petropavlovskikh I., Seckmeyer G., Simon P.C., Steinbrecht W., Strahan S.: The Network for the Detection of Atmospheric Composition Change (NDACC): History, status and perspectives, Atmos. Chem. Phys., 18, 4935–4964, 2018
Laeng, A., von Clarmann, T., Stiller, G., Dinelli, B. M., Dudhia, A., Raspollini, P., Glatthor, N., Grabowski, U., Sofieva, V., Froidevaux, L., Walker, K. A., and Zehner, C.: Merged ozone profiles from four MIPAS processors, Atmos. Meas. Tech., 10, 1511–1518, 10.5194/amt-10-1511-2017, 2017.
Laeng, A., Eckert, E., von Clarmann, T., Kiefer, M., Hubert, D., Stiller, G., Glatthor, N., López-Puertas, M., Funke, B., Grabowski, U., Plieninger, J., Kellmann, S., Linden, A., Lossow, S., Babenhauserheide, A., Froidevaux, L., and Walker, K.: On the improved stability of the version 7 MIPAS ozone record, Atmos. Meas. Tech., 11, 4693–4705, 10.5194/amt-11-4693-2018, 2018
Garane K., Lerot C., Coldewey-Egbers M., Verhoelst T., Zyrichidou I., Balis D. S., Danckaert T., Goutail F., Granville J., Hubert D., Koukouli M. E., Keppens A., Lambert J.-C., Loyola D., Pommereau J.-P., Van Roozendael M., and Zehner C.: Quality assessment of the Ozone_cci Climate Research Data Package (release 2017): 1. Ground-based validation of total ozone column data products, Atmos. Meas. Tech., 11, 1385-1402, 2018.
Schneidereit, A., and Peters, D. H. W.: Long-term wintertime trend of zonally asymmetric ozone in boreal extratropics during 1979-2016, Atmosphere, 9, 10.3390/atmos9120468, 2018.
Sofieva, V. F., Kyrölä, E., Laine, M., Tamminen, J., Degenstein, D., Bourassa, A., Roth, C., Zawada, D., Weber, M., Rozanov, A., Rahpoe, N., Stiller, G., Laeng, A., von Clarmann, T., Walker, K. A., Sheese, P., Hubert, D., van Roozendael, M., Zehner, C., Damadeo, R., Zawodny, J., Kramarova, N., and Bhartia, P. K.: Merged SAGE II, Ozone_cci and OMPS ozone profile dataset and evaluation of ozone trends in the stratosphere, Atmos. Chem. Phys., 17, 12533–12552, 10.5194/acp-17-12533-2017, 2017.
Steinbrecht, W., et al.: An update on ozone profile trends for the period 2000 to 2016, Atmos. Chem. Phys., 17, 10675-10690, 10.5194/acp-17-10675-2017, 2017.

Steinbrecht, W., Hegglin, M. I., Harris, N., and Weber, M.: Is global ozone recovering?, Comptes Rendus - Geoscience, 350, 368-375, 10.1016/j.crte.2018.07.012, 2018.
Tao, M., Konopka, P., Ploeger, F., Yan, X., Wright, J. S., Diallo, M., Fueglistaler, S., and Riese, M.: Multitimescale variations in modeled stratospheric water vapor derived from three modern reanalysis products, Atmos. Chem. Phys., 19, 6509-6534, 10.5194/acp-19-6509-2019, 2019.
Weber, M., Coldewey-Egbers, M., Fioletov, V. E., Frith, S. M., Wild, J. D., Burrows, J. P., Long, C. S., and Loyola, D.: Total ozone trends from 1979 to 2016 derived from five merged observational datasets-the emergence into ozone recovery, Atmos. Chem. Phys., 18, 2097-2117, 10.5194/acp-18-2097-2018, 2018.
Zhou, M., Langerock, B., Wells, K. C., Millet, D. B., Vigouroux, C., Sha, M. K., Hermans, C., Metzger, J. M., Kivi, R., Heikkinen, P., Smale, D., Pollard, D. F., Jones, N., Deutscher, N. M., Blumenstock, T., Schneider, M., Palm, M., Notholt, J., Hannigan, J. W., and De Mazière, M.: An intercomparison of total column-averaged nitrous oxide between ground-based FTIR TCCON and NDACC measurements at seven sites and comparisons with the GEOS-Chem model, Atmos. Meas. Tech., 12, 1393-1408, 10.5194/amt-12-1393-2019, 2019.

Polar Ozone

Denton, M. H., Kivi, R., Ulich, T., Clilverd, M. A., Rodger, C. J., and von der Gathen, P.: Northern Hemisphere Stratospheric Ozone Depletion Caused by Solar Proton Events: The Role of the Polar Vortex, Geophys. Res. Lett., 45, 2115-2124, 10.1002/2017GL075966, 2018.
Grooß, J. U., Müller, R., Spang, R., Tritscher, I., Wegner, T., Chipperfield, M. P., Feng, W., Kinnison, D. E., and Madronich, S.: On the discrepancy of HCl processing in the core of the wintertime polar vortices, Atmos. Chem. Phys., 18, 8647-8666, 10.5194/acp-18-8647-2018, 2018.
Hoffmann, L., Spang, R., Orr, A., Joan Alexander, M., Holt, L. A., and Stein, O.: A decadal satellite record of gravity wave activity in the lower stratosphere to study polar stratospheric cloud formation, Atmos. Chem. Phys., 17, 2901-2920, 10.5194/acp-17-2901-2017, 2017.
Johansson, S., Woiwode, W., Höpfner, M., Friedl-Vallon, F., Kleinert, A., Kretschmer, E., Latzko, T., Orphal, J., Preusse, P., Ungermann, J., Santee, M. L., Jurkat-Witschas, T., Marsing, A., Voigt, C., Giez, A., Krämer, M., Rolf, C., Zahn, A., Engel, A., Sinnhuber, B. M., and Oelhaf, H.: Airborne limb-imaging measurements of temperature, HNO3, O3, ClONO2, H2O and CFC-12 during the Arctic winter 2015/2016: Characterization, in situ validation and comparison to Aura/MLS, Atmos. Meas. Tech., 11, 4737-4756, 10.5194/amt-11-4737-2018, 2018.
Johansson, S., Santee, M. L., Grooß, J. U., Höpfner, M., Braun, M., Friedl-Vallon, F., Khosrawi, F., Kirner, O., Kretschmer, E., Oelhaf, H., Orphal, J., Sinnhuber, B. M., Tritscher, I., Ungermann, J., Walker, K. A., and Woiwode, W.: Unusual chlorine partitioning in the 2015/16 Arctic winter lowermost stratosphere: Observations and simulations, Atmos. Chem. Phys., 19, 8311-8338, 10.5194/acp-19-8311-2019, 2019.
Jurkat, T., Voigt, C., Kaufmann, S., Grooß, J. U., Ziereis, H., Dörnbrack, A., Hoor, P., Bozem, H., Engel, A., Bönisch, H., Keber, T., Hüneke, T., Pfeilsticker, K., Zahn, A., Walker, K. A., Boone, C. D., Bernath, P. F., and Schlager, H.: Depletion of ozone and reservoir species of chlorine and nitrogen oxide in the lower Antarctic polar vortex measured from aircraft, Geophys. Res. Lett., 44, 6440-6449, 10.1002/2017GL073270, 2017.
Khosrawi, F., Kirner, O., Sinnhuber, B. M., Johansson, S., Höpfner, M., Santee, M. L., Froidevaux, L., Ungermann, J., Ruhnke, R., Woiwode, W., Oelhaf, H., and Braesicke, P.: Denitrification, dehydration and ozone loss during the 2015/2016 Arctic winter, Atmos. Chem. Phys., 17, 12893-12910, 10.5194/acp-17-12893-2017, 2017.
Khosrawi, F., Kirner, O., Stiller, G., Höpfner, M., Santee, M. L., Kellmann, S., and Braesicke, P.: Comparison of ECHAM5/MESSy Atmospheric Chemistry (EMAC) simulations of the Arctic winter 2009/2010 and 2010/2011 with Envisat/MIPAS and Aura/MLS observations, Atmos. Chem. Phys., 18, 8873-8892, 10.5194/acp-18-8873-2018, 2018.
Marsing, A., Jurkat-Witschas, T., Groo, J. U., Kaufmann, S., Heller, R., Engel, A., Hoor, P., Krause, J., and Voigt, C.: Chlorine partitioning in the lowermost Arctic vortex during the cold winter 2015/2016, Atmos. Chem. Phys., 19, 10757-10772, 10.5194/acp-19-10757-2019, 2019.
Meraner, K., and Schmidt, H.: Climate impact of idealized winter polar mesospheric and stratospheric ozone losses as caused by energetic particle precipitation, Atmos. Chem. Phys., 18, 1079-1089, 10.5194/acp-18-1079-2018, 2018.
Müller, R., Grooß, J. U., Mannan Zafar, A., Robrecht, S., and Lehmann, R.: The maintenance of elevated active chlorine levels in the Antarctic lower stratosphere through HCl null cycles, Atmos. Chem. Phys., 18, 2985-2997, 10.5194/acp-18-2985-2018, 2018.
Schütze, K., Charles Wilson, J., Weinbruch, S., Benker, N., Ebert, M., Günther, G., Weigel, R., and Borrmann, S.: Sub-micrometer refractory carbonaceous particles in the polar stratosphere, Atmos. Chem. Phys., 17, 12475-12493, 10.5194/acp-17-12475-2017, 2017.
Oelhaf, H., Sinnhuber, B.-M., Woiwode, W., Bönisch, H., Bozem, H., Engel, A., Fix, A.,, Friedl-Vallon, F., Grooß, J.-U., Hoor, P., Johansson, S., Jurkat-Witschas, T., Kaufmann, S., Krämer, M.,, Krause, J., Kretschmer, E., Lörks, D., Marsing, A., Orphal, J., Pfeilsticker, K., Pitts, M., Poole, L., Preusse, P., Rapp, M., Riese, M., Rolf, C., Ungermann, J., Voigt, C., Volk, C.M., Wirth, M., Zahn, A., and Ziereis, H.: POLSTRACC: Airborne experiment for studying the Polar Stratosphere in a Changing Climate with the high-altitude long-range research aircraft HALO, POLSTRACC: Airborne experiment for studying the Polar Stratosphere in a Changing Climate with the high-altitude long-range research aircraft HALO, Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-18-0181.1, 2019.
Sinnhuber, M., Berger, U., Funke, B., Nieder, H., Reddmann, T., Stiller, G., Versick, S., Von Clarmann, T., and Wissing, J. M.: NOy production, ozone loss and changes in net radiative heating due to energetic particle precipitation in 2002-2010, Atmos. Chem. Phys., 18, 1115-1147, 10.5194/acp-18-1115-2018, 2018.
Tritscher, I., Grooß, 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.
Wetzel, G., Oelhaf, H., Höpfner, M., Friedl-Vallon, F., Ebersoldt, A., Gulde, T., Kazarski, S., Kirner, O., Kleinert, A., Maucher, G., Nordmeyer, H., Orphal, J., Ruhnke, R., and Sinnhuber, B. M.: Diurnal variations of BrONO2 observed by MIPAS-B at midlatitudes and in the Arctic, Atmos. Chem. Phys., 17, 14631-14643, 10.5194/acp-17-14631-2017, 2017.
Wohltmann, I., Lehmann, R., and Rex, M.: A quantitative analysis of the reactions involved in stratospheric ozone depletion in the polar vortex core, Atmos. Chem. Phys., 17, 10535-10563, 10.5194/acp-17-10535-2017, 2017.

Wohltmann, I., Lehmann, R., and Rex, M.: Update of the Polar SWIFT model for polar stratospheric ozone loss (Polar SWIFT version 2), Geosci. Model Dev., 10, 2671-2689, 10.5194/gmd-10-2671-2017, 2017.
Woiwode, W., Höpfner, M., Bi, L., Khosrawi, F., and Santee, M. L.: Vortex-Wide Detection of Large Aspherical NAT Particles in the Arctic Winter 2011/12 Stratosphere, Geophys. Res. Lett., 46, 13420-13429, 10.1029/2019GL084145, 2019.
Zafar, A. M., Müller, R., Grooss, J. U., Robrecht, S., Vogel, B., and Lehmann, R.: The relevance of reactions of the methyl peroxy radical (CH3O2) and methylhypochlorite (CH3OCl) for Antarctic chlorine activation and ozone loss, Tellus, B: Chem. Phys. Meteorol., 70, 1-18, 10.1080/16000889.2018.1507391, 2018.

Asian Monsoon and Tibetan Plateau

Brunamonti, S., Jorge, T., Oelsner, P., Hanumanthu, S., Singh, B. B., Ravi Kumar, K., Sonbawne, S., Meier, S., Singh, D., Wienhold, F. G., Ping Luo, B., Boettcher, M., Poltera, Y., Jauhiainen, H., Kayastha, R., Karmacharya, J., Dirksen, R., Naja, M., Rex, M., Fadnavis, S., and Peter, T.: Balloon-borne measurements of temperature, water vapor, ozone and aerosol backscatter on the southern slopes of the Himalayas during StratoClim 2016-2017, Atmos. Chem. Phys., 18, 15937-15957, 10.5194/acp-18-15937-2018, 2018.
Höpfner, M., J. Ungermann, S. Borrmann, R. Wagner, R. Spang, Martin Riese, G. Stiller, O. Appel, A. Batenburg, S. Bucci, F. Cairo, A. Dragoneas, F. Friedl-Vallon, A. Hünig, S. Johansson, L. Krasaukas, B. Legras, T. Leisner, C. Mahnke, O. Moehler, S. Molleker, R. Müller, T. Neubert, J. Orphal, P. Preusse, M. Rex, H. Saathoff, F. Stroh, R. Weigel, and I. Wohltmann, Ammonium nitrate particles formed in upper troposphere sourced from ground ammonia during Asian monsoons, Nature Geoscience, 12, 10.1038/s41561-019-0385-8, 2019.
Lelieveld, J., Bourtsoukidis, E., Brühl, C., Fischer, H., Fuchs, H., Harder, H., Hofzumahaus, A., Holland, F., Marno, D., Neumaier, M., Pozzer, A., Schlager, H., Williams, J., Zahn, A., and Ziereis, H.: The south asian monsoon—pollution pump and purifier, Science, 361, 270-273, 10.1126/science.aar2501, 2018.
Li, D., Vogel, B., Müller, R., Bian, J., Günther, G., Li, Q., Zhang, J., Bai, Z., Vömel, H., and Riese, M.: High tropospheric ozone in Lhasa within the Asian summer monsoon anticyclone in 2013: Influence of convective transport and stratospheric intrusions, Atmos. Chem. Phys., 18, 17979-17994, 10.5194/acp-18-17979-2018, 2018.
Škerlak, B., Pfahl, S., Sprenger, M., and Wernli, H.: A numerical process study on the rapid transport of stratospheric air down to the surface over western North America and the Tibetan Plateau, Atmos. Chem. Phys., 19, 6535-6549, 10.5194/acp-19-6535-2019, 2019.
Y Vogel, B., Müller, R., Günther, G., Spang, R., Hanumanthu, S., Li, D., Riese, M., and Stiller, G. P.: Lagrangian simulations of the transport of young air masses to the top of the Asian monsoon anticyclone and into the tropical pipe, Atmos. Chem. Phys., 19, 6007–6034, https://doi.org/10.5194/acp-19-6007-2019, 2019.
Yan, X., Konopka, P., Ploeger, F., Tao, M., Müller, R., Santee, M. L., Bian, J., and Riese, M.: El Niño Southern Oscillation influence on the Asian summer monsoon anticyclone, Atmos. Chem. Phys., 18, 8079-8096, 10.5194/acp-18-8079-2018, 2018.

Upper Troposphere – Lower Stratosphere and Tropical Tropopause Layer

Charlesworth, E. J., Birner, T., and Albers, J. R.: Ozone Transport-Radiation Feedbacks in the Tropical Tropopause Layer, Geophys. Res. Lett., 46, 14195-14202, 10.1029/2019GL084679, 2019.
Chipperfield M.P., Dhomse S., Hossaini R, Feng W., Santee M.L., Weber M., Burrows J.P., Wild J.D., Loyola D., Coldewey-Egbers M.: On the Cause of Recent Variations in Lower Stratospheric Ozone, Geophysical Research Letters, vol. 45, 2018
Dacie, S., Kluft, L., Schmidt, H., Stevens, B., Buehler, S. A., Nowack, P. J., Dietmüller, S., Abraham, N. L., and Birner, T.: A 1D RCE study of factors affecting the tropical tropopause layer and surface climate, J. Clim., 32, 6769-6782, 10.1175/JCLI-D-18-0778.1, 2019.
Heller, R., Voigt, C., Beaton, S., Dörnbrack, A., Giez, A., Kaufmann, S., Mallaun, C., Schlager, H., Wagner, J., Young, K., and Rapp, M.: Mountain waves modulate the water vapor distribution in the UTLS, Atmos. Chem. Phys., 17, 14853-14869, 10.5194/acp-17-14853-2017, 2017.
Robrecht, S., Vogel, B., Grooß, J. U., Rosenlof, K., Thornberry, T., Rollins, A., Krämer, M., Christensen, L., and Müller, R.: Mechanism of ozone loss under enhanced water vapour conditions in the mid-latitude lower stratosphere in summer, Atmos. Chem. Phys., 19, 5805-5833, 10.5194/acp-19-5805-2019, 2019.
Roy, C., Fadnavis, S., Müller, R., Ayantika, D. C., Ploeger, F., and Rap, A.: Influence of enhanced Asian NOx emissions on ozone in the upper troposphere and lower stratosphere in chemistry-climate model simulations, Atmos. Chem. Phys., 17, 1297-1311, 10.5194/acp-17-1297-2017, 2017.
Woiwode, W., Dörnbrack, A., Bramberger, M., Friedl-Vallon, F., Haenel, F., Höpfner, M., Johansson, S., Kretschmer, E., Krisch, I., Latzko, T., Oelhaf, H., Orphal, J., Preusse, P., Sinnhuber, B. M., and Ungermann, J.: Mesoscale fine structure of a tropopause fold over mountains, Atmos. Chem. Phys., 18, 15643-15667, 10.5194/acp-18-15643-2018, 2018.

Modelling and Climate Change

Dhomse, S. S., Kinnison, D., Chipperfield, M. P., Salawitch, R. J., Cionni, I., Hegglin, M. I., Abraham, N. L., Akiyoshi, H., Archibald, A. T., Bednarz, E. M., Bekki, S., Braesicke, P., Butchart, N., Dameris, M., Deushi, M., Frith, S., Hardiman, S. C., Hassler, B., Horowitz, L. W., Hu, R. M., Jöckel, P., Josse, B., Kirner, O., Kremser, S., Langematz, U., Lewis, J., Marchand, M., Lin, M., Mancini, E., Marécal, V., Michou, M., Morgenstern, O., O'Connor, F. M., Oman, L., Pitari, G., Plummer, D. A., Pyle, J. A., Revell, L. E., Rozanov, E., Schofield, R., Stenke, A., Stone, K., Sudo, K., Tilmes, S., Visioni, D., Yamashita, Y., and Zeng, G.: Estimates of ozone return dates from Chemistry-Climate Model Initiative simulations, Atmos. Chem. Phys., 18, 8409-8438, 10.5194/acp-18-8409-2018, 2018.
Harari, O., Garfinkel, C. I., Ziskin Ziv, S., Morgenstern, O., Zeng, G., Tilmes, S., Kinnison, D., Deushi, M., Jöckel, P., Pozzer, A., O'Connor, F. M., and Davis, S.: Influence of Arctic stratospheric ozone on surface climate in CCMI models, Atmos. Chem. Phys., 19, 9253-9268, 10.5194/acp-19-9253-2019, 2019.
Kreyling, D., Wohltmann, I., Lehmann, R., and Rex, M.: The Extrapolar SWIFT model (version 1.0): Fast stratospheric ozone chemistry for global climate models, Geosci. Model Dev., 11, 753-769, 10.5194/gmd-11-753-2018, 2018.

Langematz, U.: Future ozone in a changing climate, Comptes Rendus - Geoscience, 350, 403-409, 10.1016/j.crte.2018.06.015, 2018.
Langematz, U.: Stratospheric ozone: down and up through the anthropocene, ChemTexts, 5, 10.1007/s40828-019-0082-7, 2019.
Maronga B., Banzhaf S., Burmeister C., Esch T., Forkel R., Fröhlich D., Fuka V., Gehrke K., Geleti J., Giersch S., Gronemeier T., Groß G., Heldens W., Hellsten A., Hoffmann F., InagakiA., Kadasch E., Kanani- Sühring F. Ketelsen K., Khan B., Knigge C, Knoop H., Krˇ P., Kurppa M., Maamari H., Matzarakis A., Mauder M., Pallasch M., Pavlik D., Pfafferott J., Resler J., Rissmann S., Russo E., Salim M., Schrempf M., Schwenkel J., Seckmeyer G., Schubert S., Sühring M., vonTils R., Vollmer L., Ward S. Witha B., Wurp H., Zeidler J., Raasch S.: The PALM model system 6.0 for atmospheric and oceanic boundary-layer flows: model description and applications in urban environments, Geosci. Model Dev., 13, 1–38, 2020 https://doi.org/10.5194/gmd-13-1-2020, 2020.
Maronga B., Gross G., Raasch S., Banzhaf S., Forkel R., Helden W., Kanani-Suehring F., Matzarakis A., Mauder M., Pavlik D., Pfafferott J., Schubert S., Seckmeyer G., Sieker H., Trusilov K.: Development of a new urban climate model based on the model PALM - Project overview, planned work, and first achievements, Met.Zeitschrift, DOI 10.1127/metz/2019/0909, 2019
Matthes, K., Funke, B., Andersson, M. E., Barnard, L., Beer, J., Charbonneau, P., Clilverd, M. A., Dudok De Wit, T., Haberreiter, M., Hendry, A., Jackman, C. H., Kretzschmar, M., Kruschke, T., Kunze, M., Langematz, U., Marsh, D. R., Maycock, A. C., Misios, S., Rodger, C. J., Scaife, A. A., Seppälä, A., Shangguan, M., Sinnhuber, M., Tourpali, K., Usoskin, I., Van De Kamp, M., Verronen, P. T., and Versick, S.: Solar forcing for CMIP6 (v3.2), Geosci. Model Dev., 10, 2247-2302, 10.5194/gmd-10-2247-2017, 2017.
Maycock, A. C., Matthes, K., Tegtmeier, S., Schmidt, H., Thiéblemont, R., Hood, L., Akiyoshi, H., Bekki, S., Deushi, M., Jöckel, P., Kirner, O., Kunze, M., Marchand, M., Marsh, D. R., Michou, M., Plummer, D., Revell, L. E., Rozanov, E., Stenke, A., Yamashita, Y., and Yoshida, K.: The representation of solar cycle signals in stratospheric ozone - Part 2: Analysis of global models, Atmos. Chem. Phys., 18, 11323-11343, 10.5194/acp-18-11323-2018, 2018.
Meul, S., Langematz, U., Kröger, P., Oberländer-Hayn, S., and Jöckel, P.: Future changes in the stratosphere-to-troposphere ozone mass flux and the contribution from climate change and ozone recovery, Atmos. Chem. Phys., 18, 7721-7738, 10.5194/acp-18-7721-2018, 2018.
Nowack, P. J., Braesicke, P., Luke Abraham, N., and Pyle, J. A.: On the role of ozone feedback in the ENSO amplitude response under global warming, Geophys. Res. Lett., 44, 3858-3866, 10.1002/2016GL072418, 2017.
Nowack, P., Braesicke, P., Haigh, J., Abraham, N. L., Pyle, J., and Voulgarakis, A.: Using machine learning to build temperature-based ozone parameterizations for climate sensitivity simulations, Env. Res. Lett., 13, 10.1088/1748-9326/aae2be, 2018.
Nowack, P. J., Abraham, N. L., Braesicke, P., and Pyle, J. A.: The Impact of Stratospheric Ozone Feedbacks on Climate Sensitivity Estimates, J. Geophys. Res., 123, 4630-4641, 10.1002/2017JD027943, 2018.
Pohlmann, H., Müller, W. A., Bittner, M., Hettrich, S., Modali, K., Pankatz, K., and Marotzke, J.: Realistic Quasi-Biennial Oscillation Variability in Historical and Decadal Hindcast Simulations Using CMIP6 Forcing, Geophys. Res. Lett., 46, 14118-14125, 10.1029/2019GL084878, 2019.
Polvani, L. M., Wang, L., Abalos, M., Butchart, N., Chipperfield, M. P., Dameris, M., Deushi, M., Dhomse, S. S., Jöckel, P., Kinnison, D., Michou, M., Morgenstern, O., Oman, L. D., Plummer, D. A., and Stone, K. A.: Large Impacts, Past and Future, of Ozone-Depleting Substances on Brewer-Dobson Circulation Trends: A Multimodel Assessment, J. Geophys. Res., 124, 6669-6680, 10.1029/2018JD029516, 2019.
Rieger, V. S., Mertens, M., and Grewe, V.: An advanced method of contributing emissions to short-lived chemical species (OH and HO2): The TAGGING 1.1 submodel based on the Modular Earth Submodel System (MESSy 2.53), Geosci. Model Dev., 11, 2049-2066, 10.5194/gmd-11-2049-2018, 2018.
Schrempf M., Haluza D., Simic S., Riechelmann S., Graw K., Seckmeyer G.: Is multidirectional UV exposure responsible for increasing melanoma prevalence with altitude? A Hypothesis Based on Calculations with a 3D-Human Exposure Model, A novel method to calculate solar UV exposure relevant to vitamin D production in humans, Int. J. Environ. Res. Public Health, 2016
Schrempf M., Thuns N., Lange K., Seckmeyer G.: Impact of Orientation on the Vitamin D Weighted Exposure of a Human in an Urban Environment, Int. J. Environ. Res. Public Health, 14(8), 920; doi:10.3390/ijerph14080920, 2017
Schröter, J., Rieger, D., Stassen, C., Vogel, H., Weimer, M., Werchner, S., Förstner, J., Prill, F., Reinert, D., Zängl, G., Giorgetta, M., Ruhnke, R., Vogel, B., and Braesicke, P.: ICON-ART 2.1: a flexible tracer framework and its application for composition studies in numerical weather forecasting and climate simulations, Geosci. Model Dev., 11, 4043–4068, https://doi.org/10.5194/gmd-11-4043-2018, 2018.
Seckmeyer G., Mustert C., Schrempf M., McKenzie R.L., Liley B.J., Kotkamp M., Bais A.F., Gillotay D., Slaper H., Siani A-M., Smedley A.R.D., Webb A.: Why is it so hard to gain enough Vitamin D by solar exposure in the European winter?, Met.Zeitschrift, DOI 10.1127/metz/2018/0855, 27(3), 2018
Weimer, M., Schröter, J., Eckstein, J., Deetz, K., Neumaier, M., Fischbeck, G., Hu, L., Millet, D. B., Rieger, D., Vogel, H., Vogel, B., Reddmann, T., Kirner, O., Ruhnke, R., and Braesicke, P.: An emission module for ICON-ART 2.0: implementation and simulations of acetone, Geosci. Model Dev., 10, 2471–2494, https://doi.org/10.5194/gmd-10-2471-2017, 2017.
Winterstein, F., Tanalski, F., Jöckel, P., Dameris, M., and Ponater, M.: Implication of strongly increased atmospheric methane concentrations for chemistry-climate connections, Atmos. Chem. Phys., 19, 7151-7163, 10.5194/acp-19-7151-2019, 2019.

Dynamics and Brewer Dobson Circulation

Diallo, M., Riese, M., Birner, T., Konopka, P., Müller, R., Hegglin, M. I., Santee, M. L., Baldwin, M., Legras, B., and Ploeger, F.: Response of stratospheric water vapor and ozone to the unusual timing of El Niño and the QBO disruption in 2015-2016, Atmos. Chem. Phys., 18, 13055-13073, 10.5194/acp-18-13055-2018, 2018.
Diallo, M., Konopka, P., Santee, M. L., Müller, R., Tao, M., Walker, K. A., Legras, B., Riese, M., Ern, M., and Ploeger, F.: Structural changes in the shallow and transition branch of the Brewer-Dobson circulation induced by El Niño, Atmos. Chem. Phys., 19, 425-446, 10.5194/acp-19-425-2019, 2019.
Funke, B., Ball, W., Bender, S., Gardini, A., Lynn Harvey, V., Lambert, A., López-Puertas, M., Marsh, D. R., Meraner, K., Nieder, H., Paivarinta, S. M., Pérot, K., Randall, C. E., Reddmann, T., Rozanov, E., Schmidt, H., Seppälä, A., Sinnhuber, M., Sukhodolov, T., Stiller, G. P., Tsvetkova, N. D., Verronen, P. T., Versick, S., Von Clarmann, T., Walker, K. A., and Yushkov, V.: HEPPA-II model-measurement intercomparison project: EPP indirect effects during the dynamically perturbed NH winter 2008/2009, Atmos. Chem. Phys., 17, 3573-3604, 10.5194/acp-17-3573-2017, 2017.
Haase, S., and Matthes, K.: The importance of interactive chemistry for stratosphere-troposphere coupling, Atmos. Chem. Phys., 19,

3417-3432, 10.5194/acp-19-3417-2019, 2019.
Kunkel, D., Hoor, P., Kaluza, T., Ungermann, J., Kluschat, B., Giez, A., Lachnitt, H. C., Kaufmann, M., and Riese, M.: Evidence of small-scale quasi-isentropic mixing in ridges of extratropical baroclinic waves, Atmos. Chem. Phys., 19, 12607-12630, 10.5194/acp-19-12607-2019, 2019.
Linz, M., R.A. Plumb, E.P. Gerber, F.J. Haenel, G. Stiller, D.E. Kinnison, A. Ming, J. Neu, S. Solomon, The strength of the diabatic circulation of the stratosphere, Nature Geoscience, 10, 663-667, doi: 10.1038/ngeo3013, 2017.
Lubis, S. W., Silverman, V., Matthes, K., Harnik, N., Omrani, N. E., and Wahl, S.: How does downward planetary wave coupling affect polar stratospheric ozone in the Arctic winter stratosphere?, Atmos. Chem. Phys., 17, 2437-2458, 10.5194/acp-17-2437-2017, 2017.
Peters, D. H. W., Schneidereit, A., and Karpechko, A. Y.: Enhanced stratosphere/troposphere coupling during extreme warm stratospheric events with strong polar-night jet oscillation, Atmosphere, 9, 10.3390/atmos9120467, 2018.
Romanowsky, E., Handorf, D., Jaiser, R., Wohltmann, I., Dorn, W., Ukita, J., Cohen, J., Dethloff, K., and Rex, M.: The role of stratospheric ozone for Arctic-midlatitude linkages, Sci. Rep., 9, 10.1038/s41598-019-43823-1, 2019.
Stiller, G. P., Fierli, F., Ploeger, F., Cagnazzo, C., Funke, B., Haenel, F. J., Reddmann, T., Riese, M., and von Clarmann, T.: Shift of subtropical transport barriers explains observed hemispheric asymmetry of decadal trends of age of air, Atmos. Chem. Phys., 17, 11177–11192, 10.5194/acp-17-11177-2017, 2017.
Thiéblemont, R., Ayarzagüena, B., Matthes, K., Bekki, S., Abalichin, J., and Langematz, U.: Drivers and Surface Signal of Interannual Variability of Boreal Stratospheric Final Warmings, J. Geophys. Res., 124, 5400-5417, 10.1029/2018JD029852, 2019.

New Instruments & Retrievals

Arosio, C., Rozanov, A., Malinina, E., Eichmann, K. U., Von Clarmann, T., and Burrows, J. P.: Retrieval of ozone profiles from OMPS limb scattering observations, Atmos. Meas. Tech., 11, 2135-2149, 10.5194/amt-11-2135-2018, 2018.
Eleftheratos, K., Zerefos, C. S., Balis, D. S., Koukouli, M.-E., Kapsomenakis, J., Loyola, D. G., Valks, P., Coldewey-Egbers, M., Lerot, C., Frith, S. M., Søvde-Haslerud, A., Isaksen, I. S. A., and Hassinen, S.: The use of QBO, ENSO, and NAO perturbations in the evaluation of GOME-2 MetOp A total ozone measurements, Atmos. Meas. Tech., 12, 987-1011, 2019.
Fix, A., Steinebach, F., Wirth, M., Schäfler, A., and Ehret, G.: Development and application of an airborne differential absorption lidar for the simultaneous measurement of ozone and water vapor profiles in the tropopause region, Appl. Opt., 58, 5892-5900, 10.1364/AO.58.005892, 2019.
Garane, K., Koukouli, M.-E., Verhoelst, T., Lerot, C., Heue, K.-P., Fioletov, V., Balis, D., Bais, A., Bazureau, A., Dehn, A., Goutail, F., Granville, J., Griffin, D., Hubert, D., Keppens, A., Lambert, J.-C., Loyola, D., McLinden, C., Pazmino, A., Pommereau, J.-P., Redondas, A., Romahn, F., Valks, P., Van Roozendael, M., Xu, J., Zehner, C., Zerefos, C., and Zimmer, W.: TROPOMI/S5P total ozone column data: global ground-based validation and consistency with other satellite missions, Atmos. Meas. Tech., 12, 5263–5287, 2019.
Glatthor, N., von Clarmann, T., Stiller, G. P., Kiefer, M., Laeng, A., Dinelli, B. M., Wetzel, G., and Orphal, J.: Differences in ozone retrieval in MIPAS channels A and AB: a spectroscopic issue, Atmos. Meas. Tech., 11, 4707–4723, 10.5194/amt-11-4707-2018, 2018.
Inness, A., Flemming, J., Heue, K.-P., Lerot, C., Loyola, D., Ribas, R., Valks, P., van Roozendael, M., Xu, J., and Zimmer, W.: Monitoring and assimilation tests with TROPOMI data in the CAMS system: near-real-time total column ozone, Atmos. Chem. Phys., 19, 3939-3962, 2019
Hüneke, T., Aderhold, O.-A., Bounin, J., Dorf, M., Gentry, E., Grossmann, K., Grooß, J.-U., Hoor, P., Jöckel, P., Kenntner, M., Knapp, M., Knecht, M., Lörks, D., Ludmann, S., Raecke, R., Reichert, M., Weimar, J., Werner, B., Zahn, A., Ziereis, H., and Pfeilsticker, K.: The novel HALO mini-DOAS instrument: Inferring trace gas concentrations from air-borne UV/visible limb spectroscopy under all skies using the scaling method, Atmos. Meas. Tech., 10, 4209-4234, doi:10.5194/amt-10-4209-2017, 2017.
Liu, S., Valks, P., Pinardi, G., De Smedt, I., Yu, H., Beirle, S., and Richter, A.: An improved total and tropospheric NO2 column retrieval for GOME-2, Atmos. Meas. Tech., 12, 1029-1057, 10.5194/amt-12-1029-2019, 2019.
Seckmeyer G., Lagos Rivas L., Gaetani C., Heinzel J.W., Schrempf M.: Biologische und medizinische Wirkungen solarer Strahlung (Biological and medical effects of solar radiation), in Promet, Heft 100, Strahlungsbilanzen, Chapter 13, Deutscher Wetterdienst (DWD), 2018
Stutz, J., Werner, B., Spolaor, M., Scalone, L., Festa, J., Tsai, C., Cheung, R., Colosimo, S. F., Tricoli, U., Raecke, R., Hossaini, R., Chipperfield, M. P., Feng, W., Gao, R. S., Hintsa, E. J., Elkins, J. W., Moore, F. L., Daube, B., Pittman, J., Wofsy, S., and Pfeilsticker, K.: A new Differential Optical Absorption Spectroscopy instrument to study atmospheric chemistry from a high-altitude unmanned aircraft, Atmos. Meas. Tech., 10, 1017-1042, 10.5194/amt-10-1017-2017, 2017.
Xu, J., Schreier, F., Wetzel, G., de Lange, A., Birk, M., Trautmann, T., Doicu, A., and Wagner, G.: Performance assessment of balloon-borne trace gas sounding with the terahertz channel of TELIS, Remote Sensing, 10, 10.3390/rs10020315, 2018.
Xu J., Schüssler O., Loyola D., Romahn F., and Doicu A.: A Novel Ozone Profile Shape Retrieval Using Full-Physics Inverse Learning Machine (FP-ILM), IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 10, no. 12, pp. 5442-5447, 2017.
Zuber, R., Sperfeld, P., Riechelmann, S., Nevas, S., Sildoja, M. and Seckmeyer, G.: Adaption of an array spectroradiometer for total ozone column retrieval using direct solar irradiance measurements in the UV spectral range, Atmos. Meas. Tech., 11, 2477-2484, 10.5194/amt-11-2477-2018, 2018.
Zuber R., Sperfeld P., Riechelmann S., Nevas S., Sildoja M., Seckmeyer G.: Adaption of an array spectroradiometer for total ozone column retrieval using direct solar irradiance measurements in the UV spectral range, Atmos. Meas. Tech., 11, 2477-2484, https://doi.org/10.5194/amt-11-2477-2018, 2018
Zuber R., Stührmann A., Gugg-Helminger A., Seckmeyer G.: Technology for detecting spectral radiance by a snapshot multi-imaging spectroradiometer, Measurement Science and Technology, 2017

Stratospheric Aerosol & Geo-Engineering

Ansmann, A., Baars, H., Chudnovsky, A., Mattis, I., Veselovskii, I., Haarig, M., Seifert, P., Engelmann, R., and Wandinger, U.: Extreme levels of Canadian wildfire smoke in the stratosphere over central Europe on 21-22 August 2017, Atmos. Chem. Phys.,

18, 11831-11845, 10.5194/acp-18-11831-2018, 2018.
Brenna, H., Kutterolf, S., and Krüger, K.: Global ozone depletion and increase of UV radiation caused by pre-industrial tropical volcanic eruptions, Sci. Rep., 9, 10.1038/s41598-019-45630-0, 2019.
Brühl, C., Schallock, J., Klingmüller, K., Robert, C., Bingen, C., Clarisse, L., Heckel, A., North, P., and Rieger, L.: Stratospheric aerosol radiative forcing simulated by the chemistry climate model EMAC using Aerosol CCI satellite data, Atmos. Chem. Phys., 18, 12845-12857, 10.5194/acp-18-12845-2018, 2018.
Fadnavis, S., Müller, R., Kalita, G., Rowlinson, M., Rap, A., Li, J. L. F., Gasparini, B., and Laakso, A.: The impact of recent changes in Asian anthropogenic emissions of SO2 on sulfate loading in the upper troposphere and lower stratosphere and the associated radiative changes, Atmos. Chem. Phys., 19, 9989-10008, 10.5194/acp-19-9989-2019, 2019.
Glatthor, N., Höpfner, M., Leyser, A., Stiller, G. P., von Clarmann, T., Grabowski, U., Kellmann, S., Linden, A., Sinnhuber, B.-M., Krysztofiak, G., and Walker, K. A.: Global carbonyl sulfide (OCS) measured by MIPAS/Envisat during 2002–2012, Atmos. Chem. Phys., 17, 2631–2652, 10.5194/acp-17-2631-2017, 2017.
Günther, A., Höpfner, M., Sinnhuber, B.-M., Griessbach, S., Deshler, T., von Clarmann, T., and Stiller, G.: MIPAS observations of volcanic sulfate aerosol and sulfur dioxide in the stratosphere, Atmos. Chem. Phys., 18, 1217–1239, 10.5194/acp-18-1217-2018, 2018.
Malinina, E., Rozanov, A., Rozanov, V., Liebing, P., Bovensmann, H., and Burrows, J.P.: Aerosol particle size distribution in the stratosphere retrieved from SCIAMACHY limb measurements, Atmos. Meas. Tech., 11, 2085-2100, 10.5194/amt-11-2085-2018, 2018.
Martinsson, B. G., J. Friberg, O. S. Sandvik, M. Hermann, P. F. J. van Velthoven, and A. Zahn, Particulate sulfur in the upper troposphere and lowermost stratosphere – sources and climate forcing, Atmos. Chem. Phys., 17, 10937–10953, 10.5194/acp-17-10937-2017, 2017.
Martinsson, B. G., J. Friberg, O. S. Sandvik, M. Hermann, P. F. J. van Velthoven, and A. Zahn, Formation and composition of the UTLS aerosol, npj climate and atmospheric science, 2:40, 10.1038/s41612-019-0097-1, 2019.
Niemeier, U., and Tilmes, S.: Sulfur injections for a cooler planet, Science, 357, 246-248, 10.1126/science.aan3317, 2017.
Rollins, A. W., T. D. Thornberry, L. A. Watts, P. Yu, K. H. Rosenlof, M. Mills, E. Baumann, F. R. Giorgetta, T. V. Bui, M. Höpfner, K. A. Walker, C. Boone, P. F. Bernath, P. R. Colarco, P. A. Newman, D. W. Fahey, R. S. Gao, The role of sulfur dioxide in stratospheric aerosol formation evaluated by using in situ measurements in the tropical lower stratosphere, Geophys. Res. Lett., 44, 4280– 4286, 10.1002/2017GL072754, 2017.
Sandvik, O. S., J. Friberg, B. G. Martinsson, P. F. J. van Velthoven, M. Hermann, and A. Zahn, Intercomparison of in-situ aircraft and satellite aerosol measurements in the stratosphere, Nature Scientific reports, 9: 15576, 10.1038/s41598-019-52089-6, 2019.

5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING
(e.g., national projects, international projects, other collaboration (nationally, internationally))

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.

In the EU project StratClim (coordinated by AWI) aircraft measurements were carried out in summer 2017 in the upper troposphere and lower stratosphere of the Asian Summer Monsoon region, using the high altitude research aircraft M55 Geophysica, along with regular balloon soundings. A large number of profiles and horizontal segments of ozone, aerosol and cloud particles, and a complete set of relevant gaseous species were measured (see www.stratoclim.org). The aircraft campaign was led by FZ-Jülich, DLR, and CNR (Italy). Other partners were MPI-C, KIT, AWI, the Universities Mainz, Darmstadt, and Wuppertal, as well as six other European institutes. The balloons were launched by ETH-Z (Switzerland) and AWI.

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.

National DFG Research Unit Vol-Impact (FOR 2820): Revisiting the volcanic impact on atmosphere and climate – preparations for the next big volcanic eruption. Participants: GEOMAR Kiel, KIT, MPI-M, U Bremen, U Greifswald, U Hamburg, U Leipzig, U Edinburgh, NASA Langley Research Center.

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/

DLR, Deutsches Zentrum für Luft- und Raumfahrt, Earth Observation Center, https://www.dlr.de/eoc/; Institut für Physik der Atmosphäre, https://www.dlr.de/pa/

DWD, Deutscher Wetterdienst, www.dwd.de/ozon

FU Berlin, Institut für Meteorologie Freie Universität Berlin, https://www.geo.fu-berlin.de/met

FZ Jülich, Forschungszentrum Jülich, IEK7 Stratosphäre, https://www.fz-juelich.de/iek/iek-7/DE/Home/home_node.html; IEK8 Troposphäre, https://www.fz-juelich.de/iek/iek-8/DE/Home/home_node.html

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/

U Bremen, Institut für Umweltphysik Universität Bremen, 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

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

U Heidelberg, Institut für Umweltphysik Universität Heidelberg, https://www.iup.uni-heidelberg.de/de/institute/atmosphere

U Mainz, Institut für Physik der Atmosphäre Universität Mainz, https://www.ipa.uni-mainz.de

TROPOS, Leibniz Institut für Troposphären Forschung, https://www.tropos.de/