

German National Report to the 10th meeting of WMO/UNEP Ozone Research Managers, Geneva, 28-30 March 2017

German agencies and institutes remain active in ozone and UV monitoring and research. they regularly contribute to the WMO/UNEP Scientific Assessments, and to Scientific Working and Advisory Groups. Table 1 summarizes institutes and their activities. Generally, universities and research centers (MPI, DLR, KIT, FZ-Jülich, AWI) are more research and project oriented. Government agencies (DWD, BfS, UBA) are more focused on long-term measurements and monitoring. Germany is a key player for several satellite instruments (SCIAMACHY, MIPAS, GOME-2/MetOp-A,B,C). It is also supporting international quality-assurance and quality-control activities by hosting the World Calibration Centre for Ozone Sonde (WCCOS) and the WMO RA VI Regional Dobson Calibration Center (RDCC-E, in cooperation with the Czech Republic).

Table 1 German Institutes involved in ozone/UV research (R), development (D), modeling (MD), monitoring (MT), quality assessment /quality control (QA/QC)

Institute	Location	Fields	Keywords
Deutscher Wetterdienst (DWD) www.dwd.de	Hohenpeissenberg, Lindenberg	MT, R, QA/QC	RDCC-E, NDACC, GAW
Alfred Wegener Institut für Polar u. Meeresforschung (AWI) www.awi.de	Potsdam, Bremerhaven	R, MT, MD, D	Neumayer, Ny Ålesund, Polarstern, Palau, ATLAS, MATCH
Forschungszentrum Jülich (FZJ) www.fz-juelich.de	Jülich	R, QA/QC, MD	Calibration O ₃ -Sonde, JOSIE, CLaMS
MPI f. Meteorologie (DKRZ) www.mpimet.mpg.de	Hamburg	R, MD	MPI_ESM, EMAC, climate
DLR, DLR/IMF, DLR/DFD, DLR/PA atmos.eoc.dlr.de/gome2 www.dlr.de/pa www.wdc.dlr.de	Oberpfaffenhofen	R, MD, MT, QA/QC	GOME-2, EMAC, Air-Traffic
IAP Kühlungsborn, www.iap-kborn.de	Kühlungsborn	R, D, MT	Middle Atmosphere, lidar Alomar,
Bundesamt f. Strahlenschutz (BfS) www.bfs.de	Salzgitter	MT	UV
Umweltbundesamt (UBA), www.umweltbundesamt.de	Berlin	MT,	Air quality
Uni Bremen, IUP www.iup.uni-bremen.de	Bremen	R, D, MT	SCIAMACHY, GOME-2, MICROWAVE, DOAS, FTIR
Uni Köln, Inst. f. Meteorologie, www.geomet.uni-koeln.de	Köln	R, MD	EURAD,
FU Berlin, Inst. f. Meteorologie , www.geo.fu-berlin.de/met	Berlin	R, MD	EMAC, QBO, Stratosphere
Uni Frankfurt, Inst. f. Meteorologie, www.geo.uni-frankfurt.de/iau	Frankfurt	R, MT	CFC's, age-of-air, chemical composition
Uni Mainz, MPI f. Chemie (MPIC) www.atmosphere.mpg.de	Mainz	R, MD	EMAC/CCM
Uni Heidelberg, IUP www.physik.uni-heidelberg.de	Heidelberg	R, QA/QC	DOAS, Bromine, Iodine
GEOMAR, Kiel www.geomar.de	Kiel	R, MD	Middle Atmosphere, Bromine
Karlsruhe Institute of Technology (KIT) www.imk.kit.edu	Karlsruhe, Garmisch-Partenkirchen (IfU)	R, D, MD, MT, QA/QC	MIPAS, NDACC, LIDAR, IAGOS-CARIBIC, HALO, Balloon, Modelling
Uni München (LMU-MIM) www.meteo.physik.uni-muenchen.de	München	R, MD, MT	Radiation, UV
Uni Hannover, Inst. f. Meteorologie www.muk.uni-hannover.de	Hannover	R	UV

1. OBSERVATIONAL ACTIVITIES

German agencies are active in long-term ground-based monitoring and in ongoing satellite measurements of ozone and related trace gases. Regular ground-based measurements of ozone using Dobson and Brewer Spectrometers and/or ozone sondes are taken since the late 1960s at Lindenberg/Potsdam and Hohenpeißenberg, since the mid-1980s at the Antarctic Georg-Foster and Neumayer stations, and at the Arctic AWIPEV/Koldewey station on Spitsbergen. Within the framework of the Network for the Detection of Atmospheric Composition Change (NDACC) microwave radiometers, Fourier Transform InfraRed Spectrometers (FTIRs) and Lidars are deployed at the NDACC stations Hohenpeißenberg/Zugspitze, Kiruna, Izana, AWIPEV and Merida (Venezuela). Regular UV measurements are taken by BfS and other institutes at about 10 sites in Germany.

IUP Bremen is involved in satellite instrument and algorithm development, as well as advanced data processing, e.g. for upcoming new missions like Sentinel 5P (launch in 2017) and Sentinels 4 (geostationary platform) and 5 (launches in 2020). Scientific data processing for SCIAMACHY (2002-2012), OMI (since 2004) and GOME-2 (since 2006) are done as well by IUP. Several ground-based DOAS, microwave, and FTIR spectrometers at selected locations are run to monitor stratospheric species like O₃, NO₂, BrO, and OCIO (stratosphere) as well as tropospheric species (MAXDOAS). All instruments are part of the NDACC (Network for the Detection of Atmospheric Change). The IUP combined ozone column dataset from European nadir viewing (downward looking) satellite UV/vis spectrometers now encompasses twenty years. It is used for detecting global long-term trends due to ozone depleting substances (ODS) and climate change within the international framework provided by the Vienna Convention, and the Montreal Protocol and its Amendments to protect the ozone layer. IUP regularly contributes to the WMO Scientific Assessments of Ozone Depletion (e.g. Pawson et al., 2014) and to the BAMS State of the Climate Report (Weber et al., 2016).

Karlsruhe Institute of Technology (KIT) coordinates the IAGOS-CARIBIC in-service aircraft observatory, ground-based FTIR measurements at four NDACC sites (Karlsruhe, Kiruna, Izana and Garmisch), infra-red remote sensing from balloon and airborne platforms and plays a leading role in retrieval, scientific analyses and quality control of MIPAS/ENVISAT satellite observations. KIT coordinated the Arctic aircraft campaign “The Polar Stratosphere in a Changing Climate” (POLSTRACC) using the German High Altitude and Long-Range Research Aircraft HALO in winter 2015/16. IAGOS-CARIBIC (www.iagos.org) is a long-term European Research Infrastructure with a well-equipped laboratory (19 instruments) deployed for ~500 flight hours per year onboard a Lufthansa passenger aircraft.

Germany's Meteorological Service (DWD) is running a comprehensive ground-based measurement program at the Observatories Hohenpeißenberg and Lindenberg, monitoring the ozone vertical distribution and total ozone columns on a regular and long-term basis. Special efforts are put into high quality and long-term consistency. The time series now cover 50 years for column ozone and ozone profiles, and almost 30 years for stratospheric LIDAR observations. Data are regularly submitted to the data centers at Toronto (WOUDC), NDACC, NILU and Thessaloniki. In addition to the operational UV-network of the BfS, DWD continues to measure UV-B radiation for research and development purposes.

The **German Aerospace Centre (DLR)** provides operational processing for satellite measurements of ozone and other trace gases (total NO₂, tropospheric NO₂, SO₂, BrO, H₂O, HCHO), as well as cloud information from GOME-2/MetOp-A, and B. DLR-EOC is also leading the development of the operational systems for the TROPOMI/Sentinel-5-Precursor mission. DLR also hosts the World Data Center for Remote Sensing of the Atmosphere WDC-RSAT (www.wdc.dlr.de), and operates the German high altitude research aircraft (HALO).

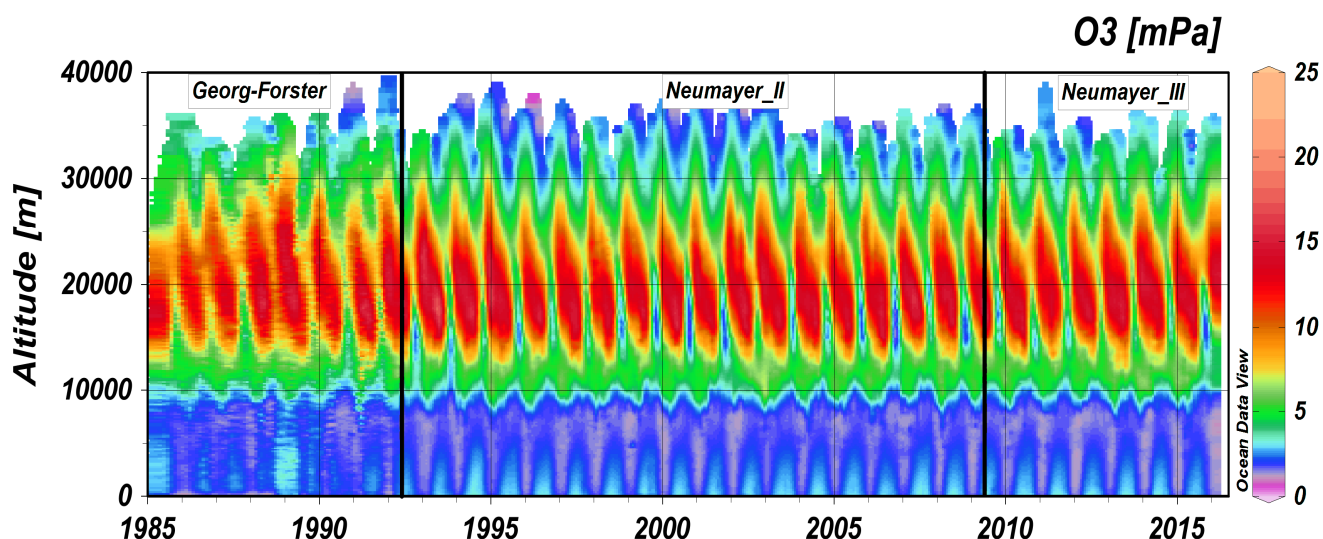


Fig. 1: Time and altitude plot of ozone partial pressure from German ozone soundings over Antarctica. Plot by G. König-Langlo, AWI Bremerhaven.

The **Alfred Wegener Institute for Polar and Marine Research (AWI)** operates two fully equipped polar stations in the Arctic (AWIPEV/Ny-Ålesund), and Antarctic (Neumayer) and temporarily onboard RV POLARSTERN. Regular vertical ozone balloon soundings at Neumayer continue the very long Antarctic sounding record that started at the former Georg Forster station in 1985 (see Fig. 1). A full suite of NDACC measurements is running at AWIPEV/Spitsbergen, in cooperation with Uni Bremen. This includes ozone-soundings by ECC-sondes, Lidar, microwave, DOAS, FTIR and UV-spectrometers. In addition, the same radiation measurements as at Neumayer-Station are performed as part of the BSRN. Currently ozone soundings are also done in the tropics, at Palau, Micronesia.

A number of **dedicated aircraft campaigns** with research aircrafts Geophysica and HALO with the focus on ozone research have been carried out with an extensive set of instruments determining the chemical composition of the air. In the winter 2015/2016, the project POLSTRACC with the German research aircraft HALO took place successfully. At the focus of this large campaign were observations of ozone and ozone-related chemical compounds in the lowest stratosphere.

1.1. Calibration activities

Forschungszentrum Jülich hosts the World Calibration Centre for Ozone Sonde (WCCOS). WCCOS is part of the quality assurance plan for balloon borne ozone sondes that are in routine use in the GAW observation network of the WMO. Since its inception in 1995, WCCOS provides an experimental chamber that simulates conditions in the atmosphere as a balloon ascends from the surface to the stratosphere. The Jülich Ozone Sonde Intercomparison Experiments (JOSIE) have evaluated and improved the performance of the ozone sondes substantially.

Previous JOSIE-intercomparisons have clearly demonstrated that even small differences of sensing techniques, sensor types or operating procedures can introduce significant inhomogeneities in the long term ozone sounding records between different sounding stations or within each station individually. To resolve these artifacts the WCCOS presently leads the “Ozone Sonde Data Quality Assessment (O3S-DQA)” activity with the primary goal of homogenizing selected long term ozone sonde data sets of the global ozone sounding networks. In addition, in 2016 the WCCOS started in collaboration with SHADOZ, with the preparation of a new JOSIE-campaign that is planned to take place in Fall 2017 at the WCCOS. From both activities we expect a new set of recommendations for ozone sonde procedures and data processing to reduce uncertainties between long term sounding records from 10-20 % down to the 5 % level.

The **Regional Dobson Calibration Centre for WMO RA VI Europe (RDCC-E) at the Meteorological Observatory Hohenpeissenberg (MOHp)** is closely co-operating with the Solar and Ozone Observatory at Hradec Kralove (SOO-HK, Czech Republic). It has been responsible for

second level calibration and maintenance service of approximately 20 operational Dobson spectrophotometers in Europe since 1999, including the Antarctic Dobsons at Halley Bay (British Antarctic Survey BAS) and Vernadsky (Ukraine). Refurbishment of European Dobsons that have been out of operation and their relocation, mostly outside of RA VI, has become more and more important.

The success of the global Dobson calibration system can be seen in Fig. 2. The majority of Dobson spectrometers coming in from years of field work now match the reference instrument within 1%, already in the initial comparison.

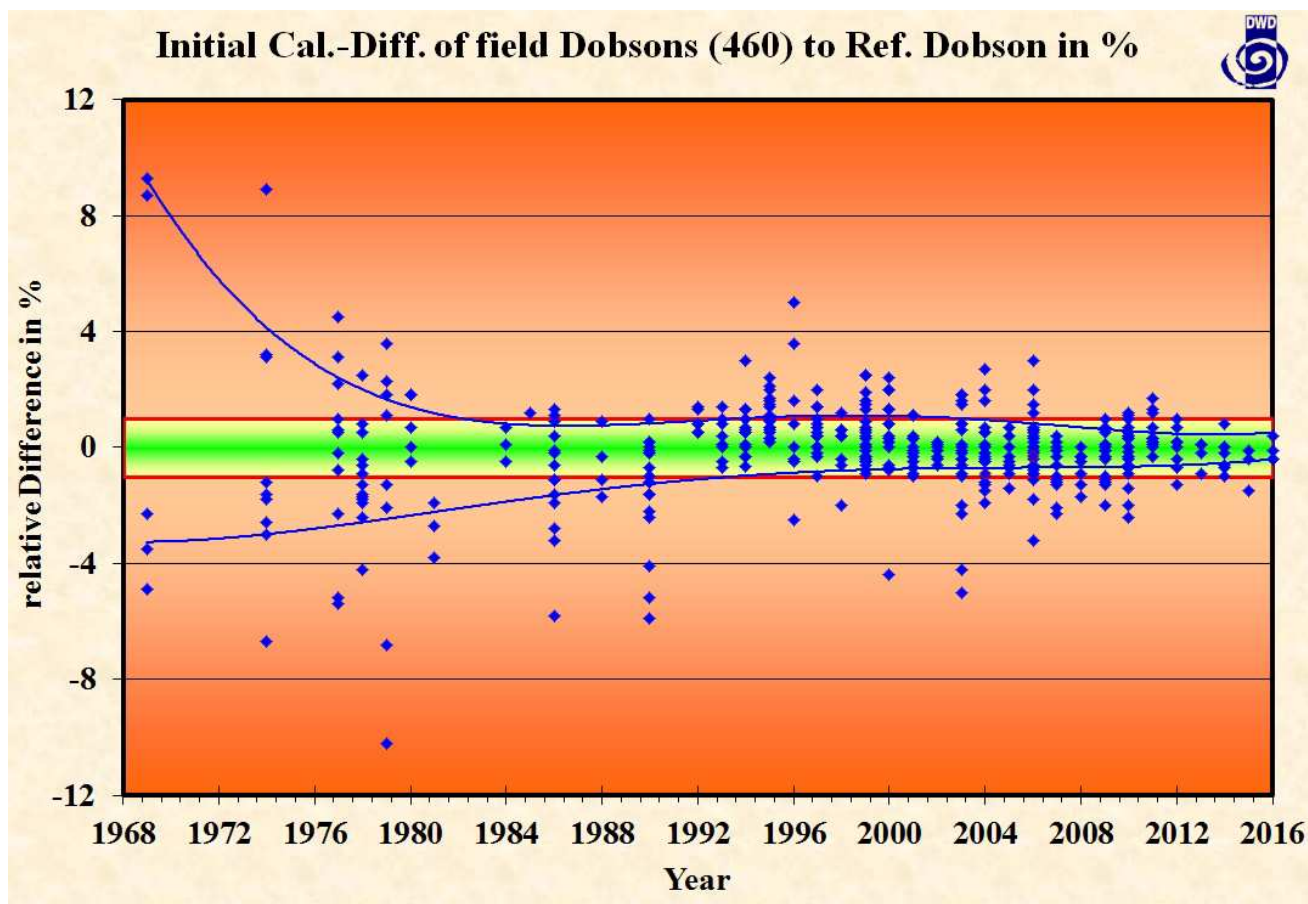


Fig. 2: Relative difference between field Dobson and reference instrument during initial calibration. Plot by U. Köhler, DWD Hohenpeissenberg.

Large progress in the standardization of ozone absorption cross-section was made in recent years by the ACSO initiative (Orphal et al., 2016). German researches were closely involved and **IUP Bremen** has already provided new and improved ozone absorption cross-sections at high spectral resolution ($\sim 0.03\text{nm}$) and covering atmospheric temperatures between 193 and 293 K and the wavelength range 230-1050 nm (Serdyuchenko et al., 2013, Gorshelev et al., 2013, Orphal et al., 2016). Currently ozone cross-sections are measured again at **IUP** to improve in particular the ozone Huggins band region (300-340 nm) using improved and more stable light sources and more sensitive detectors as part of a metrological project to improve traceability of ozone measurements.

1.2. UV-measurements

The working group of **G. Seckmeyer at the Institute of Meteorology and Climatology of Leibniz University Hannover** continued their development of novel non-scanning multidirectional spectroradiometers for simultaneous measurements of spectral sky radiance (Riechelmann et.al. 2013). These MultiDirectional Spectroradiometers (MUDIS) can measure the spectral sky radiance as a function of zenith and azimuth angle with high spectral and temporal resolution. A new instrument – called AMUDIS (advanced multidirectional spectroradiometer) - now covers the wavelength range of 250–1700 nm at 150 different directions simultaneously. Compared to the MUDIS instrument, the spectral resolution is much better (< 1 nm). The newly developed spectroradiometers are versatile instruments with a wide range of application possibilities, including vitamin D weighted exposure determination, solar energy applications, derivation of trace gases, investigation of material aging (e.g. on facades), radiance and plant growth applications and more.

For the determination of vitamin D weighted exposure and the explanation of the height dependence of skin cancer incidence, a novel method has been applied by integrating the incident solar spectral radiance over all relevant parts of the human body (Schrempf et al., 2016). Earlier investigations are based on the irradiance on surfaces, whereas the new method takes into account the complex geometry of the radiation field and the geometry of the human body (Fig. 3).

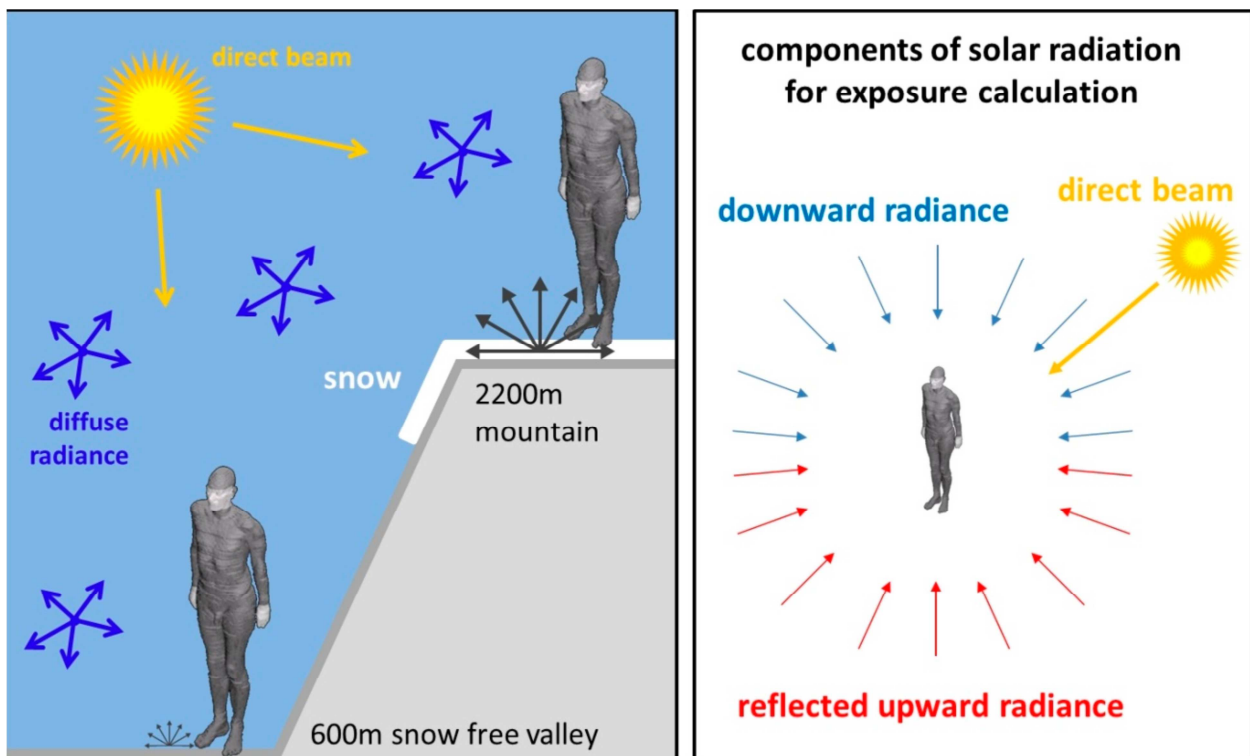


Fig. 3: Schematics of radiance components contributing to exposure of the human body (right), and their change with altitude and surface cover (left). By G. Seckmeyer, U. Hannover.

These new investigations explain why melanoma incidence rates for Austrian inhabitants living at higher altitude increase by as much as 30% per 100 m altitude. This strong increase cannot simply be explained by the known increase of erythemally-weighted irradiance with altitude, which ranges between 0.5% and 4% per 100 m. Rather, a good part of the discrepancy is explained by upwelling UV radiation; e.g., reflected by snow-covered surfaces. These new results imply that upwelling radiation plays a significant role in the increase of melanoma incidence with altitude.

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

AWI has been instrumental in coordinating Match balloon-sonde campaigns for the observation of polar ozone losses. Whenever meteorological conditions were suitable for Arctic ozone loss, Match campaigns have been carried out for more than 20 years. They are a major component of European and world-wide ozone research, documenting the long-term evolution of polar ozone loss over the Arctic. The Arctic stratospheric winter 2015/16 was the coldest ever observed, resulting in high chlorine activation and large ozone loss. The observed ozone loss was comparable to, or even larger than the loss in the former record winter 2010/11 (Fig. 4).

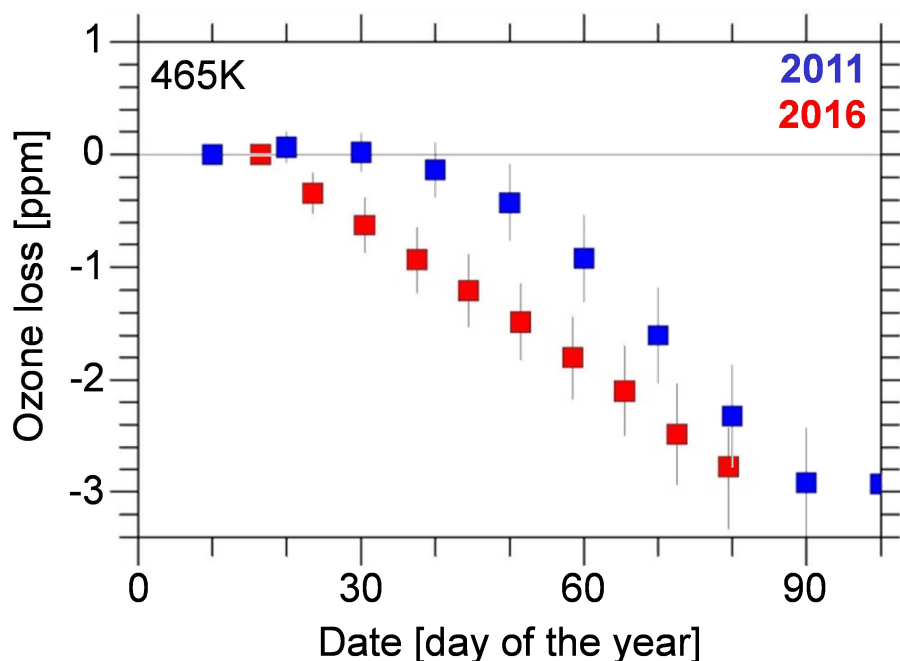


Fig. 4: “Accumulated ozone losses in the Arctic winters 2011 and 2016 at approx. 19 km altitude (465 K potential temperature) as determined with Match. No analysis beyond day 80 (2016) was possible because of the disturbed vortex in 2016.

Graphic: Peter von der Gathen, Alfred Wegener Institute.

The **Arctic aircraft campaign POLSTRACC** (The Polar Stratosphere in a Changing Climate) was successfully performed in winter 2015/16, coordinated by KIT and in cooperation with partners from Research Centre Jülich, German Aerospace Centre (DLR) and the Universities of Frankfurt, Mainz, Heidelberg and Wuppertal. The German High Altitude and Long-Range Research Aircraft HALO was equipped with a large number of in-situ and remote sensing instruments, including the imaging infra-red limb sounding instrument GLORIA. More than 150 flight hours were performed in the Arctic stratosphere between December 2015 and March 2016. The Arctic winter 2015/16 was exceptionally cold with widespread occurrence of polar stratospheric clouds. Substantial Arctic ozone depletion in the lower stratosphere was observed and the relevant processes investigated by the POLSTRACC campaign.

Stratospheric chlorine and bromine trend measurements at the **IMK and IfU** sites (ground-based), as well as air-craft and balloon-borne measurements from **Frankfurt and Heidelberg Universities**, indicate declining chlorine and bromine since the mid to late 1990ies, confirming success of the Montreal protocol. Data from University of Heidelberg and collaborating laboratories (NOAA and BIRA) show that the contribution of CH_3Br and the halons to total stratospheric bromine has also started to decline in recent years, but the variable contribution of mainly naturally emitted very short lived brominated source gases (VSLs) and the measurement precision still obscures the trend (see Fig. 5). To better quantify the input of bromine from VSLs, University Frankfurt has measured the complete suite of short lived bromine source gases which are thought to be relevant to the stratosphere. These include CH_2Br_2 , CHBr_3 and three mixed bromo-chlorocarbons. Their mixing ratios in the upper tropical troposphere have been quantified from Borneo/Malaysia. From these results a total input of bromine from VLSL of 2.9 ± 0.3 ppt (Sala et al., 2014) was derived, well in line with current estimates from WMO 2014, or results in Fig. 6.

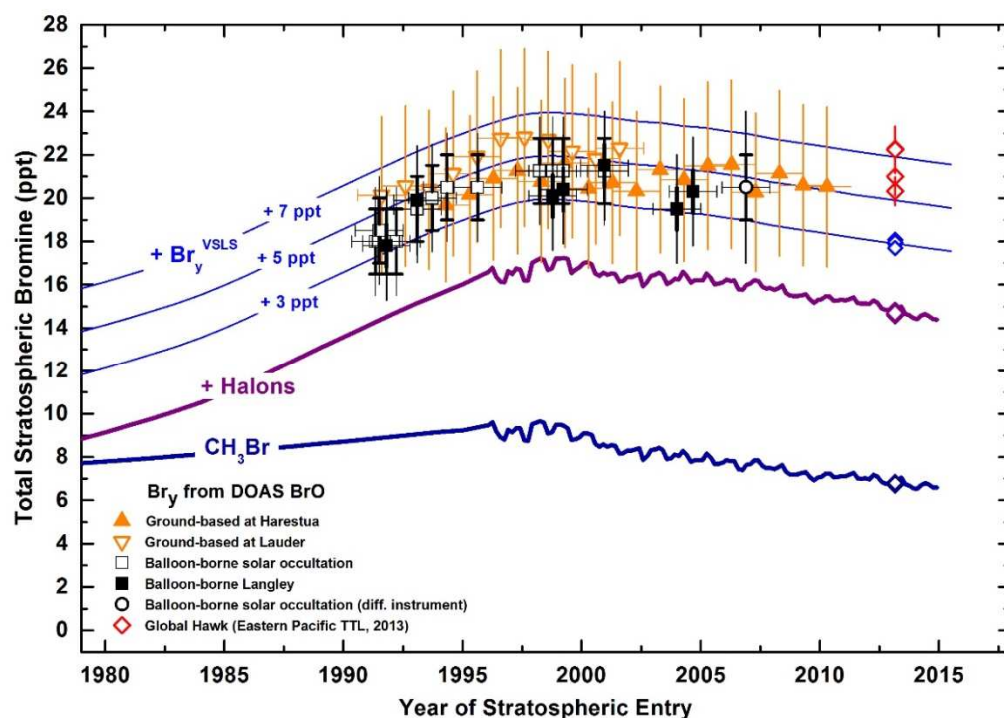


Fig. 5: Total stratospheric bromine (B_{ry}) from balloon-borne BrO observations (squares), airborne observations onboard the Global Hawk, (diamonds), and annual means from ground-based measurements (orange triangles) at Harestua (60°N) and Lauder (45°S). The stratospheric data are compared to bromine at the Earth's surface, with varying amounts of very short lived bromine species added (blue lines). By K. Pfeilsticker IUP Heidelberg.

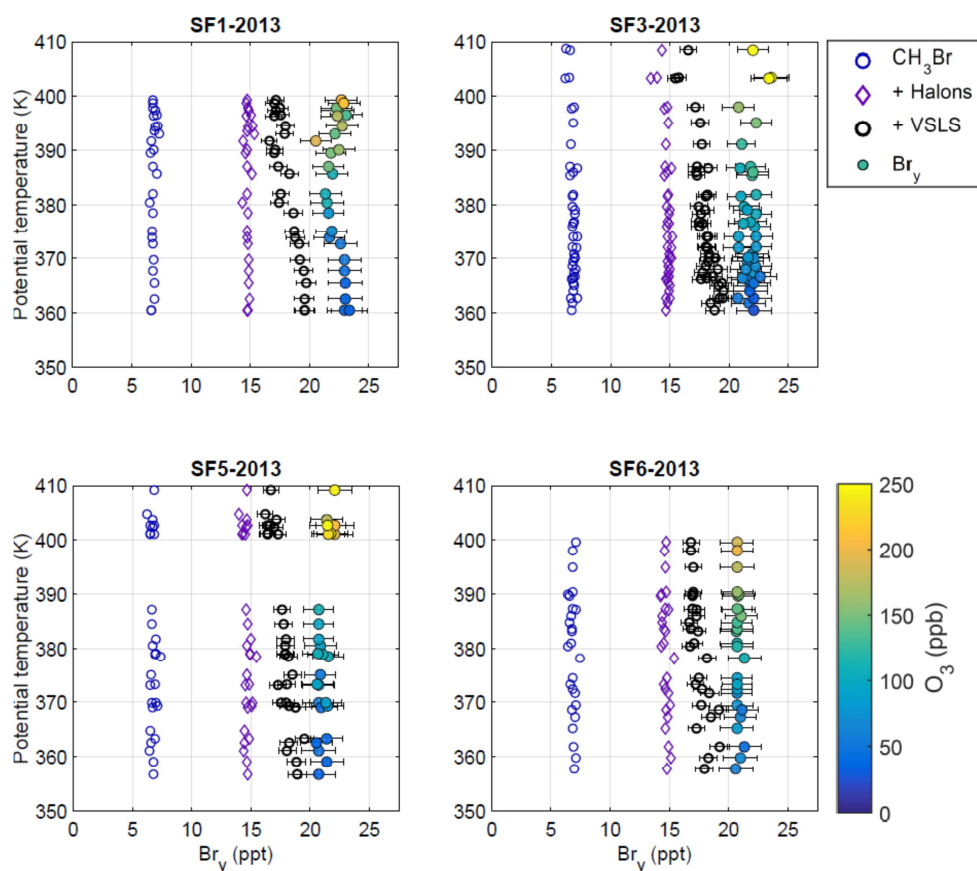


Fig. 6: Total bromine as a function of potential temperature (Θ) for all dives during the 2013 NASA-ATTREX flights (SF1 to SF6) across the tropical tropopause layer (TTL) over the Eastern Pacific in 2013. The contributions from CH_3Br (blue circles), halons (purple), brominated VSLs (black) and the measured inorganic fraction (coloured circles) are summed. From Werner et al., 2017.

Ozone measurements at **Hohenpeißenberg** (see Fig. 7) now have reached their 50th anniversary. Total ozone has not declined since the late 1990s. Significant ozone increases are seen in the upper stratosphere only (not shown), a first sign of a beginning ozone recovery. However, for the total ozone column and the lower stratosphere increases are not that clear and transport related variations are large. Factors like the Arctic Oscillation (AO) contribute majorly. The wide range of ozone values observed in recent years, therefore, is still obscuring the slow and small recovery signal indicated by the red line in Fig. 10.

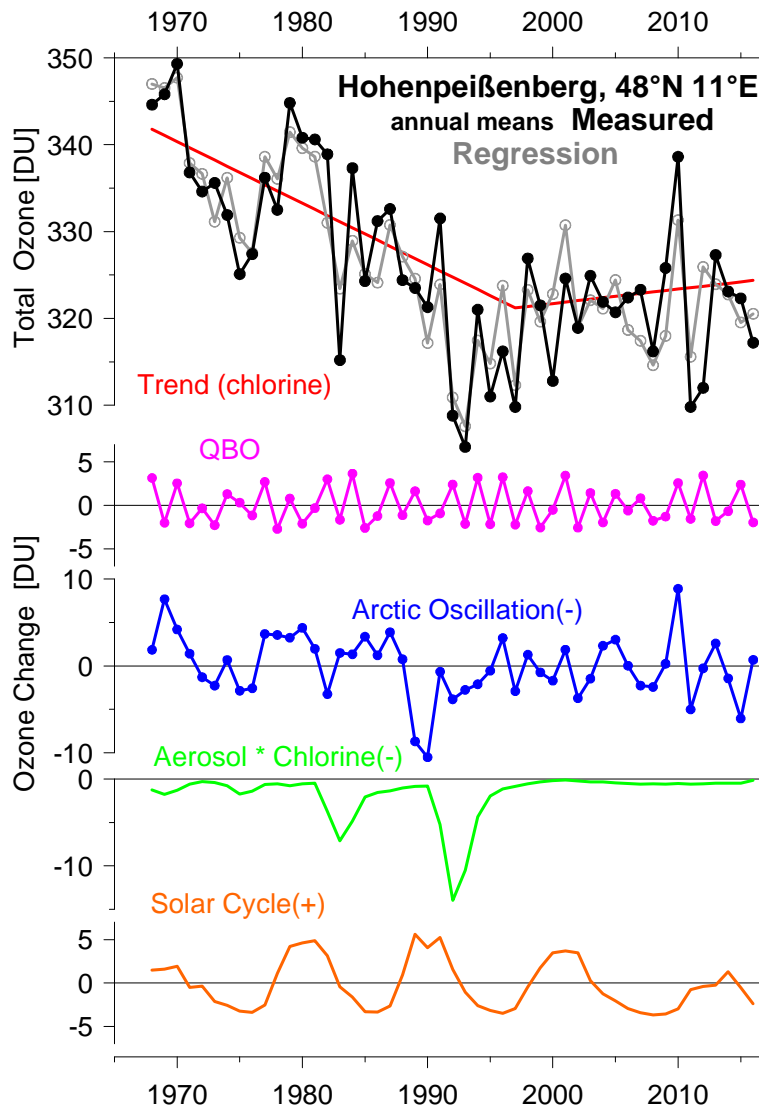


Fig. 7: Observed annual mean total ozone at Hohenpeißenberg, and multiple linear regression analysis of the magnitude of contributing factors. Top: Black: Observations at Hohenpeißenberg (47.8°N, 11°E). Gray: Multiple linear regression result. Red: Ozone variation attributed to Effective Equivalent Stratospheric Chlorine (EESC). Lower graphs: Ozone variation attributed to the QBO (magenta), to the Arctic Oscillation (AO, blue), to enhanced stratospheric aerosol (green), and to the 11-year solar cycle (orange). Plot by W. Steinbrecht, DWD.

World-wide total ozone columns from ground-based and satellite observations are regularly compiled by the **Institute for Umwelt-Physik (IUP) at Bremen University**. Results are given in Fig. 8. Also in this Figure, total ozone shows large inter-annual variability and no significant trends since 2000, following a brief but strong increase from the middle 1990. Nevertheless, the period of continuous decline of about 4%/decade observed since the late 1970s (Fig. 8) has clearly ended. The current observations are within the range of results from an ensemble of chemistry climate models (CCMVAL-2) that account for changing greenhouse gases as well as ozone depleting substances (ODS).

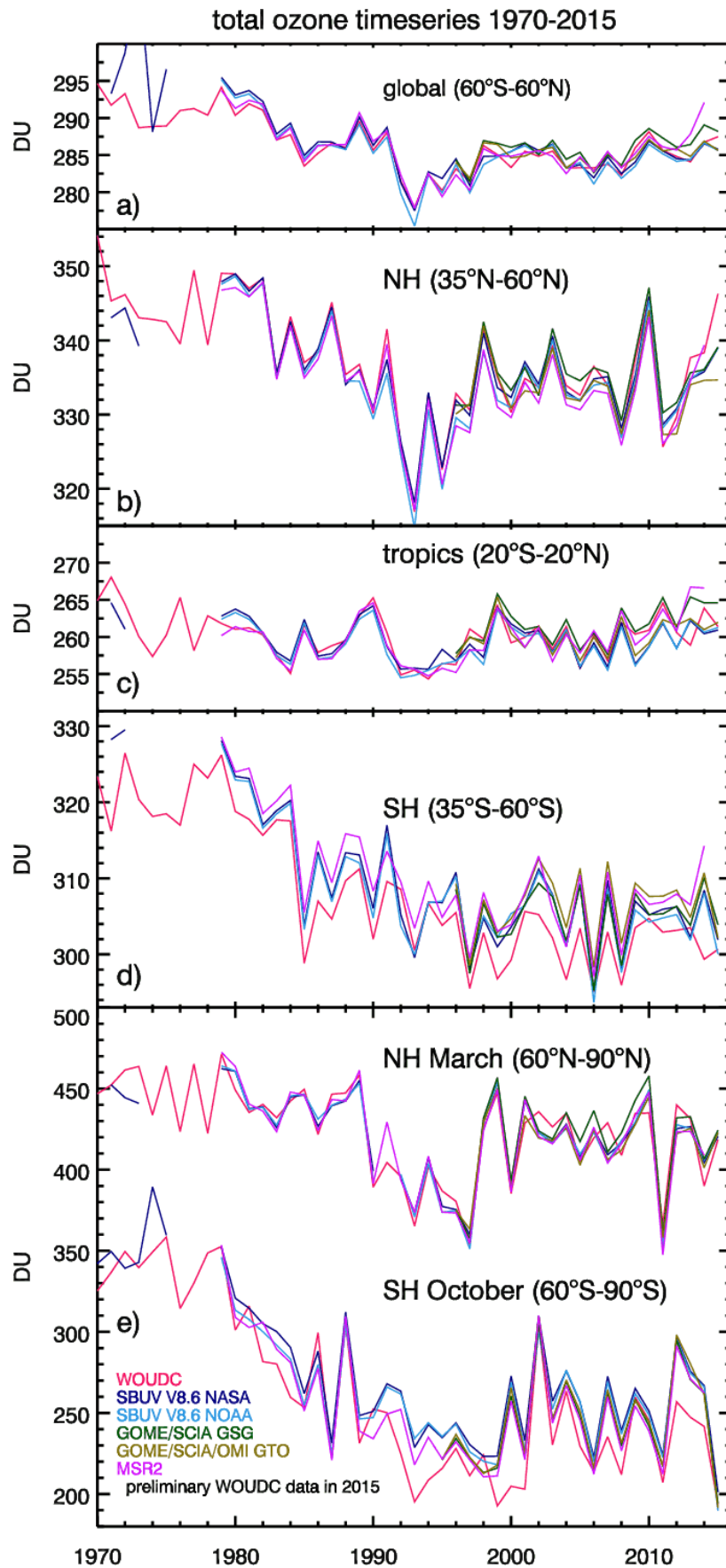


Fig. 8: Timeseries of annual mean total ozone in four zonal bands (a-d), as well as polar total ozone in March (NH) and October (SH) (e). Data are from WOUDC ground-based measurements combining Brewer, Dobson, SAOZ, and filter spectrometer data (red) the BUV/SBUV/SBUV2 V8.6 merged products from NASA (dark blue) and NOAA (light blue), the GOME/SCIAMACHY/GOME-2 products GSG from University of Bremen (dark green) and GTO from ESA/DLR (light green) and the MSR V2 assimilated dataset from KNMI extended with GOME-2 data. From Weber et al., 2016.

FTIR measurements from **KIT** together with ground-based FTIR data from eight NDACC sites were used to investigate trends in the ozone profile. While there is no significant trend in FTIR ozone column data there is a positive trend in the partial column of the upper stratosphere at most sites, in particular in the Arctic (Vigouroux et al., ACP, 2015).

Additional attention has been given to the evolution of tropospheric ozone. **IUP** implemented three different approaches that combine cloud information and ozone column from nadir viewing space measurements to derive tropospheric ozone columns. Both methods (Convective Cloud Differential (CCD) and Cloud Slicing (CS)) are statistical methods that derive mean quantities by averaging over sampled data in pre-defined grid boxes and their applicability is limited to the tropical region. Limb-nadir matching combines stratospheric columns (from limb observations) with collocated total columns (from nadir observations, Ebojie et al., 2014, 2016). Using these techniques, tropospheric ozone satellite data (GOME, SCIAMACHY, GOME-2) have been merged into a single long-term dataset (1995-present) for investigating trends and variability (Leventidou et al., 2016). MIPAS/ENVISAT was also used within a study to separate stratospheric from tropospheric ozone variation. This study showed that the halogen-induced stratospheric ozone loss is partly compensated by tropospheric ozone increase, particularly in the tropics (Shepherd et al., 2014, see Fig. 9)

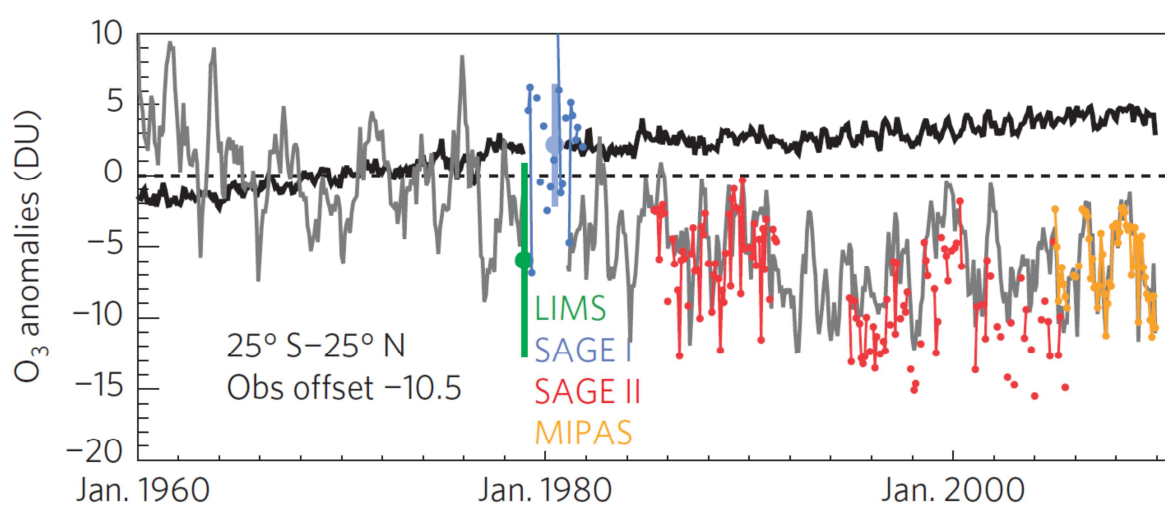


Fig. 9. Tropical ozone anomalies from model simulations (black: tropospheric partial column and gray: stratospheric column) together with satellite observations of stratospheric ozone anomalies. Halogen induced stratospheric ozone loss is partly masked by the increase in tropospheric ozone. From Shepherd et al., 2014.

Many groups work on improving and extending their data retrievals. IUP Bremen, e.g., has improved the quality of global vertical distributions of ozone and other atmospheric constituents (NO₂, BrO, H₂O, aerosols) retrieved from SCIAMACHY limb measurements. The main objective is to achieve quality and stability of the resulting time series, required for trend analyses. Supporting modelling studies are performed to explain the observed behaviour of the stratospheric species. Furthermore, the work on data from the recent limb sensor OMPS (on Suomi-NPP) is performed to extend long-term time series of stratospheric ozone and aerosol by merging with SCIAMACHY.

The agreement of SCIAMACHY ozone profiles with other satellite measurements, in particular MLS, shows large improvements. Ozone trends from 2004 to 2011 have been updated from Gebhardt et al. (2014) and are shown in Fig. 10. The increase in upper stratospheric ozone since 2002 is consistent with the decline in stratospheric halogen related to the Montreal Protocol phasing out ozone depleting substances. In certain regions of the atmosphere, however, a continuous decline in ozone is observed (~10 hPa in the tropics). This is likely related to changes in NO_y and tropical upwelling. Continued efforts also go into improving data analysis for the MIPAS instrument. See e.g. Fig. 11 which demonstrates the improved quality of several current retrieval algorithms.

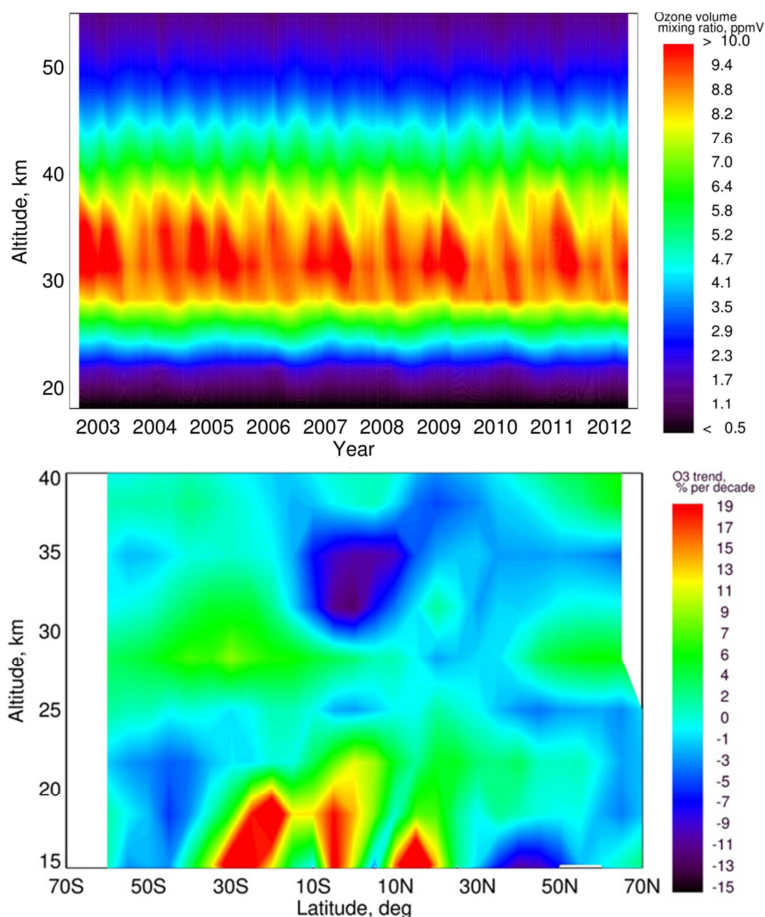


Fig. 10: Time series for the tropics between 10°S and 10°N (top) and linear change for zonal mean data from a linear regression (bottom) for the SCIAMACHY limb ozone data set V3.5 from 2004 to 2011. Plot by A. Rozanov, Univ. Bremen.

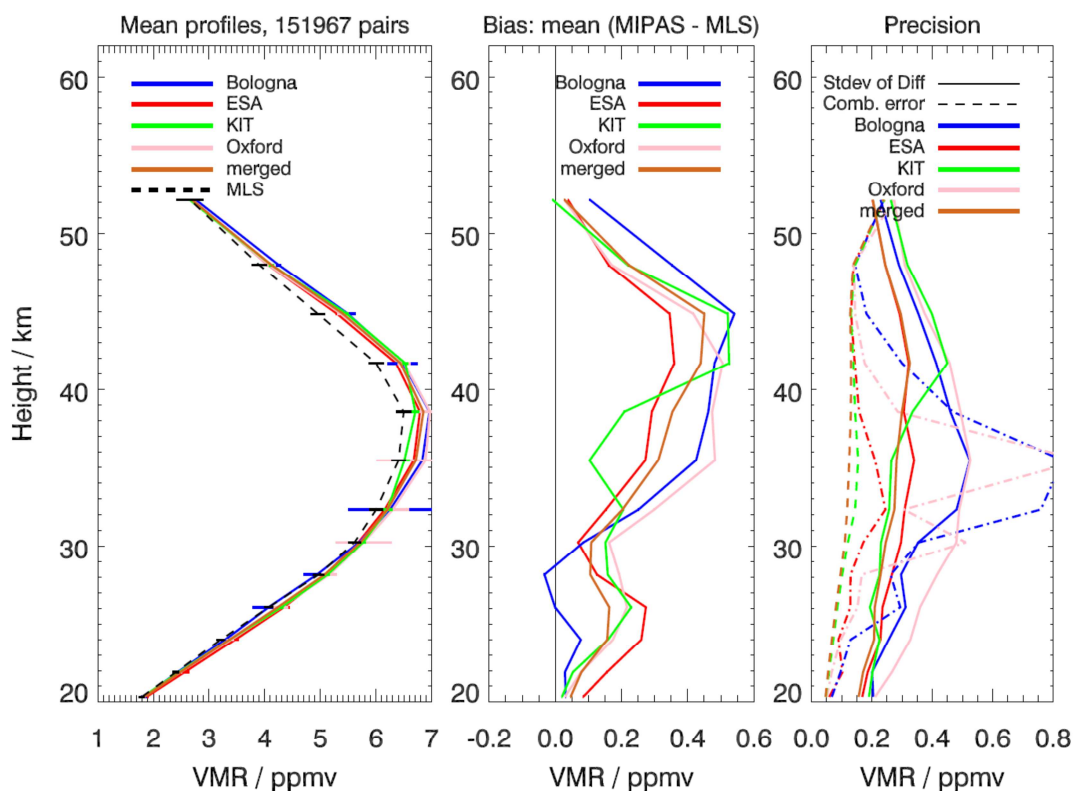


Fig. 11: Validation of the merged MIPAS/ENVISAT data set from four different processors with independent MLS data. From Laeng et al., 2016.

Routine ozone monitoring is also carried out by DLR (WDC-RSAT). Since the loss of ENVISAT in early 2012, only the AURA-MLS instrument is still providing ozone limb soundings. DLR has been assimilating MLS profile retrievals for O₃, HCl, H₂O, N₂O and HNO₃ into the 4Dvar chemical data assimilation system SACADA/DLR. Analyses are provided on a daily basis (wdc.dlr.de/sensors/mls). DLR also assimilates GOME-2 total column ozone using the ROSE/DLR model (wdc.dlr.de/sensors/gome2). In contrast to observations, analyses allow global mapping of the synoptic ozone and trace gas distribution, e.g. during the polar night.

These assimilated fields can be used to assess the trend of the ozone-hole size since 2007. Figure 12 shows this development of ozone-hole size (OHS) up to 2016. The latest year, 2016, is illustrated by the red line. Recent years saw a strong variation without a clear trend. During October and November, the strongest inter-annual variability can be found. While the OHS was especially large in September and October 2015 (among the largest in the last 10-years), the 2016 ozone hole showed average size with a rather early recovery. In 2015, in contrast, extremely low temperatures and a stable vortex prolonged stratospheric ozone depletion well into November (e.g., WMO ozone bulletins 2015).

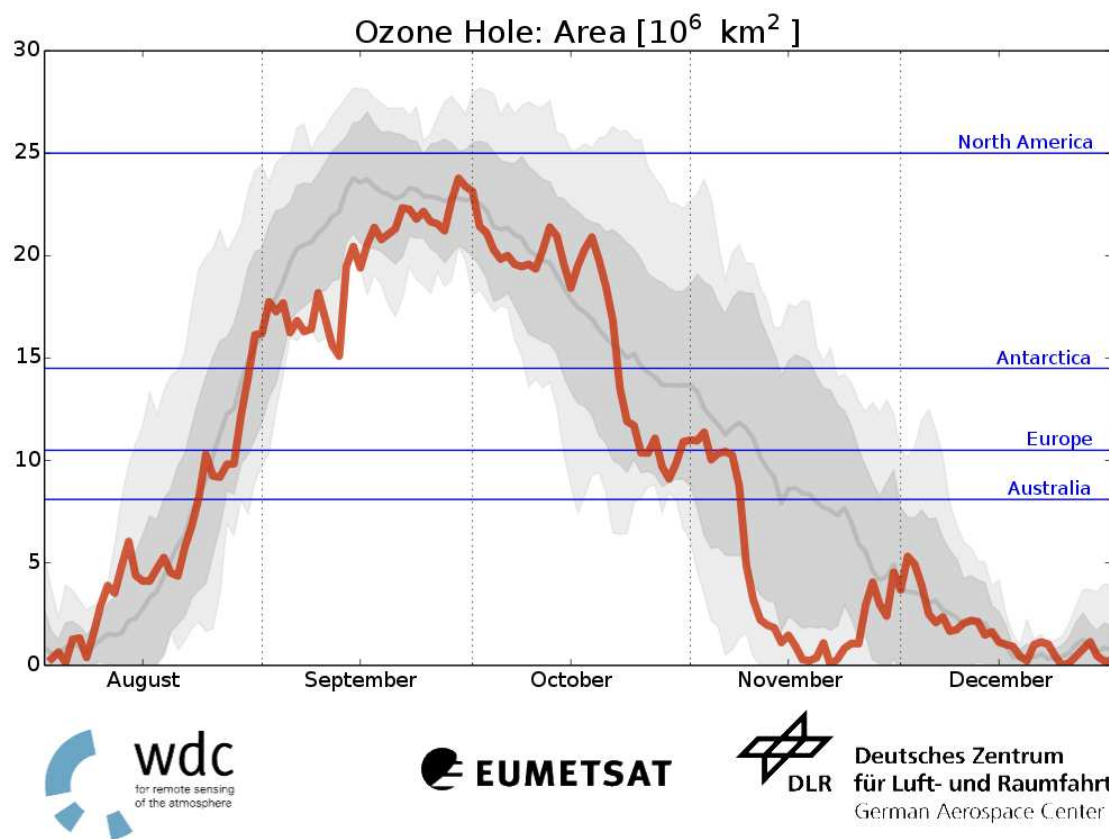


Fig. 12: Daily size of the Antarctic ozone hole from ROSE/DLR assimilation of GOME-2 data. Light grey area: Minimum to maximum range of daily data observed since 2007. Dark grey area: ± 1 standard deviation around the mean (dark grey line). Red line: Evolution of the 2016 ozone hole. Plot by wdc.dlr.de.

Frankfurt University has continued investigations into the **trend in mean age of air** in the stratosphere. Age-of-air is an important diagnostic for changes in the strength of the Brewer-Dobson circulation. In the past, observations of a wide range of halocarbons, including the most important chlorine and bromine source gases were made by large and expensive stratospheric balloons carrying whole air samplers. These measurements have not been continued during the last years due to missing financial resources. University Frankfurt has instead focused on the AirCore technique (Karion et al., 2010). It allows measurements of CO₂ and Methane and thus derivation of mean age up to altitudes of about 30 km (Membrive et al., 2016). AirCore is light weight and can be flown on small balloons. U Frankfurt has used these observations to prolong their time series of mean age in the mid latitude stratosphere of the Northern Hemisphere (Engel et al., 2009). The trend derived from this new data set, shown in Fig. 13, and now spanning 40 years, is $+0.15 \pm 0.18$ years (Engel et al., in preparation, 2017). The positive trend is slightly smaller than the previous estimate but shows good agreement within the uncertainty range. These extended time series emphasize that a large negative trend in mean age of air in the middle stratosphere at Northern Hemisphere mid latitudes is difficult to reconcile with observations.

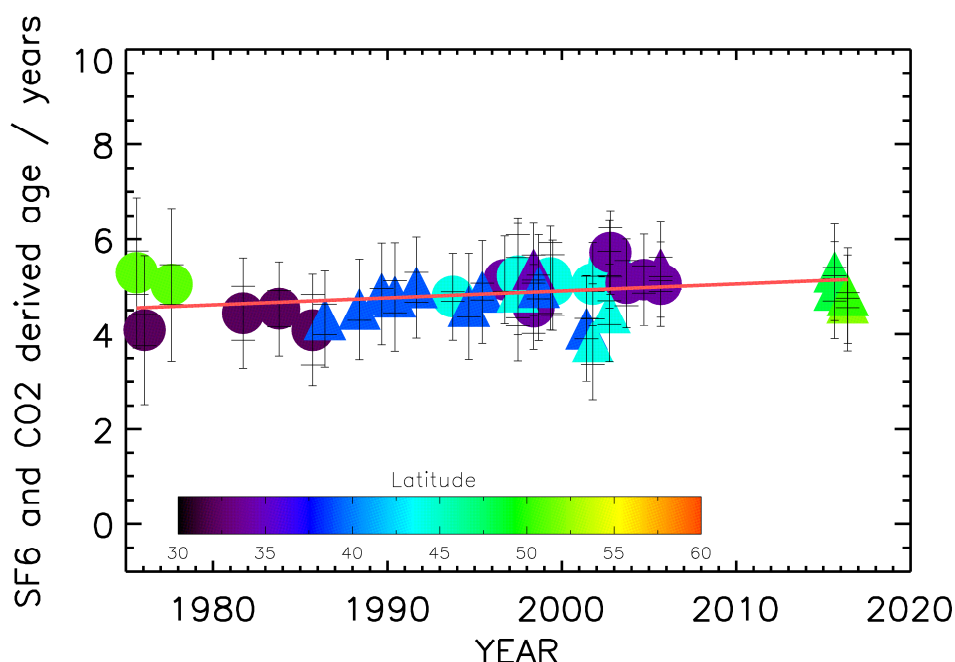


Fig. 13: Trend in mean age-of-air for the extratropical stratosphere derived from U Frankfurt air samples. The data points for 2015/16 are based on the AirCore technique. Update of Engel et al. 2009.

University Frankfurt has also developed new instrumentation for measurements of halocarbons. The classical measurement technique combines gas chromatographic separation with mass spectrometric detection using a quadrupole mass spectrometer. The use of a time-of-flight (TOF) mass spectrometer (MS), however, has significant advantages (Obersteiner et al., 2016; Hoker et al., 2015). The TOF-MS yields full-scan mass information, whereas the Quadrupole only measures certain pre-selected masses. The TOF-MS data thus constitute a full digital air archive, as all ions are recorded. Data can be later be evaluated for species not targeted at the time of measurements. Regular measurements with the new technique were started in 2013 at the Taunus Observatory near Frankfurt. They present the first long term measurements of halocarbons in Germany and they pioneer the new technique, allowing for future identification of interesting species. Since early 2014, similar measurements are performed on canisters sampled at the clean air station Mace Head in Ireland. The Taunus observatory is situated in the centre of Germany. It is well situated to provide observations for inverse modelling to derive emissions of halocarbons from Germany and parts of Central Europe.

3. THEORY, MODELLING, AND OTHER RESEARCH

A number of models, including chemistry-climate models (CCMs) are used in Germany 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 staff. 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** (Jöckel et al., 2016). Coordinated model simulations and analyses are being performed. EMAC has been used to simulate the decadal trends from the 1960s to 2100. These results have and will continue to contribute significantly to WMO/UNEP Scientific Assessments of Ozone including the upcoming one.

At **MPI for Chemistry** a version of EMAC with interactive stratospheric and tropospheric aerosol, including volcanic effects, was developed as contribution to the SPARC-Initiative SSIRC and the EU-project StratoClim (Brühl et al, 2015). SO₂ data from MIPAS on ENVISAT provided by **KIT** were essential to attribute the volcanic injections into the UT/LS. MIPAS is also used for model validation. **AWI** is developing and employing the ATLAS CTM, which has been used for, e.g., modeling polar ozone depletion or 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, like the models used in the IPCC reports. So far these use prescribed ozone only. The fast new SWIFT enables the inclusion of interactions of ozone and climate in these models, which has not been feasible in the past due to computational constraints.

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 (Grooß et al., 2014). CLaMS has been used extensively in the scientific flight planning for various aircraft measurements campaigns (e.g. POLSTRACC, StratoClim). Research on Polar Stratospheric Clouds (PSCs) has led to the development of a new PSC type classification from MIPAS observations (Spang et al., 2016) and to further insights into PSC nucleation (Engel et al., 2013; 2014, Hoyle et al, 2013). A simple measure for polar ozone loss is regularly derived from satellite total column observations and wind data (Müller et al., 2008). Figure 14 shows an update of this proxy for Arctic ozone depletion until the year 2016.

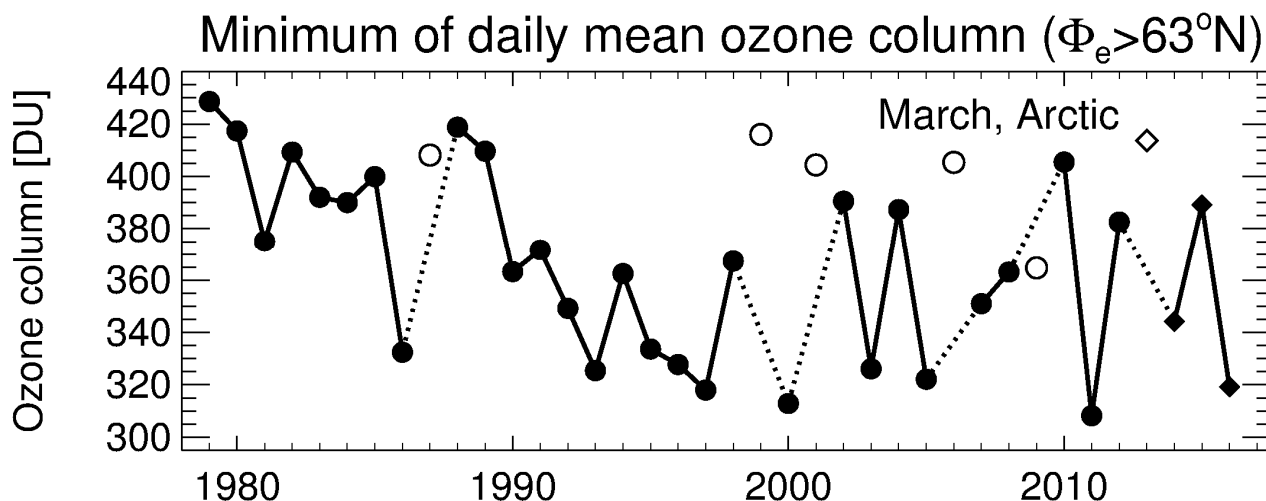


Fig. 14: Measure of Arctic ozone depletion given as the minimum of daily average column ozone poleward of 63° equivalent latitude in March. Open circles represent years in which the polar vortex broke up before March. Update from Müller et al. 2008, and WMO 2014.

KIT scientists have been involved in a number of ozone modelling activities with chemistry-climate, chemistry transport, and process models, as well as model development. Bednarz et al. (2016) investigated the importance of chemistry and dynamics for future Arctic ozone recovery. Sinnhuber and Meul (2015) investigated the impact of emissions of brominated very short-lived substances on past stratospheric ozone trends.

The working group **Atmospheric Dynamics at the Institut für Meteorologie of Freie Universität Berlin** (head: Prof. Dr. Ulrike Langematz) uses EMAC, as well as observations, to study the effects of changes in anthropogenic emissions of ozone depleting substances (ODSs) and greenhouse gases (GHGs) on stratospheric ozone. Using output from transient CCMVal-2 CCM simulations from 1960 to 2000 with prescribed changes of ozone depleting substance concentrations in conjunction with observations, Langematz et al (2016) examined the extent of anthropogenically-driven Antarctic ozone depletion prior to 1980. The year 1980 has often been used as a benchmark for the return of Antarctic ozone to conditions assumed to be unaffected by emissions of ozone depleting substances (ODSs), implying that anthropogenic ozone depletion in Antarctica started around 1980. A regression model was applied to attribute CCM modelled and observed changes in Antarctic total column ozone to halogen-driven chemistry prior to 1980. All models consistently show a long-term, halogen-induced negative trend in Antarctic ozone from 1960 to 1980 in response to rising ODSs (Figure 15). The anthropogenically-driven ozone loss from 1960 to 1980 of 49.8 ± 6.2 % of the total anthropogenic ozone depletion from 1960 to 2000 in the CCMs is lower but consistent with the ozone decline of 56.4 ± 6.8 % estimated from ozone observations. This analysis clarified that while the return of Antarctic ozone to 1980 values remains a valid milestone, achieving that milestone is not indicative of full recovery of the Antarctic ozone layer from the effects of ODSs.

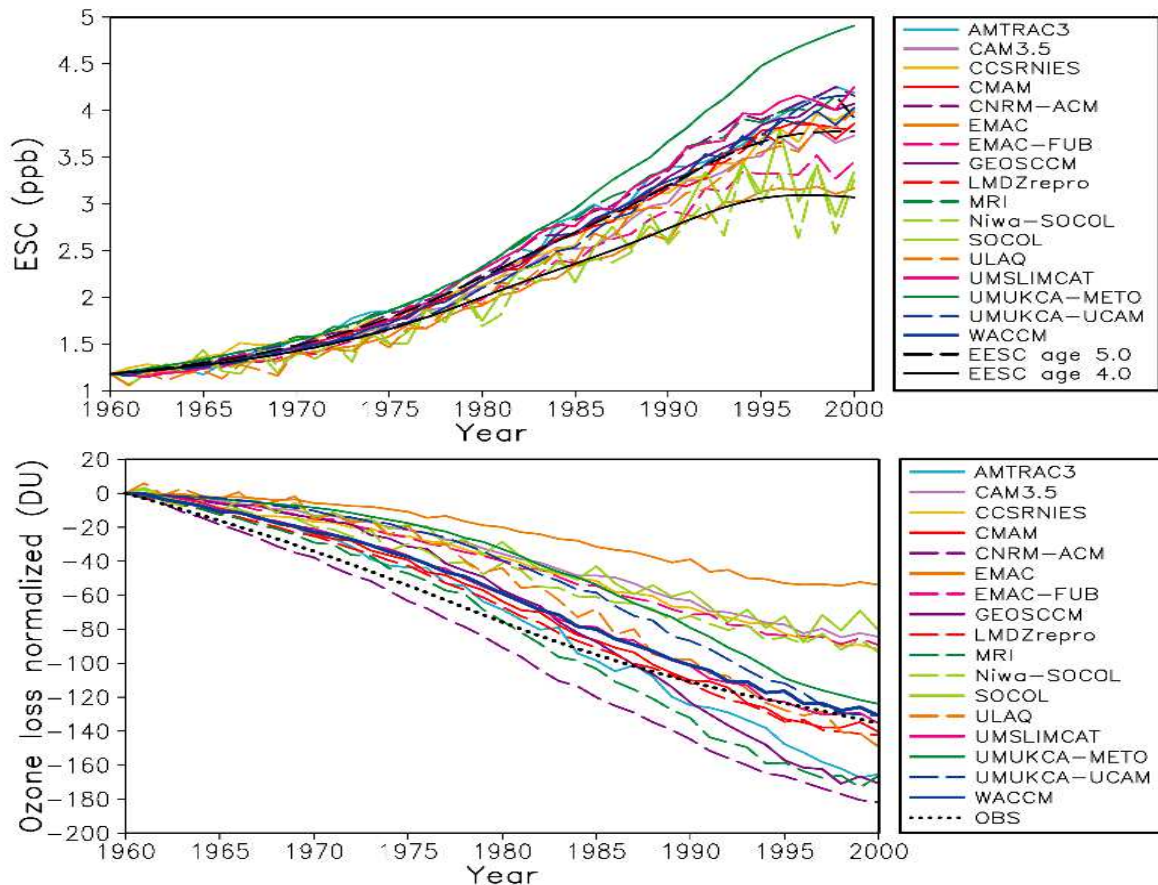


Fig. 15: top: Evolution of Antarctic September/October/November (SON) average ESC (in ppb) in the REF-B1 CCM simulations between 1960 and 2000, adjusted to a common baseline of 1960. Black lines show EESC (in ppb), provided by Newman et al. [2007] for mean transit times of 4 (solid) or 5 (dashed) years. Bottom: Antarctic total ozone column depletion (in DU, SON average) between 1960 and 2000 due to ESC in the CCMs and due to EESC in observations, adjusted to a common baseline (1960 mean of CCMs). From Langematz et al., 2016.

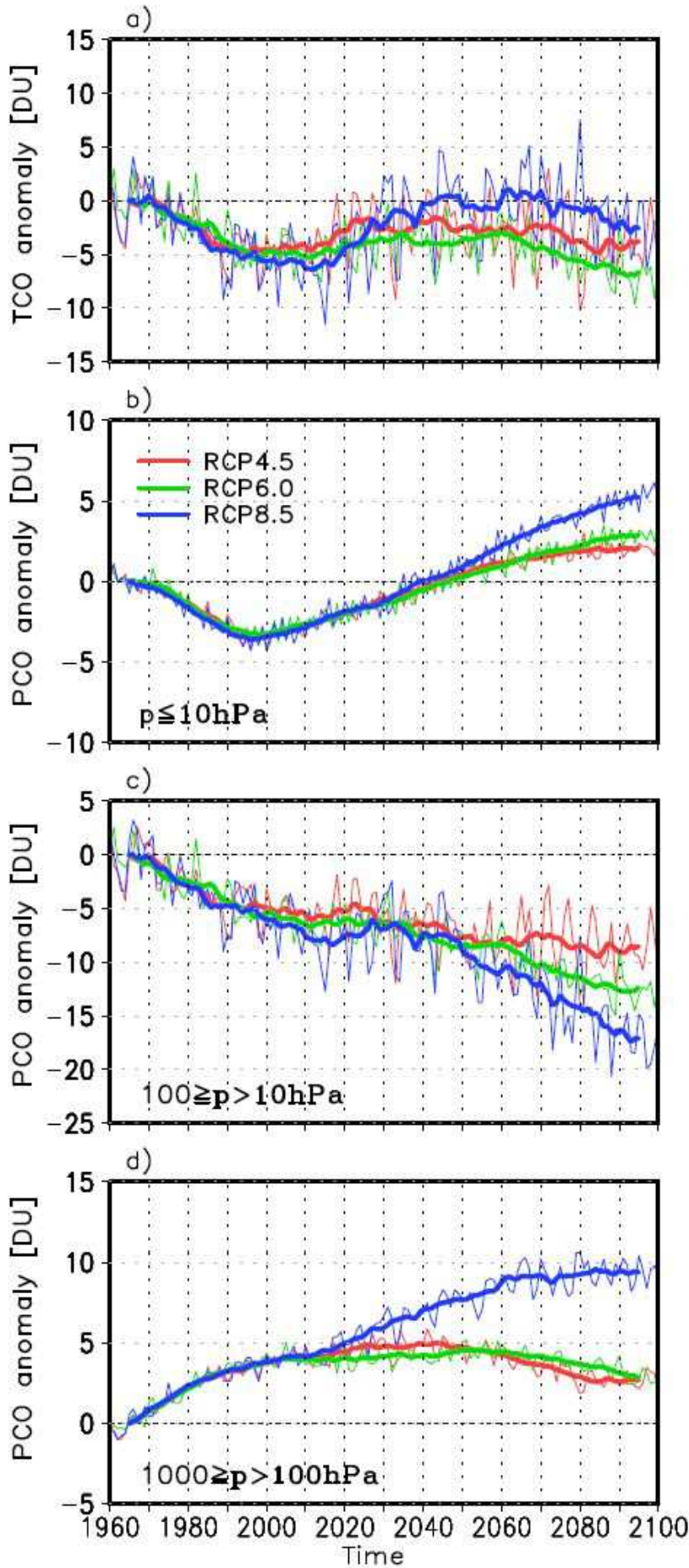


Fig. 16: (a) Time series of annual mean tropical (20°S–20°N) total column ozone anomaly to the 1960–1970 mean for the RCP4.5 (red), RCP6.0 (green), and RCP8.5 (blue) simulations, (b–d) same but for the partial columns in the upper stratosphere (pressure $\leq 10 \text{ hPa}$), middle stratosphere ($100 \text{ hPa} \geq \text{pressure} > 10 \text{ hPa}$), and troposphere ($1000 \text{ hPa} \geq \text{pressure} > 100 \text{ hPa}$). Thick solid lines give the smoothed time series. From Meul et al. 2016.

The future evolution of tropical total column ozone (TCO) is affected not only by the expected decline of ODSs but also by the uncertain increase of GHG emissions. Meul et al. (2016) assessed the range of tropical TCO projections in simulations with the EMAC CCM forced by three different GHG scenarios (Representative Concentration Pathway RCP4.5, RCP6.0, and RCP8.5). Figure 16 shows that tropical TCO will be lower by the end of the 21st century compared to the 1960s in all scenarios, with the largest decrease in the medium RCP6.0 scenario. Contributions for different atmospheric layers vary in magnitude and sign. This means that significant uncertainties for the projected TCO come from uncertain magnitude of stratospheric column decrease and tropospheric ozone increase, which vary significantly between scenarios. In all three scenario simulations, future stratospheric column decrease is not compensated by increases in tropospheric ozone. In Fig. 17, the concomitant increase in harmful ultraviolet irradiance is strongest in the medium RCP6.0 scenario and reaches up to 15% in specific regions, while in the extreme RCP8.5 scenario a strong increase in tropospheric ozone due to high future methane emissions mitigates stratospheric tropical ozone decreases and the increase in harmful surface irradiance.

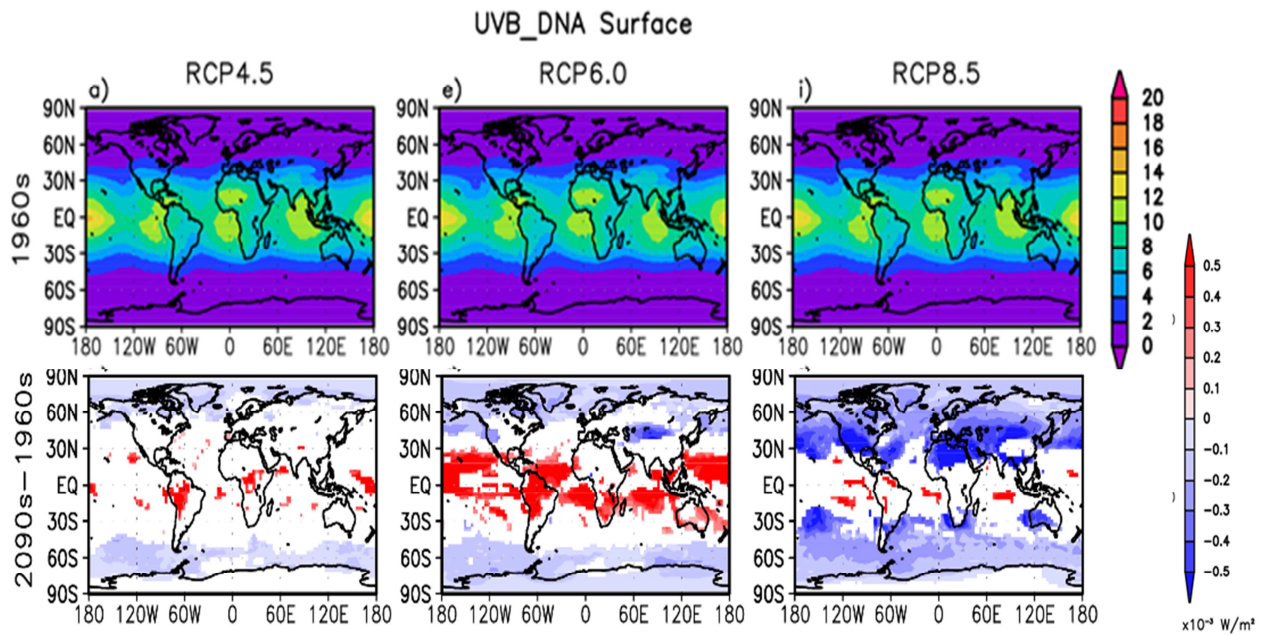


Fig. 17: Top row: Geographical distribution of the 21st century annual mean UV-index, i.e. UV-B radiation weighted with the DNA damage action spectrum (UVB-DNA) at the surface, for the RCP4.5 (left), RCP6.0 (middle) and RCP8.5 (right) simulations, Bottom row: Change in UVB-DNA from 1960 to 2100 for the three RCP scenarios (2100-1960, in 10^{-3} W/m²). Statistically significant changes at the 95% confidence level are colored. From Meul et al., 2016.

4. DISSEMINATION OF RESULTS

4.1 Data reporting and providing

German ozone and related data are regularly submitted to the World Ozone and UV Data Centers at Toronto (WOUDC), to NDACC and to rapid delivery data centers in Thessaloniki, and at NILU. In addition DLR hosts the World Data Center for Remote Sensing of the Atmosphere, WDC-RSAT, and provides operational processing and data delivery for GOME-2 Metop total ozone columns and other trace gases. See Fig. 18 for examples and URLs. In addition data and results are available from a number of institutes through the websites given in Table 1 at the beginning of this report. FZ Jülich, for example, provides information of chemical ozone loss in the Arctic within the Earth System Knowledge Platform (ESKP). The site iek-7.eskp.fz-juelich.de provides actual CLaMS model calculations of ozone depletion during the Arctic winter and its comparisons with previous years. Also the temperature-based proxy V_PSC and estimations of the UV Index increase due to ozone depletion are provided. General information sources for UV radiation, arguably most important for the general public, are detailed in the next sub-section.

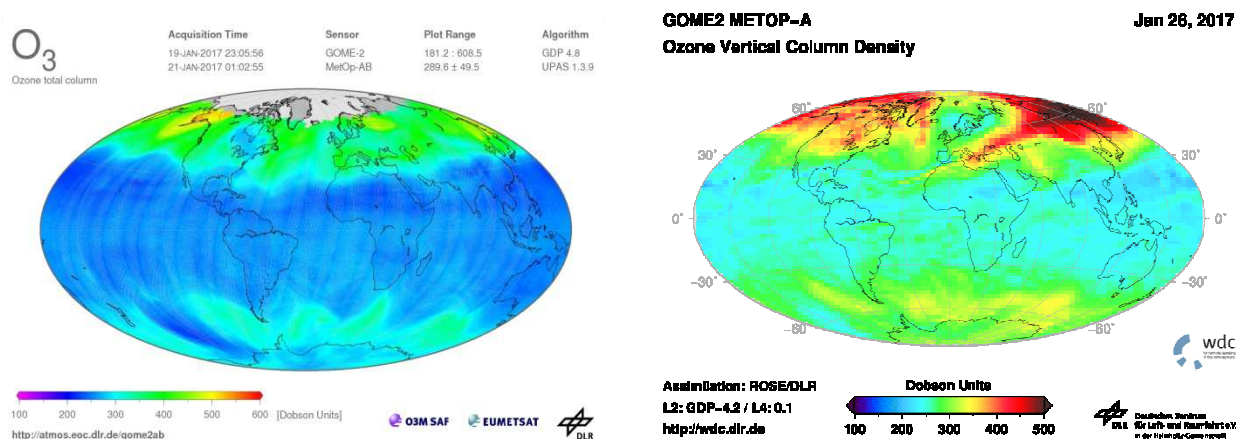


Fig. 18: Ozone total columns from MetOp-A,B/GOME-2 for January 2017. Left: Data product from DLR processing in the framework of EUMETSAT Ozone-SAF ([atmos.eoc.dlr.de/gome2](http://atmos.eoc.dlr.de/gome2ab)). Right: Assimilated data product from Chemistry Transport Model (wdc.dlr.de).

4.2 Information to the public

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

When necessary, press releases and dedicated warnings are published by the appropriate agencies and institutes. In addition, outreach activities include open houses, tours, events and internship programs.

4.3 Selected recent scientific papers

For a complete list of ozone related publications from Germany, the use of bibliographic search engines is recommended (e.g. scholar.google.com or isiknowledge.com/WOS)

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5. PROJECTS AND COLLABORATION

German institutions have participated in a number of national and EU funded research projects, special measurement campaigns and modeling studies, such as SHARP, ROMIC, CAWSES, MACC, CAMS, SHIVA, STRATOCLIM, RECONCILE, CCMVal, CCMI, SPARC and SSIRC. They also play an important role in EUMETSAT and ESA projects. DLR-EOC, for example, is responsible for the operational GOME-2 total and tropospheric ozone and trace gas processing (total NO₂, tropospheric NO₂, SO₂, BrO, H₂O, HCHO) in the framework of the EUMETSAT O3M-SAF. DLR, KIT, and IUP Bremen are key partners in the ESA CCI project to provide the Total Ozone Essential Climate Variable (GTO-ECV). 14 active Arctic and 2 Antarctic Match campaigns, coordinated by AWI, and additional 3 passive Arctic Match analyses, funded by the EU and national institutes, have been carried out since the winter 1991/92, most recently in the Northern Hemisphere winter 2016/2017. These campaigns have been instrumental for our current understanding of chemical ozone loss in the Arctic.

Since 1 December 2013 AWI coordinates the EU project StratoClim (budget ~12 million Euros, 28 partners from 11 European countries) which aims to strengthen our understanding of the role of stratospheric aerosols, ozone and water vapor on climate. Within that project an airborne campaign was carried out in the Bay of Bengal in 2016 and a station on the West Pacific Island Palau is taking measurements with ozone-sondes and a FTIR for at least 2 years.

KIT scientists are member of ESA's MIPAS Quality Working Group, the ACE-FTS Science team and various science teams of international space experiments. Further, they are involved and play a leading role in the Network for the Detection of Atmospheric Composition Change (NDACC), in a number of SPARC activities (WAVAS, SDI, Stratospheric Sulphur, CCMI, SI2N and LOTUS) and participate to ESA's Climate Change Initiative, where the KIT-IMK ozone product from MIPAS is preferred over the official ESA data product. KIT contributes to the STRATOCLIM EC project, the DFG Research Unit SHARP, and the BMBF research program ROMIC. J. Orphal is president of the ACSO committee of WMO/IO3C/IGACO (see also Orphal et al., 2016).

IUP Bremen scientists are members of ESA's SCIAMACHY Quality Working Group and are on the advisory boards of upcoming new missions (Sentinel 5P, 4, and 5). They are participating in several ESA/DLR projects (validation, verification algorithm development, Copernicus program) and part of various science teams of international space missions. IUP Bremen was involved in the DFG Research Unit SHARP and is involved in the BMBF Priority Program ROMIC.

German modelling groups are contributing to the International Chemistry-Climate-Model Intercomparison (CCMI), where key simulations for the prediction of the future evolution of the ozone layer under various scenarios for changing ODS and greenhouse gas concentrations are being done. CCMI will deliver key input for the next UNEP/WMO Scientific Assessment of Ozone Deple-

tion. It is expected that German scientists will contribute substantially again to the upcoming assessment.

Key Programs:

ROMIC – Role of the Middle Atmosphere in Climate – BMBF German Federal Ministry for Research

MiKlip I, II, - Mid-range Climate Prediction - – BMBF German Federal Ministry for Research

SHARP – Stratospheric Change and its Role for Climate Prediction – Deutsche Forschungsgemeinschaft.

IAGOS-D - In-service Aircraft for a Global Observing System – BMBF German Federal Ministry for Research

POLSTRACC - Polar Stratosphere in a Changing Climate – Helmholtz Gesellschaft and Deutsche Forschungsgemeinschaft.

SHIVA - Stratospheric Ozone: Halogen Impacts in a Varying Atmosphere- European Community, Framework 7

STRATOCLIM - Stratospheric and upper tropospheric processes for better climate predictions – European Community, Framework 7

MACC II / III - Monitoring Atmospheric Composition and Climate Interim Implementation - European Community, Framework 7, Horizon 2020

CAMS – Copernicus Atmospheric Monitoring Service – European Commission

ESA_CCI – ESA Climate Change Initiative – European Space Agency

6. FUTURE PLANS

Generally, German ozone observations and research activities are expected to continue along the indicated lines. Funding is expected to continue from national and European sources and projects, however, with a generally decreasing trend.

The German Aerospace Centre (DLR-EOC) is leading the development of the operational system for processing the TROPOMI/Sentinel-5-Precursor data (to be launched in 2017) in close collaboration with leading scientists from the institutes KNMI (The Netherlands) , SRON (The Netherlands). IUP Bremen, MPIC Mainz, BIRA (Belgium), and RAL (UK). In the same way, DLR-EOC will play a key role in the processing of the Sentinel 4 and Sentinel 5 data.

KIT, together with the Research Center Jülich, is Lead Investigator of the German satellite project AtmoSat, carrying a limb-2D-imaging infrared spectrometer, in order to observe the chemical composition and dynamics of the upper troposphere, the stratosphere and the lower thermosphere, at unprecedented spatial resolution and coverage. AtmoSat is currently being evaluated by the German Wissenschaftsrat. If accepted, AtmoSat will be launched in 2023 with a proposed lifetime of at least 5 years. During the POLSTRACC (The Polar Stratosphere in a Changing Climate) campaign in winter 2015/2016 a large number of trace gases were measured in the lower stratosphere and UTLS, by a number of instruments from different institutes onboard the German research aircraft HALO. Similar aircraft campaigns are envisioned for the future.

Within the EU project StratoClim AWI and Uni Bremen together with international collaborators will perform measurements with ozonesondes, FTIR and a multi-wavelength cloud/aerosol lidar for about 2 years on the West Pacific island Palau.

German modeling simulation activities will continue within the international framework of, e.g., CCMI, to clarify the expected evolution of ozone (recovery, super-recovery, tropical decline), but also to address the important links with climate change (tropospheric warming, stratospheric cooling, changes in wave driving, possible acceleration of the Brewer Dobson circulation).

7. NEEDS AND RECOMMENDATIONS

- Adequate tracking of the expected ozone layer recovery process requires continuing high-quality measurements of total ozone and ozone profiles by satellites and ground-based systems for the next decades. High-quality data and long-term records of ozone, temperature, and UV must have high priority.
- Quality Assurance/Quality Control activities like calibration centres are essential in order to achieve the required accuracy of the global ozone observing system. They lay the foundation for satellite validation, for ozone monitoring, and for trend analyses.
- Within this context, the finalization and implementation of new ozone cross-section/absorption coefficients across the various instruments, both ground-based and satellite-borne, with an accuracy reaching 1% or better, remains a high priority.
- The complex coupling of ozone, atmospheric chemistry, transports and climate changes is still not fully understood. High quality, long-term data sets and continued modelling efforts are key prerequisites to understand and track the underlying processes.
- Further model studies are required to better quantify the expected substantial changes in both ozone and temperature distributions, and for different emission scenarios.
- Critical stratospheric constituents that are relevant for ozone and green-house warming/stratospheric cooling need to be monitored in the future as well. This monitoring program must include a limited number of high quality ground-based stations targeting the middle atmosphere, as well as direct sampling of stratospheric air from air-borne platforms such as high flying aircrafts and balloons.
- The lack of future limb sounding satellite instruments is of great concern. Vertically resolved profiles not only of ozone but also other key constituents are essential for monitoring and attribution of future ozone changes, resulting from recovery from man-made halogen loading, but also under the influence of a changing climate.