Still a large number of institutions in Germany have been very active in ozone and UV research and monitoring. Table 1 as a summary shows a compilation of these institutes and their activities. Generally, universities and research centers (MPI, DLR, KIT, FZ-Jülich, AWI) are more research oriented, government agencies (DWD, BfS, UBA) are focused on long-term monitoring. Germany is a key player for several satellite instruments (GOME, SCIAMACHY, MIPAS, GOME-2/MetOp-A, GOME-2/MetOp-B). Ground based long-term observations in Germany are provided primarily by DWD (Hohenpeissenberg and Lindenberg stations) and by AWI in the Arctic and Antarctic (Ny-Ålesund/Koldewey and Neumayer stations). UV-monitoring is carried out by BfS, UBA and DWD. Germany is also supporting crucial international quality-assurance and quality-control activities by hosting the World Calibration Centre for Ozone Sondes (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)

<table>
<thead>
<tr>
<th>Institute</th>
<th>Location</th>
<th>Fields</th>
<th>Keywords</th>
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<tbody>
<tr>
<td>Deutscher Wetterdienst (DWD)</td>
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<td>MT, R, QA/QC</td>
<td>RDCC-E, NDACC, GAW</td>
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<td>Alfred Wegener Institut für Polar u. Meeresforschung (AWI)</td>
<td>Potsdam, Bremerhaven</td>
<td>R, MT, D</td>
<td>Neumayer, Ny-Ålesund, Polarstern, MATCH</td>
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<td>Forschungszentrum Jülich (FZJ)</td>
<td>Jülich</td>
<td>R, QA/QC, MD</td>
<td>Calibration O&lt;sub&gt;3&lt;/sub&gt;-Sonde, JOSIE, ClaMS</td>
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<td>Oberpfaffenhofen</td>
<td>R, MD, MT, QA/QC</td>
<td>GOME, SCIAMACHY, GOME-2, ECHAM, Air-Traffic</td>
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<td>R, D, MT</td>
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<td>Bundesamt f. Strahlenschutz (BfS)</td>
<td>Salzgitter</td>
<td>MT</td>
<td>UV</td>
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<tr>
<td>Umweltbundesamt (UBA), <a href="http://www.umweltbundesamt.de">www.umweltbundesamt.de</a></td>
<td>Berlin</td>
<td>MT</td>
<td>Air quality</td>
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<tr>
<td>Uni Bremen, IUP, <a href="http://www.iup.uni-bremen.de">www.iup.uni-bremen.de</a></td>
<td>Bremen</td>
<td>R, D, MT</td>
<td>GOME, SCIAMACHY, GOME-2, MICROWAVE, DOAS, FTIR</td>
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<td>R, MD</td>
<td>EURAD,</td>
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<td>Uni Mainz, MPI f. Chemie (MPI)</td>
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<td>R, MD</td>
<td>ECHAM/Chem</td>
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<td>R, MD</td>
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<td>Karlsruhe</td>
<td>R, D, MD, MT, QA/QC</td>
<td>MIPAS, FTIR, ENVISAT, LIDAR, CARIBIC</td>
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</table>
1. OBSERVATIONAL ACTIVITIES

German agencies are major players in long-term ground-based monitoring and in ongoing satellite measurements of ozone and related trace gases.

Table 2. Operational ground-based network for long-term measurements of ozone and UV

<table>
<thead>
<tr>
<th>Type of observation</th>
<th>Location</th>
<th>Org.</th>
<th>Instrument</th>
<th>Type/No.</th>
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<td>Brewer</td>
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<td>Microtops</td>
<td>No. 3128, No. 3785</td>
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<td>Dobson</td>
<td>No. 071</td>
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<td>Lindenberg</td>
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<td>Brewer</td>
<td>No. 030, No. 078, No. 118</td>
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<td>Garmisch, Karlsruhe Izana, Kiruna</td>
<td>IMK, IFU</td>
<td>FTIR</td>
<td></td>
<td>2002</td>
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<td>DWD</td>
<td>Dobson RDCC-E</td>
<td>No. 064</td>
<td>1999</td>
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<td>DWD</td>
<td>Ozonosonde</td>
<td>Brewer-Mast</td>
<td>1967</td>
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<td>LIDAR (Stratosphere)</td>
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<td>Ozonosonde</td>
<td>ECC</td>
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<td>Ny Alesund (Svalbard)</td>
<td>AWI</td>
<td>LIDAR</td>
<td>1991</td>
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<td>Ny Alesund (Svalbard)</td>
<td>IUP</td>
<td>μWave Radiometer</td>
<td>2002</td>
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<td>Forster + Neumayer (Antarctica)</td>
<td>AWI</td>
<td>Ozonosonde</td>
<td>ECC (since 1992)</td>
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<td>Bentham DM 150, DM 300</td>
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IUP Bremen is the lead PI for the SCIAMACHY instrument on ENVISAT (2002-2012), and GOME (1995-2011), both for instrument and algorithm development, as well as advanced data processing. Scientific data processing for GOME-2 (since 2006) are done as well by IUP.

The Institute für Meteorologie und Klimaforschung (IMK) of the Karlsruhe Institute for Technology (KIT) operates ozone analyzers aboard the CARIBIC observatory (www.caribic.de) which is based on a 1.5 ton automated measurement container deployed monthly on 4 consecutive long distance flights. A precise large scale UTLS climatology has been established and is continued. CARIBIC is part of IAGOS (www.iagos.org) which combines the MOZAIc approach (packag-
es aboard a large number of aircraft for ozone and other trace gases and aerosol) with the CARIBIC approach (a large automated flying atmospheric chemistry observatory). IAGOS is being fostered by the German Ministry of Education and research as a European Infrastructure. IAGOS-CORE and IAGOS-CARIBIC form, especially at times when satellite capabilities have been reduced, an increasingly important pillar in global scale observations.

**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 cover more than four decades for column ozone and ozone profiles (Dobson since 1964 (Potsdam/Lindenberg) and 1967 (Hohenpeissenberg) and Brewer since 1983, balloon-sonde since 1967, and more than 25 years for stratospheric LIDAR observations up to 48km (since 1987). 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-EOC)** provides the operational satellite total ozone and tropospheric ozone data for the sensors GOME, SCIAMACHY, GOME-2/MetOp-A, and GOME-2/MetOp-B. In the same way DLR-EOC is leading the development of the operational systems for the TROPOMI/Sentinel-5-Precursor mission. Ozone as well as trace gas measurements (total NO2, tropospheric NO2, SO2, BrO, H2O, HCHO) and cloud information from GOME-2 are fee available two hours after sensing. The following figure 1 shows the ozone measured by the GOME-2 sensors on September 29th, 2013. DLR/DFD is providing much of the ground-processing for several satellite missions and also hosts the World Data Centre for Remote Sensing of the Atmosphere (WDC-RSAT).

![Ozone total column](http://atmos.eoc.dlr.de/gome2ab)

**Fig. 1:** Ozone hole as measured by the GOME-2 sensors operated in tandem on-board the MetOp-A and MetOp-B satellites. Plot by D. Loyola, DLR.

The **Alfred Wegener Institute for Polar and Marine Research (AWI)** operates two fully equipped polar stations in the Arctic (Koldewey/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. 2). A full suite of NDACC measurements is running at the primary station Koldew-
ey/Spitsbergen. 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.

Column measurements of ozone and other gases/variables relevant to ozone loss are performed with FTIR and DOAS at the German-French station AWIPEV in Ny-Ålesund/Spitsbergen. (AWI together with U. Bremen). Profile measurements of ozone and other gases/variables are done with ozone soundings at Neumayer Station (Antarctica) and at the German-French station AWIPEV in Ny-Ålesund/Spitsbergen, where also a Microwave (U. Bremen) is operated.

While ENVISAT was lost in April 2012, processing of new MIPAS/ENVISAT data versions is still going on. Data products generated at KIT-IMK include global fields of ozone, temperature, tropospheric source gases and their decomposition products (e.g. H2O, CH4, N2O, CFC-11, CFC-12, HCFC-22, COCl, SF6, SO2, OCS), chlorine radicals and reservoirs (ClO, ClONO2, HOCl), nitrogen reactants and reservoirs (NO, NO2, HNO3, N2O5, ClONO2, HNO4, BrONO2), odd hydroxyl reservoirs (HOCl, HOX), pollutants relevant to upper tropospheric ozone chemistry (CO, C2H6, C2H2, HCN, formic acid, acetone, PAN), and cloud particle properties of PSCs relevant for the polar ozone loss.

Trends of chlorine reservoir species, HCl and ClONO2, and of HF were derived by KIT-IMK from ground-based FTIR data of 17 NDACC sites, and were compared with model data (Kohlhepp et. al., ACP 2012). For the period of 2000 to 2009 a decrease of HCl and ClONO2 was observed at all sites. The latitudinal dependence is also discussed in the paper. Together with our colleagues from AEMET (Spain), a long-term time series of ozone was derived from Izana FTIR observations. Furthermore, a detailed error characterisation and comparison with data from other techniques and finally, a trend study is given (Garcia et al., AMT 2012 & Garcia et al., AMTD 2014).

1.1. Calibration activities

The Forschungszentrum Jülich hosts the World Calibration Centre for Ozone Sondes (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.

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 a group of ozone sonde experts under the lead of the WCCOS started in 2012 in the context of the SPARC/IGACO-O3/IOC initiative on “Understanding past changes in the vertical distribution of ozone” 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. We aim to reduce uncertainties between long term

Fig. 2: Time and altitude plot of ozone partial pressure from German ozone soundings over Antarctica. Plot by G. König-Langlo, AWI Bremerhaven.
sounding records from 10-20% down to 5-10% through the use of generic transfer functions. It is expected to finalize the activity by 2015 by providing a well documented and homogenized ozone sonde data set that can be used for long term ozone trend determination and satellite validation purposes.

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 now approximately 20 operational Dobson spectrophotometers in Europe since 1999, including the Antarctic Dobsons at Halley Bay (British Antarctic Survey BAS) and Vernadsky (Ukraine). The support of the establishment of the Regional Dobson Calibration Centre for WMO RA I Africa, to be run by the South African Weather Service has been continued. The refurbishment of European Dobsons being out of operation and their relocation mostly outside of RA VI became more and more important.

The success of the calibration activities in the global Dobson calibration system can be seen in Fig. 3. A majority of the Dobsons to be calibrated match with the reference instrument during the initial comparison with 1%.

Fig. 3: Relative difference between field Dobson and reference instrument during initial calibration. Plot by U. Köhler, DWD Hohenpeissenberg.
MIPAS/ENVISAT data products, particularly O3, CH4 and CFCs, were extensively validated by comparison with independent measurements. For MIPAS-ozone the instrumental drift has been quantified in order to be able to calculate drift-corrected trends (Figure 4).

Fig. 4: This figure shows the trend in stratospheric ozone - between 10 and 50km - as derived from MIPAS measurements for the time period of July 2002 to April 2012. Hatched areas denote trends which are less than twice as large as their error and, thus, less significant than to the 2-sigma level.

A more detailed description of this figure is given under 2. Results from Observations and Analysis in the section MIPAS results obtained by the Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (KIT-IMK).
1.2. UV-measurements

The working group of G. Seckmeyer of the Institute of Meteorology and Climatology from the Leibniz University Hannover recently developed a new non-scanning multidirectional spectroradiometer Instrument for simultaneous measurements of spectral sky radiance. The Instrument is a non-scanning MultiDirectional Spectroradiometer (MUDIS), which can measure the spectral sky radiance as a function of zenith and azimuth angle with a high spectral and temporal resolution. The instrument is based on a hyperspectral imager and measures spectral sky radiance in the wavelength range of 250–600 nm at 113 different directions simultaneously (Riechelmann et al. (2013)).

The newly developed spectroradiometers are versatile Instruments with a wide range of application possibilities. Some of these are for example: vitamin D weighted Exposure determination, Solar Energy Applications, Derivation of trace gases by DOAS techniques, investigation of aging of materials (e.g. on facades), Radiance and plant growth applications and more.

For the determination of vitamin D weighted exposure a novel method by integrating the incident solar spectral radiance over all relevant parts of the human body has been developed (Seckmeyer et al., 2013). 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. Seckmeyer et al. (2013) assumed that sufficient vitamin D can be produced within the human body in one minute for a completely uncovered body in vertical posture in summer at midlatitudes (e.g. Rome, June 21, noon, UV index of 10) and calculated the exposure times needed in other situations or seasons to gain enough vitamin D. The results showed that at the winter solstice (December 21, noon, cloudy) at least in central Europe sufficient vitamin D cannot be obtained with realistic clothing, even if the exposure were extended to all daylight hours.

To determine the erythemally weighted irradiance, dosimeters could be used. The Institute compared the doses of erythemally weighted irradiances derived from polysulphone (PS) and electronic ultraviolet (EUV) dosimeters with measurements obtained using a reference spectroradiometer. The results of the Investigation published in Seckmeyer et al. 2012 concluded that while UV dosimeters are useful for their design purpose, namely to estimate personal UV exposures, they should not be regarded as an inexpensive replacement for meteorological grade instruments.

A further instrument developed by the working group of Herr Seckmeyer is the hemispherical sky imager (HSI) system. The system contains a commercial compact CCD (charge coupled device) camera equipped with a fish-eye lens. This system is capable of measuring sky luminance with high spatial and temporal resolution of more than a million pixels and every 20 seconds respectively. In addition radiance data are derived from images of the HSI system as well. The results are presented in Tohsing et al. (2013) and Tohsing et al. (2014). Furthermore long term cloud monitoring is performed.

Within the network of atmospheric composition change an intercomparison of UV spectroradiometers is planned at the Leibniz University of Hannover, Germany in summer 2014. The participants will likely come from Germany, France, Austria and Chile.
Dr. Koepke’s radiation group at the Meteorological Institute of the Ludwig-Maximilians-University (MIM-LMU) has been performing regular UV-observations in Munich and on the Zugspitze (UFS Zugspitze) in close co-operation with Prof. Blumthaler from the University Innsbruck (Austria) since 2004. The following two figures 5a and b show the climatology of the corresponding UV-Index at both locations.

**Fig. 5a and b: IV-Index at the stations Munich (left panel) and Zugspitze (right panel)**

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 ozone loss Match campaigns have been carried out for 20 years. They are a major component of European and world-wide ozone research. They document the long-term evolution of polar ozone loss over the Arctic. The unusually cold Arctic winter vortex of 2010/2011 has resulted in the largest ozone loss ever measured above the Arctic (Fig. 6), comparable to a normal Antarctic winter. Substantial ozone loss but less than expected ozone loss was observed in the most recent winter 2013/14.

**Fig. 6: “Arctic 2011 Ozone hole profiles”: Ozone loss profile. Illustration of the vertical profile of the ozone hole at an altitude of around 15 and 25 kilometres. The red curve shows that the ozone loss profile in spring 2011 was largely comparable to the Antarctic ozone holes. Graphic: Markus Rex, Alfred Wegener Institute.**

AWI in collaboration with the University Bremen and the GEOMAR have shown the existence of a pronounced minimum in the tropospheric column of ozone over the West Pacific (see Fig.7), the main source region for stratospheric air. Modelling based on this finding and a single
measurement of OH available in air from this area suggest a corresponding minimum of the tropospheric column of OH. This has the potential to amplify the impact of surface emissions on the stratospheric composition. Specifically, the role of emissions of biogenic halogenated species for the stratospheric halogen budget and the role of increasing emissions of SO2 in South East Asia or from minor volcanic eruptions for the increasing stratospheric aerosol loading, and hence stratospheric ozone chemistry, need to be reassessed in light of these findings. This is also important since climate change will further modify OH abundances and emissions of halogenated species. The study is based on ozone sonde measurements carried out during a cruise ("TransBrom") with the RV Sonne roughly along 140–150° E in October 2009 and corroborating ozone and OH measurements from satellites, aircraft campaigns and FTIR instruments. Model calculations with the GEOS-Chem Chemistry and Transport Model (CTM) and the ATLAS CTM were used to simulate the tropospheric OH distribution over the West Pacific and the transport pathways to the stratosphere. The potential effect of the OH minimum on species transported into the stratosphere has been shown via modeling the transport and chemistry of CH2Br2 and SO2 (Fig. 8a-c).

![Ozone profiles in the West Pacific](image1)

**Fig. 7:** “West pacific ozone profiles”: Ozone profiles measured in three different marine regions: the tropical Atlantic, the tropical West Pacific and the West Pacific outside the tropics. The red curve shows that ozone is consistently at or below the detection limit throughout the troposphere over the tropical West Pacific. In the other regions the ozone concentrations are in a range typical for the troposphere. Graphic: Markus Rex, Alfred Wegener Institute.

![Ozone and OH holes](image2)

**Fig. 8a-c:** “Ozone and OH holes”: Location and extent of low ozone concentrations and thus of the OH hole over the West Pacific. Fig. 8a shows the region of origin of the air in the stratosphere, Fig. 8b ozone sonde measurements (dots) and satellite measurements (coloured map) of the total amount of ozone in the tropospheric column of air and Fig. 8c the total amount of OH in the tropospheric column of air calculated with a model. Graphic: Markus Rex, Alfred Wegener Institute.
Stratospheric chlorine trend measurements at the IMK and IfU sites (ground-based), as well as balloon-borne measurements from Frankfurt and Heidelberg Universities, indicate declining chlorine since the mid 1990ies. This shows the success of the Montréal protocol. The data from University of Heidelberg and University of Frankfort show that Bromine has also started to decline in recent years (see Fig. 9).

**Fig. 9:** Total stratosph. Bry from balloon-borne BrO observations (squares) and annual means from ground-based measurements at Harestua (60°N) and Lauder (45°S). The stratospheric data are compared to bromine (ppt) measured at the Earth’s surface, with varying amounts of very short lived Bromine species added (blue lines). By K. Pfeilsticker IUP Heidelberg.
Ozone trend analyses Hohenpeissenberg (Dobson, see Fig. 10) reveal increasing stratospheric ozone since the late 1990s. Ozone increase in the upper stratosphere (not shown) is a first sign of a beginning ozone recovery, but this is not so clear for the total ozone column and the lower stratosphere. There, dynamical factors like the Arctic Oscillation (AO) contribute majorly to the recently enhanced levels. As Figs. 6 (and also Fig. 8 and 9) indicate, 2010 was a year with much higher total ozone than observed in the last 15 to 20 years. This substantial increase in just one year can be attributed to the phase of the QBO in early 2010, and to the extreme negative phase of the AO in much of 2010 (compare Fig. 4). In contrast to 2010 the years 2011 and 2012 showed again very low values partly coming from an again reversed AO index and in addition in 2011 an ozone hole occurred over the North Pole. This ozone poor airmass reached the mid-latitudes after the break of the polar vortex in spring and early summer (see also Fig. 10 and 11).

Recent analysis of ten years of SCIAMACHY and MIPAS limb ozone profiles show an increase in upper stratospheric ozone since 2002 which are 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) which are likely related to changes in NOy and tropical upwelling. Since 2000 total ozone in the northern extratropics show large interannual variability but overall little changes after a brief period from the middle 1990s until 2000 where total ozone level strongly increased (Fig. 11). Multiple linear regressions accounting for different factors contributing to ozone changes clearly indicate that the long-term decline up to the middle 1990s has stopped in the extratropics in both hemispheres proving the success of the Montreal Protocol.
Fig. 11: Evolution of total ozone anomalies since 20021979. Plot is based on the merged SBUV/TOMS/OMI MOD V8 data record (1978-1996) and merged GOME1/SCIAMACHY/GOME2 (GSG) record. Anomalies were calculated from area weighted monthly mean zonal mean data in 5° latitude steps, by removing the seasonal mean from the period 1980-2008 (Plot by M. Weber, IUP Bremen).

Fig. 12: Timeseries of annual mean ozone from the GOME/SCIAMACHY/GOME-2 dataset along with the SBUV MOD V8.6 merged ozone and World Ozone and UV Data Center (WUDOC) ground data. Annual means are shown for various latitude bands from NH middle latitudes (30°N-60°N), tropics (25°S-25°N), to SH middle latitudes (30°S-60°S) in the lower three panels. The global mean (60°S-60°N) is shown in the top panel. Indicated in the plots are the expected change in ozone from the effect of the equivalent effective stratospheric chlorine (EESC). Tropical ozone does not show a significant long-term trend with respect to EESC changes, but solar cycle (11 years) variability is evident. The EESC curves indicate a modest (anthropogenic) recovery of ozone of roughly 2-3 DU at middle latitudes in the last ten years. However, year-to-year changes can amount to up to ±15 DU (Plot by M. Weber, IUP Bremen).
The interannual variability in extratropical total ozone is related to variability in the Brewer-Dobson circulation (Fig. 12). The variability in atmospheric dynamics resulted in extreme events like the above average total ozone levels throughout 2010 in the northern hemisphere, the substantial Arctic ozone loss in 2011, and below average ozone hole above Antarctica in 2002.

The following MIPAS results were obtained by the Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research (KIT-IMK):

Large Arctic ozone loss during the exceptionally cold winter 2010/2011 was observed by MIPAS/ENVISAT (Sinnhuber et al., 2011). Bohlinger et al. (2014) investigated the possibility that the cold Arctic winters in the stratosphere may be getting colder as a result of increases in greenhouse gases.

MIPAS SF6-based age-of-air measurements indicate decadal changes in the meridional circulation. The data hint at an overall increased tropical upwelling, together with changes in the mixing barriers. These circulation changes were also shown to affect the distribution of CFCs in the stratosphere: While a decrease of stratospheric CFC mixing ratios is clearly observed, stratospheric trends measured by MIPAS were found to differ from age-of-air corrected tropospheric trends inferred from in-situ measurements. This can only be explained by decadal changes in atmospheric age-of-air spectra or vertical mixing patterns. Also the explanation of MIPAS ozone trends requires circulation changes: otherwise the ozone trend distribution patterns cannot be understood satisfactorily.

In order to avoid artefacts in MIPAS ozone trends, special emphasis was laid on performing the trend analysis on the basis of drift-corrected data. The result of this analysis is shown in Fig. 4, where hatched areas denote significance levels of less than 2 sigma. A hemispheric asymmetry is clearly visible. Larger areas of significant positive trends (red tiles) were found in the southern hemisphere. In the northern hemisphere positive trends appear at higher altitudes, while some negative trends are present at altitudes around 20 to 30 km. In the tropics positive ozone trends were found just above the tropopause, while there are two areas of negative trends around 25 and 35 km. This is contradictory to recent literature, especially model runs, which predict negative trends just above the tropical tropopause due to increased upwelling in this region. Supposedly changes in global circulation can help to explain these differences.

MIPAS/ENVISAT measurements of sulphur compounds (SO2, COS) help to understand stratospheric sulphur chemistry, which is, due to its link to aerosol formation, also relevant for stratospheric ozone. Further, MIPAS measurements have helped to better understand the kinetics of the HOCl formation from HO2 and ClO. Another important focus of science with MIPAS data is the perturbation of ozone chemistry by air noxified/hoxified/cloxified by particle precipitation. While during solar proton events, particle-induced chemistry was observed to happen also in the stratosphere, normally NOx is generated in the thermosphere and subsides into the polar winter stratosphere, where it provides a substantial fraction of the total polar NOx.

Balloonborne observations with the MIPAS instrument have given first observations of the chlorine monoxide dimmer (ClOOCl) in the polar stratosphere and its role for polar ozone loss chemistry (Wetzel et al., 2010, Wetzel et al., 2012). Simultaneous observations of HNO3 with PSC particles emphasize the role of non-spherical particles for denitrification (Woiwode et al., 2014).

Ozone-hole monitoring (DLR)

Since 2007 near-real-time ozone observations from the GOME-2 instrument aboard MetOp have been operationally assimilated into the three dimensional chemical-transport model ROSE/DLR. These daily analyses of the global total ozone column allow for a synoptic view on the current total column ozone distribution and variability. This is especially important where direct observational data is missing, e.g. during the polar night. Figure 15 shows the daily ozone-hole size derived from the assimilated fields. Monthly means are derived to facilitate the comparison between different years (figure 14).

As part of the MACC II (Monitoring Atmospheric Composition and Climate: http://www.copernicus-atmosphere.eu/) project, the 4Dvar chemical data assimilation system SACADA performs full chemical analyses and forecasts of the stratospheric composition. Currently, total column observations of the abovementioned instrument MetOp/GOME-2 and ozone pro-
files AURA/MLS are assimilated on an operational daily basis (figure 13). Beside ozone, the MLS assimilation includes HCl, HNO3, N2O and H2O. The GOME-2 based analyses have been recently compared to other stratospheric MACC analyses (Lefever et al., 2014). The study showed the importance of profile information for good quality ozone analyses. All forecasts and analyses are available at the WDC/RSAT.

**Figure 13: Assimilated ozone field based on MLS/AURA observations.**

**Figure 14: The satellite-based ozone analyses are used to continuously monitor the interannual variability of the Antarctic ozone hole. The bullet figures depicts the evolution of the Antarctic ozone hole by the September mean for the years 2011, 2012 and 2013.**
Sampling of stratospheric air has been continued at the University of Frankfurt in an effort to monitor stratospheric chemical composition and to determine mean age, which serves as a proxy for the strength of the stratospheric circulation (Brewer-Dobson circulation). Based on these observations the long term evolution of total chlorine in the stratosphere has been calculated (Fig. 16., updated from (Engel et al., 2002)) and updated for the scientific assessment report to be pub-

\[\text{Ozone Hole: Area } [10^6 \text{ km}^2]\]

![Ozone Hole Graph](image)

**Figure 15: Daily ozone-hole size based on GOME-2 observations.**

Fig. 16: temporal evolution of total chlorine in the mid-latitude stratosphere, based on tropospheric trends and age of the air (see (Engel et al., 2002) and the upcoming scientific assessment for details).
lished in 2014. The data show that total chlorine has reached its maximum at all stratospheric levels now and is declining steadily.

Further studies by University Frankfurt included the budgets of chlorine, bromine and iodine species in the troposphere (Laube and Engel, 2008; Brinckmann et al., 2012; Sala et al., 2014; Tegtmeier et al., 2013) and the stratosphere (Laube et al., 2008; Laube et al., 2010), as well as emissions of halogen species in the troposphere, chemical transformation during the transport to the stratosphere and chemistry of the stratosphere (Hamer et al., 2013; Hossaini et al., 2013; Montzka and Reimann et al., 2011; Wetzel et al., 2010)

**Studies of stratospheric transport and its possible climate-related change.**

A key aspect for the future evolution of the stratosphere is the impact of global change on stratospheric composition, temperatures and dynamics. University Frankfurt has contributed to this issue with studies of dynamical processes and their possible changes in the past decade. In particular we investigated the long term trend in mean age using observations of age tracer CO$_2$ and SF$_6$ (Engel et al., 2009; Ray et al., 2010) from balloons and of a variety of tracers from airborne observations (Boenisch et al., 2011). These observations all indicate that the assumption of single trend in mean age (and thus overall stratospheric transport) is overly simplified (Birner and Bönisch, 2011). Rather there is increasing evidence that a strengthening of the circulation is more restricted to the lower part of the stratosphere.
3. THEORY, MODELLING, AND OTHER RESEARCH

In particular, chemistry-climate models (CCMs) are used in Germany to simulate and understand the recent changes and trends of the stratospheric ozone, and to predict the future evolution of the ozone layer. German activities are well interfaced to international programs like the SPARC/IGAC Climate-Modelling Initiative (CCMI), which has been co-led by DLR staff. EMAC, a CCM has been established; a consortium is led by DLR with partners from MPI for Chemistry and the University in Mainz, MPI for Meteorology in Hamburg, FU Berlin, and KIT. Coordinated model simulations and analyses have been performed. EMAC has been used to simulate the decadal trends from the 1960s to 2100; results contributed significantly to the recent UNEP/WMO Scientific Assessments of Ozone including the upcoming report which is now written. As an example, the Figure 17 shows spring-to-fall ratio of observed polar cap total ozone (>500) as a function of the absolute extra-tropical winter mean eddy heat flux (September to March in the Northern Hemisphere (NH) and March to September in the Southern Hemisphere (SH)) derived from ECMWF ERA-Interim data (left side). Data from the SH are shown as triangles (September over March ozone ratios) and from the NH as solid circles (March over September ratios). Selected polar total ozone distributions for selected years are shown at the top-left. Respective results performed by CCM simulations are presented on the right (updated from Weber et al., 2011).

![Figure 17: Description see text](image)

**MACC GRG model intercomparison (DLR)**

The global chemical data assimilation systems BASCOE and SACADA are run in parallel to the MOZART-IFS chemical forecasting system at ECMWF (MACC o-suite) providing independent stratospheric analyses. We here report on offline experiments using chemistry-only runs by MOZART, BASCOE and SACADA chemistry modules. By analyzing the performance of the three different chemistry schemes, it is hoped that we can learn for the future development of the C-IFS with full stratospheric chemistry. While results are consistent for most chemical species, significant differences are found for the intermediate reservoir gases leading to ozone changes of up to 20% at 10 hPa after 30 days of integration. In the upper stratosphere, differences probably due to different photolysis rates are even higher (figure 18). With respect to ozone depletion, the model’s polar stratosphere is dominated by the parameterizations of liquid and solid particles at low temperatures. In middle and low latitudes, the three reaction systems simulate significantly different gas phase partitioning. An update of the SACADA reaction system to better comply with BASCOE’s reduces some differences. But model-model deviations are still significant.
Satellite observations have been a reliable source of profile data on stratospheric trace gases for almost two decades. Thanks to improvements in data assimilation, the global distribution can now be derived at the instrument's error level, daily and with high reliability (e.g. Lefever et al., 2014). However, data gaps and instrument failure are common and can severely hamper assimilation results. What is more, the coming years will see a decline of profile resolving instruments. Therefore, Observing system simulation experiments (OSSEs) have been performed to investigate the impact of ozonesonde observations on a data assimilation system during a simulated satellite data gap in February 2003. Using the 4D-Var data assimilation system SACADA, the relative influence of launch rates and station coverage has been analyzed. Different network and sounding configurations were evaluated. Analysis skill and linear pattern correlation with respect to ERA-Interim reference data were assessed for the 20 km altitude level that is representative for the lower stratosphere (see figures 19 and 20). First-guess and analysis minus observation error statistics allowed optimization of a priori error settings. In this way, the assimilation of simulated and real-world ozone soundings could be appropriately calibrated. In summary, it is found that, during satellite data gaps, ozonesonde data can have a significant positive impact on the mean analysis skill depending both on the number of observations and the network layout. Based on the existing GAW system, a better layout with 28 stations and three soundings bi-weekly, proved clearly superior to VINTERSOL/MATCH. The positive gain in skill reached 0.26 compared to a free-running model.
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 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, which use prescribed ozone so far. This enables the inclusion of interactions of ozone and climate in this sort of models, which is not feasible due to computational constraints so far.

IUP Bremen is the PI institute for the SCIAMACHY instrument aboard the ENVISAT satellite. Research is made in the field of ozone and ozone relevant trace gas and aerosol retrievals, but also some modeling and analysis on time-scales ranging from ozone episodes to decadal changes. Scientific support includes validation and for the GOME-2, and SCIAMACHY projects, and the generation of consistent long-term data sets. IUP Bremen has also provided new ozone absorption cross-sections at high spectral resolution (~0.03nm) and covering atmospheric temperatures between 193 and 293 K and the wavelength range 230-1050 nm (Fig. 21).

**Figure 20:** The Pearson’s pattern correlation difference for February 2003 showing the overall improvement due to ozonesonde assimilation at 20 km altitude. Contour lines show significant correlation changes only.

**Figure 21:** New laboratory ozone absorption cross-section shown in the Huggins band. Indicated are also the operational Brewer and Dobson wavelengths. (Plot from Serdyuchenko, IUP).
The working group Physics of the Middle Atmosphere at the Institut für Meteorologie of Freie Universität Berlin (head: Prof. Dr. Ulrike Langematz) uses the EMAC chemistry-climate model 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. Another focus is the role of solar variability at different time-scales (27 days, 11 years, Maunder minimum) on stratospheric ozone and climate. A selection of results is presented below.

**Future Arctic Temperature and Ozone: The Role of Stratospheric Composition Changes**

(Langematz et al., 2014)

Multi-decadal simulations with the EMAC chemistry climate model were analyzed to examine the role of changing concentrations of ozone depleting substances (ODSs) and greenhouse gases (GHGs) on Arctic springtime ozone. The focus is on potential changes in the meteorological conditions relevant for Arctic ozone depletion. It is found that with rising GHG levels (as projected in the IPCC SRES A1B-scenario) the lower Arctic stratosphere will cool significantly in early winter, while no significant temperature signal is identified later in winter or spring. A seasonal shift of the lowest polar minimum temperatures from late to early winter in the second part of the 21st century occurs. However, Arctic lower stratosphere temperatures do not seem to decline to new record minima. The future Arctic lower stratosphere vortex will have a longer lifetime, as a result of an earlier formation in autumn. No extended vortex persistence is found in spring due to enhanced dynamical warming by tropospheric wave forcing. Because of the dominant early winter cooling, largest accumulated areas of polar stratospheric clouds (APSC) are projected for the middle of the 21st century. A further increase of APSC towards the end of the 21st century is prevented by increased dynamical polar warming. EMAC suggests that within the next few decades there is a chance of low Arctic springtime ozone in individual years, however there is no indication of a formation of regular Arctic ozone holes comparable to the Antarctic. Towards the end of the 21st century, when ODS concentrations will be close to pre-1960 levels, further rising GHG levels will lead to an increase of Arctic springtime ozone.

![Figure 22: Evolution of the Arctic average total ozone column in the REF (top panel) and NCC (bottom panel) simulations in March. Shown are deviations from the 1970-1982 mean [DU]. Dashed black lines indicate the dates of maximum Arctic Cly loading at 50 hPa and of its return to 1980 values. (from Langematz et al., 2014).](image)

The EMAC model projections of the future Arctic average total ozone column in Arctic spring (Figure 22, top) show that due to the regulation of ODS emissions by the Montreal protocol ozone will recover to 1970/1980s levels by the middle of the 21st century, when halogens will have strongly decreased. Due to the effects of rising GHGs (REF simulation) Arctic ozone will reach higher values by the end of the 21st century than in the past, in contrast to a hypothetical simulation with GHGs fixed at 1960 levels (non climate change NCC simulation).
Chemical contribution to future tropical ozone change in the lower stratosphere
(Meul et al., 2014)

The future evolution of tropical ozone in a changing climate was investigated by analysing time slice simulations made with the chemistry–climate model EMAC. Between the present and the end of the 21st century a significant increase in ozone is found globally for the upper stratosphere and the extratropical lower stratosphere, while in the tropical lower stratosphere ozone decreases significantly by up to 30 % (Figure 23). Previous studies have shown that this decrease is connected to changes in tropical upwelling. Here the dominant role of transport for the future ozone decrease is confirmed, but it is found that in addition changes in chemical ozone production and destruction do contribute to the ozone changes in the tropical lower stratosphere. Between 50 and 30 hPa the dynamically induced ozone decrease of up to 22% is amplified by 11–19% due to a reduced ozone production. This is counteracted by a decrease in the ozone loss causing an ozone increase by 15–28 %. At 70 hPa the large ozone decrease due to transport (~52 %) is reduced by an enhanced photochemical ozone production (+28 %) but slightly increased (~5 %) due to an enhanced ozone loss. It is found that the increase in the ozone production in the lowermost stratosphere is mainly due to a transport induced decrease in the overlying ozone column while at higher altitudes the ozone production decreases as a consequence of a chemically induced increase in the overlying ozone column. The ozone increase that is attributed to changes in ozone loss between 50 and 30 hPa is mainly caused by a slowing of the ClOx and NOx loss cycles. The enhanced ozone destruction below 70 hPa can be attributed to an increased efficiency of the HOx loss cycle. The role of ozone transport in determining the ozone trend in this region is found to depend on the changes in the net production as a reduced net production also reduces the amount of ozone that can be transported within an air parcel.

Figure 23. Latitude-height section of the change in the annual zonal mean ozone mixing ratio between the year 2000 and 2095 in ppmv (red/blue shading indicates positive/negative changes). Statistically significant changes on the 99% confidence level are coloured. Black contours indicate the relative ozone change in %, the contour interval is 10 %.

Chemistry climate model simulations of the effect of the 27 day solar rotational cycle on ozone
(Kubin et al., 2011)

The results from two simulations with the coupled chemistry climate model (CCM) ECHAM5/MESSy (EMAC) were analyzed for the effect of solar variability at the 27 day rotational time scale on ozone. One simulation is forced with constant spectral irradiances at the top of the atmosphere and the other one with daily varying irradiances using data of 1 year for solar maximum conditions. Consistent changes are applied to the photolysis scheme of the model. The model results show the main features of observed correlations between ozone and solar irradiance variability with a maximum positive correlation in the upper stratosphere and an anticorrelation in
the mesosphere. The relative sensitivity of upper stratospheric ozone to changes in the solar ultraviolet flux is estimated to be 0.3 to 0.4% per 1% change in 205 nm flux. During periods of strong 27 day variability, a similar upper stratospheric ozone sensitivity is derived. However, when the daily solar irradiance variability is weak and dominated by the 13.5 day period, the ozone sensitivity is reduced in the subtropics. The modeled temperature response is consistent with the ozone signal. When averaged over one rotational cycle, the ozone and temperature response to a neglect of the 27 day cycle is weak and statistically insignificant in the stratosphere but of non negligible magnitude and statistically significant in the equatorial mesosphere. Our results suggest that ignoring daily solar flux variations on the 27 day time scale in transient CCM simulations does not lead to a significant degradation of the time mean ozone response in the stratosphere, while in the tropical mesosphere, significant errors of up to 3% may occur.
4. DISSEMINATION OF RESULTS

4.1 Data reporting and providing

Data are regularly submitted to the data centers at Toronto, Thessaloniki, NILU and NDACC.

**World Data Center for Remote Sensing of the Atmosphere**

An important source for data is the World Data Center for Remote Sensing of the Atmosphere, WDC-RSAT. It offers scientists and the general public free access (in the sense of a “one-stop shop”) to a continuously growing collection of atmosphere-related satellite-based data sets (ranging from raw to value added data), information products and services. Focus is on atmospheric trace gases, aerosols, dynamics, radiation, and cloud physical parameters. Complementary information and data on surface parameters (e.g. vegetation index, surface temperatures) is also provided. This is achieved either by giving access to data stored at the data center or by acting as a portal containing links to other providers.

The WDC-RSAT is the most recent data center in the WMO-WDC family. In the context of IGACO within the WMO program Global Atmosphere Watch (GAW) and in line with the WMO-GAW Strategic Plan 2008-2015, WDC-RSAT especially concerns itself with linking different GAW-relevant data sets both, with each other and with models. In this context WDC-RSAT will also handle non-satellite based data which are relevant within the context of validation. As a contribution to WIGOS and in cooperation with the German Environmental Research Station Schneefernerhaus (UFS), WDC-RSAT is developing techniques providing WMO-GAW global stations with satellite based data and information products and to allow for computing-on-demand applications. Strategies and techniques to properly validate data sets, including for example data assimilation methods, are developed and tested. Aspects of the atmosphere’s variability at different temporal and spatial scales are addressed.

WDC-RSAT implemented an interactive map viewer (assessable at http://wdc.dlr.de → “Map Viewer”) which supports visualization and download of L3 and L4 data set obtained from satellite observations (e.g. MetOp/GOME-2) as well as from model analysis. The viewer is particularly designed to support the navigation through the four-dimensional space of model results (latitude / longitude / altitude / time) and the typically three-dimensional space of satellite observations (latitude / longitude / time). Examples see in Figures 24, 25 and 26.

![Figure 24: Ozone total column observations from MetOp-A/GOME-2 for 1st of February 2014 (L3 product). WDC-RSAT map viewer is assessable at http://wdc.dlr.de → “Map Viewer”.

![Figure 24: Ozone total column observations from MetOp-A/GOME-2 for 1st of February 2014 (L3 product). WDC-RSAT map viewer is assessable at http://wdc.dlr.de → “Map Viewer”.

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Figure 25: Activated chlorine at 56 hPa derived from ROSE/DLR model analysis for 1st of February 2013 (L4 product).

Figure 26: Chemically induced ozone change (ppb/day) at 56 hPa derived from ROSE/DLR model analysis for 1st of February 2013 (L4 product).
4.2 Information to the public

A noteworthy German contribution to WMO’s World Data Centers is the World Data Centre for Remote Sensing of the Atmosphere (WDC-RSAT). WDC-RSAT is hosted by the Cluster for Applied Remote Sensing at the German Aerospace Centre (DLR-CAF). WDC-RSAT offers scientists and the general public free access to a continuously growing collection of atmosphere-related satellite-based data sets and services. WDC-RSAT provides support for many Projects, e.g. the EU-funded MACC project. See http://wdc.dlr.de/ for more information.

The German Aerospace Centre (DLR-EOC) provides free access to satellite (GOME, GOME-2) atmospheric composition data and related services, see http://atmos.eoc.dlr.de/gome2 for more information.

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:
http://kunden.dwd.de/uvi/
http://www.bfs.de/de/uv/uv2/uv_messnetz/uvi/prognose.html

AWI:


Press release about tropospheric “ozone hole” in the tropical West Pacific causing an OH minimum (3 April 2014, http://www.awi.de/de/aktuelles_und_presse/pressespiele/pressespiele/detaill/item/pm_rex_englisch/?cHash=59a96f88d0c51b566b34370f5bd414)

Some of these press releases were widely picked up by the media resulting in hundreds of reports in online and print media as well as radio and tv broadcasts.

KIT-IMK trace gas climatologies from MIPAS/ENVISAT are part of the SPARC Data Initiative and accessible via http://www.sparc-climate.org/data-center/data-access/sparc-data-initiative/.

MIPAS ozone data have been selected by the Climate Change Initiative by ESA and are distributed as a harmonized data set via http://www.esa-ozone-cci.org/?q=node/161. The original data are available directly from IMK http://www.imk-asf.kit.edu/english/308.php.
4.3 Relevant scientific papers


Birner, T., and Bönisch, H.: Residual circulation trajectories and transit times into the extratropical lowermost stratosphere, Atmos. Chem. Phys., 11, 817-827, 10.5194/acp-11-817-2011, 2011.


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Jensen Eric J., Leonhard Pister, David E. Jordan, David W Fahey, Paul A. Newman, Troy Thornberry, Andrew Rollins, Glenn S. Diskin, T. Paul Bui, Matthew McGill, Dennis Hlava, R. Paul Lawson, Ru-Shan Gao, Peter Pilewskie, James Eikins, Eric Hintsa, Fred Moore, Michael J. Mahoney, Elliot Atlas, Jochen Stutz, Klaus Pfeilsticker, Steven C. Wofsy, Stephanie Hinot, Karen H. Rosenlof, The NASA Airborne Tropical TRopopause Exper...


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5. PROJECTS AND COLLABORATION

Germany continues its contribution to the preparation of the WMO ozone assessments. For the actual assessment, again several lead and co-authors, and many contributing authors came from German institutes.

German institutions also participate in a number of international and EU funded research projects, special measurement campaigns and modeling studies, such as CAWSES, SCOUT-O3, GEMS, GMES, MACC, SHIVA and RECONCILE. They play a major role in EUMETSAT and ESA projects.

The German Aerospace Centre (DLR-EOC) is responsible for the operational GOME-2 total and tropospheric ozone products, trace gas measurements (total NO2, tropospheric NO2, SO2, BrO, H2O, HCHO) and cloud information in the framework of EUMETSAT O3M-SAF project.

DLR is a key partner of ESA CCI ozone project coordinated by the BIRA (Belgium). DLR-IMF leads the team responsible for the total ozone products, DLR-PA leads the climate research group and DLR-DFD leads the system engineering team. As part of the CCI work the second version of the GOME-type Total Ozone Essential Climate Variable was created (GTO-ECV) covering the time period 1996 to 2011. There is an excellent agreement between GTO-ECV and the latest SBUV ozone data provided by NASA, see the figure 27 below.

![Graph](image)

Fig. 27: Differences in total ozone monthly zonal mean anomaly from GTO-ECV (ESA CCI), SBUV (NASA) and ground-based measurements. Courtesy D. Loyola, DLR.
German scientists are currently part of the science panel for the UNEP/WMO Scientific Assessment of Ozone Depletion: 2014 (Steinbrecht and Dameris are Lead-Authors).

Active participation in the ESA Climate Change Initiative, in particular the “Ozone_CCI”-project (DLR).

Several ongoing national and European funded projects (e.g., DFG-research group SHARP, BMBF MiKlip project STRATO, and the EU-project StratoClim) with significant parts related to investigations of the stratospheric ozone layer (DLR).

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 past northern hemisphere winter 2013/2014. These campaignsshave been instrumental for our current understanding of chemical ozone loss in the Arctic.

AWI participated in the EU project RECONCILE which addressed central questions regarding polar ozone depletion, with the objective to quantify some of the most relevant yet still uncertain physical and chemical processes. It improved prognostic modelling capabilities to realistically predict the response of the ozone layer to climate change.

AWI participated in the EU project SHIVA which focused on certain ozone depleting substances (ODSs). By combining measurements from land, ship, aircraft, and space-based platforms, with sophisticated numerical models, SHIVA aimed to better predict the rate, timing and climate-sensitivity of ozone-layer recovery, and identify potential risks to that recovery.

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 vapour on climate. Within that project an airborne campaign is planned in the Bay of Bengal in 2016 and a station on the West Pacific Island Palau will be built up including measurements with ozon sondes and a FTIR for at least 2 years.

The decline of anthropogenic chlorine in the stratosphere within the 21st century will increase the relative importance of naturally emitted, halogenated trace gases (VSLS) from the ocean on stratospheric ozone destruction. VSLS play a significant role in present day ozone depletion, in particular in combination with enhanced stratospheric sulfate aerosol concentrations. There is a need to better understand possible changes and feedbacks in a future climate especially under elevated sulfur levels in the stratosphere (Fig. 28). The questions how much of the observed stratospheric halogen and sulfur aerosol abundances originate from natural sources, in particular from oceanic emissions, and how this will change will be addressed in ongoing and future work.

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**Figure 28**: The biogeochemical cycle of brominated and iodinated short-lived trace gases, with a focus on stratospheric ozone depletion.
In order to accomplish this goal, the GEOMAR Helmholtz-Centre for Ocean Research Kiel contributed and still contributes to national and EU projects, including SHIVA, HALOCAT, SOPRAN, SOLAS, CCMVal, CCMI, SPARC; SSiRC. Research groups (Chemical Oceanography, Maritime Meteorology) at the institute measure brominated and iodinated trace gas concentrations in the ocean and atmosphere, calculate emissions from the ocean into the marine boundary layer along large-scale ship transects, investigate the oceanic sources, and model the transport of the short lived halogenated and sulphuric trace gases into the stratosphere. Lagrangian transport calculations initialized by high-resolution observational emissions demonstrate the importance of deep convective transport in the West Pacific for VSLS entrainment into the stratosphere (Tegtmeier et al., 2013; Marandino et al., 2013). In cooperation with the University of Hamburg, biogeochemical ocean models aim at simulating the oceanic concentrations of several of the compounds. Past and future emission scenarios of halogenated substances from the oceans, which are likely to increase due to climate change and increased anthropogenic sources, are investigated (Ziska et al., 2013; Hepach et al. 2014).

Scientists from GEOMAR have led several cruises in recent years into the tropical Atlantic and Pacific oceans, where the major input of trace gases into the stratosphere occurs. In the next two years cruises will follow into the Pacific and Indian Ocean, the results from which will be incorporated into the models to determine stratospheric input. Observations of VSLS are sparse and need to be extended in spatial and temporal resolution.

KIT-IMK 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 in a number of SPARC activities (WAVAS, SDI, Stratospheric Sulphur, CCMI, SPARC/IO3C/IGACO-O3/NDACC) and participate to ESA's Climate Change Initiative, where the IMK ozone product is preferred over the official ESA data product. IMK contributes to the STRATOCLIM EC project, the DFG Research Unit SHARP, and the BMBF research programme ROMIC.

Since 2009, J. Orphal from IMK Karlsruhe has been Chair of the “Absorption Cross Sections of Ozone” International Committee at WMO (WMO/IO3C/IGACO-O3). He has been leading an international initiative to review and recommend improved ozone absorption cross-sections. A new standard has not been established yet due to new findings published by Redondas et al., 2014. The planned implementation (at least for LDAR, Dobson and Brewer) has been shifted until new investigations confirm, that the new coefficient sets (from the IUP Bremen) provide a better consistence between the instrument types than the originally recommended coefficient sets (after Daumont-Brion-Malicet). A final report originally planned to be published in 2011 is therefore still pending.

The Hohenpeissenberg Observatory participated in the ESA project CEOS Intercalibration of Ground-Based Spectrometers and Lidars from 2009 to 2012

The following list comprises the projects and cooperations of the working group

**Physics of the Middle Atmosphere at the Institut für Meteorologie of Freie Universität Berlin**

**Planetary Evolution and Life**

(Atmospheric composition on Early Earth)

Funding agency: HGF-Allianz


Research alliance with 13 national and international partners

**SHARP**

*Stratospheric Change and its Role for Climate Prediction (SHARP)*

Funding agency: DFG (Research unit)

Coordination

Duration: 6 Years, 2009 – 2015

Research alliance with 7 national partners
STRATO

*The role of the stratosphere for decadal climate prediction*

Funding agency: BMBF (FONA Programm „Mittelfristige Klimaprognosen“ (MiKlip))

Duration: 01.09.2011 – 31.08.2014

Research alliance with DLR (Prof. M. Dameris) and GEOMAR Kiel (Prof. K. Matthes)

FAST-O3

*FAST-O3: Fast stratospheric ozone chemistry for global climate models*

Funding agency: BMBF (FONA Programm „Mittelfristige Klimaprognosen“ (MiKlip))

Duration: 01.09.2011 – 31.08.2014

Volume: 125,000 Euro

Research alliance with AWI Potsdam (Dr. M. Rex)

ISOLAA

*Sea-Ice and Stratospheric Ozone – Links and Impacts in the Arctic and Antarctic*

Funding agency: DFG (Schwerpunktprogramm 1158 „Antarktisforschung mit vergleichenden Untersuchungen in den arktischen Eisgebieten“)

Duration: 3 Years, from 01.12.2012

Research alliance with GEOMAR Kiel (Prof. R. Greatbatch)

SOLIC

*Quantification of Uncertainties of Solar Induced Climate Variability*

Funding agency: BMBF (Programm „Role of the Middle Atmosphere in Climate“ (ROMIC))

Duration: 3 Years, start in March 2014

Research alliance with GEOMAR Kiel (Prof. K. Matthes) and KIT Karlsruhe (Dr. M. Sinnhuber)

StratoClim

*Stratospheric and upper tropospheric processes for better climate predictions*

Funding agency: EU (ENV.2013.6.1-2)

Duration: 4 Years, from December 2013

Research alliance with 21 European partners

Contribution to *WMO/UNEP Assessment of Stratospheric Ozone 2014* by Ulrike Langematz (Review Editor of Chapter 2, Contributor to Chapter 3)

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 early 2016) 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.

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

The new airborne imaging infra-red spectrometer GLORIA provides two-dimensional and three-dimensional (through tomography) distributions of a large number of trace gases in the lower stratosphere and UTLS. GLORIA was operated already very successfully on two aircraft cam-
campaigns and will be used in future missions with the German research aircraft HALO. KIT-IMK is coordinating together with many German partners the HALO campaign POLSTRACC (The Polar Stratosphere in a Changing Climate), currently scheduled for winter 2015/2016.

German modeling activities will continue to focus on the expected evolution of ozone (recovery, super-recovery, tropical decline), but also on 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**

- Continuing high-quality measurements of total ozone and ozone profiles by satellites on the global scale and by ground-based systems have to be insured for the next decades. The high-quality data of long-term records of ozone and UV especially from selected stations (e.g. super sites) are a crucial precondition to follow the expected recovery of the ozone layer from man-made halogens, and to understand the substantial cooling of the stratosphere and warming of the troposphere that are expected over the next decades from man-made climate change. Therefore the maintenance of the ground network (Dobson, Brewer, sondes, Lidar) has to be fostered.

- New limb/occultation satellite mission is needed as number of limb satellites will decline. This might cause gaps and results in a loss of satellite date with vertical resolution.

- The complex coupling of ozone, atmospheric chemistry, transports and climate changes is still not fully understood. Further research is needed to better understand the underlying processes and to improve model predictions of the expected substantial changes in both ozone and temperature distributions of the middle atmosphere.

- In this context, there is a need for better and more consistent long-term temperature data in the stratosphere.

- Quality Assurance/Quality Control activities like calibration centres must be supported to maintain the high quality standards of the ground stations. This is necessary for satellite validation, for ozone monitoring, and for trend analyses.

- The current process of final determination and implementation of new ozone cross-section/absorption coefficients should get highest priority to obtain consistency between the various instruments either ground-based or satellite-borne.

- Availability of space-borne infrared limb emission instruments after MIPAS (i.e. 2014) is essential for future ozone research.