National Report of Belgium

for the 11th WMO/UNEP Ozone Research Managers Meeting

Montreal, 8-10 July 2020

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FOREWORD

This report compiles contributions provided by four Belgian research institutes, whose contact details will be found in ANNEX F:

- the Institute of Astrophysics and Geophysics of the University of Liège (ULiège),
- the Service de Chimie Quantique et Photophysique of the Université Libre de Bruxelles (ULB),
- the Royal Meteorological Institute (RMI) and
- the Royal Belgian Institute for Space Aeronomy (BIRA-IASB).

1 OBSERVATIONAL ACTIVITIES

All four institutes are actively involved in the long-term monitoring of atmospheric ozone, gaseous species important for the ozone chemical budget, e.g. catalyst reservoirs and ozone-depleting substances (ODS), aerosol properties or ultra-violet radiation. Measurements of chemical species include the vertical distribution as well as partial and total columns, and they use IR and UV-Visible spectrometry or electrochemical cells. Measurements are performed at or from ground-based stations and from satellites. Data are exploited by the four institutions for budget, process, validation, ozone-climate interactions and long-term trend studies.

The list of the twenty-eight stations hosting instruments operated and exploited by the four Belgian scientific institutes is displayed in ANNEX A (Table A 1). The table provides the station geolocation and the type of data collected. Details on the instruments, the retrieved physical quantities, the time record duration, the data usage and other observational information is also provided in ANNEX A (Table A1, Table A2 and footnotes). Ten of these stations are affiliated with international monitoring networks and report data to shared central databases.

ULiège, ULB and BIRA are involved in several satellite missions measuring ozone and ozone relevant species (halogens, NOy, BrO, HCFC, CFC…). The detail of the satellite missions with which the institutes are associated is provided in ANNEX B.

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

The vertical column of ozone and other species is monitored at eleven of the ground-based stations (ANNEX A, Table A 1) by ULiège, BIRA-IASB and RMI (see ANNEX A, Tables A2 and A3).

ULiège, ULB and BIRA-IASB are involved in several satellite missions measuring the total column of ozone and of ozone relevant species – see detail in ANNEX B.

1.2 Profile measurements of ozone and other gases/variables relevant to ozone loss

The vertical profile of ozone and other species is monitored from the ground or from balloons at eight of the stations (ANNEX A, Table A 1) by ULiège, BIRA-IASB and RMI (see ANNEX A, Tables A2 and A3). Some of the instruments also provide aerosol optical depth (AOD) data or aerosol backscatter profiles (see ANNEX A,Table A 2).

ULB and BIRA-IASB are involved in satellite missions measuring the vertical distribution of ozone, ozone depleting substances (ODS) and other species relevant to ozone chemistry – see detail in ANNEX B.

1.3 UV measurements

RMI and BIRA-IASB monitor the UV irradiance and ancillary parameters by spectroradiometers in Belgium and in Antarctica (see detail in ANNEX A,Table A 2).

At Uccle, RMI's two Brewer spectrophotometers are also used to monitor the UV-B radiation intensities. They perform several scans per day (number depending on the time the sun is above the horizon).

Since January 2011, also the Brewer in Antarctica performs UV spectral measurements during its operational periods in the austral summer.

1.4 Calibration / Validation activities

Calibration / validation activities of the four institutes are enumerated in detail in ANNEX C. In summary, they can be divided in three types of activities:

- In compliance with the international network requirements, ULiège, BIRA-IASB and RMI regularly calibrate the ground-based and balloon-borne instruments they operate (listed in ANNEX A, Table A 2), and perform uncertainty analyses and budgets
- ULB and BIRA-IASB are actively involved in Cal/Val activities of atmospheric composition satellite missions and data retrievals
- ULB and BIRA-IASB are actively involved in the evaluation and ground-based validation of the Copernicus Atmospheric Monitoring Service (CAMS) and of the Copernicus Climate Change Service (C3S).
- BIRA-IASB is involved in several initiatives and projects to harmonise retrievals, data products and validation procedures across networks, measurement platforms and EO thematic domains, and to define data and service quality standards in compliance with the GEO-CEOS Quality Assurance Framework for Earth Observation (QA4EO).

2 RESULTS FROM OBSERVATIONS AND ANALYSIS

2.1 The Royal Meteorological Institute (RMI)

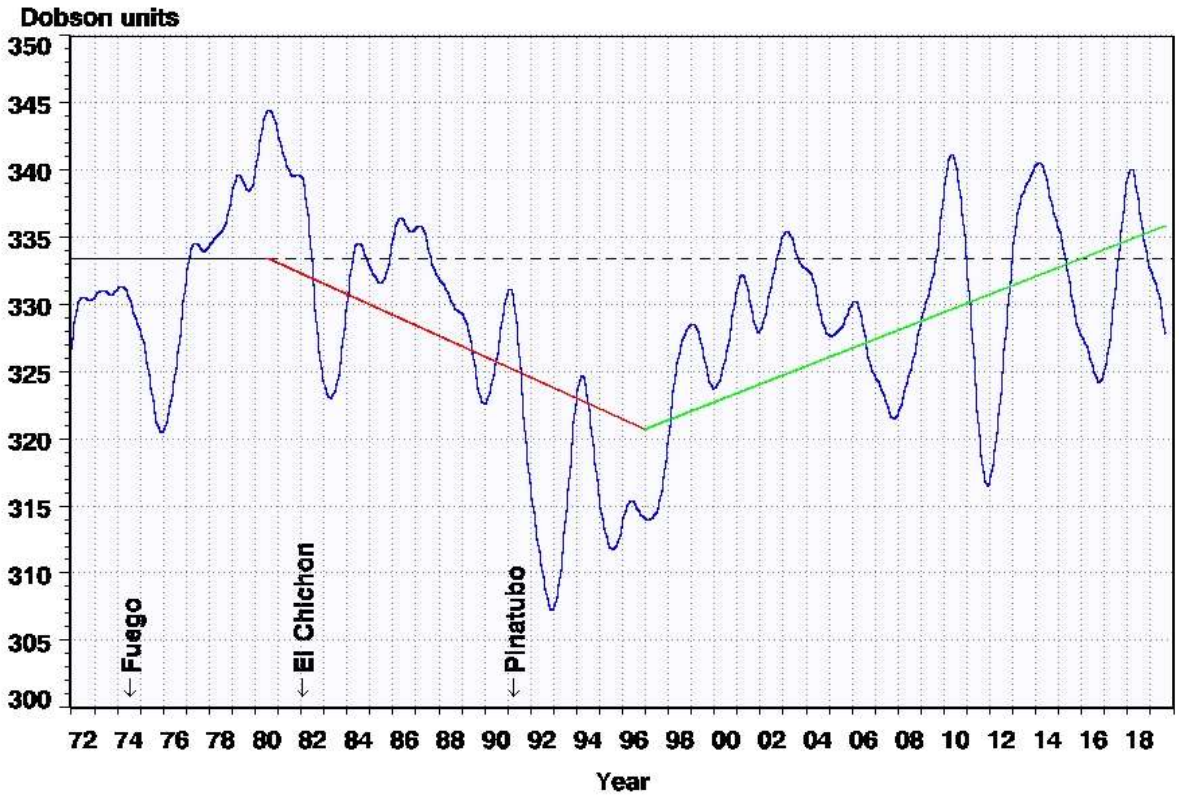

Figure 1. Running annual mean of total ozone (in Dobson Units) from Dobson and Brewer spectrophotometers at Uccle, together with a stepwise regression. The times of major volcanic eruptions, affecting the ozone layer are also indicated.

Research on the evolution of total atmospheric ozone and its distribution versus altitude at northern mid-latitudes, in particular above Belgium revealed a mean temporal decrease in 'good' ozone in the stratosphere and an increase in 'bad' ozone in the troposphere. With the help of model calculations it was shown that both changes are primarily of anthropogenic origin. Further observations in Uccle (Brussels) showed that observed levels of harmful UV-B irradiance at ground level anti-correlate with levels of stratospheric ozone. Initiatives have been taken to warn the general public about health risks resulting from excessive exposure to the sun in summertime.

Figure 1 shows the time evolution of the ozone column over Uccle based on the combined data of the Dobson (1971-1989) and the Brewer Instruments (1990-now). The ozone column decreased about 2.3% per decade in the period 1980-1997 and afterwards there are signs of an increase of about 2.0% per decade. The ozone soundings have shown us that the decrease occurs in the lower stratosphere, especially during winter and early spring. In the troposphere, on the contrary, the ozone concentrations tend to increase due to photochemical reactions in polluted air.

The ozone measurements at the Antarctic Station princess Elisabeth are reported to the WOUDC as they become available.

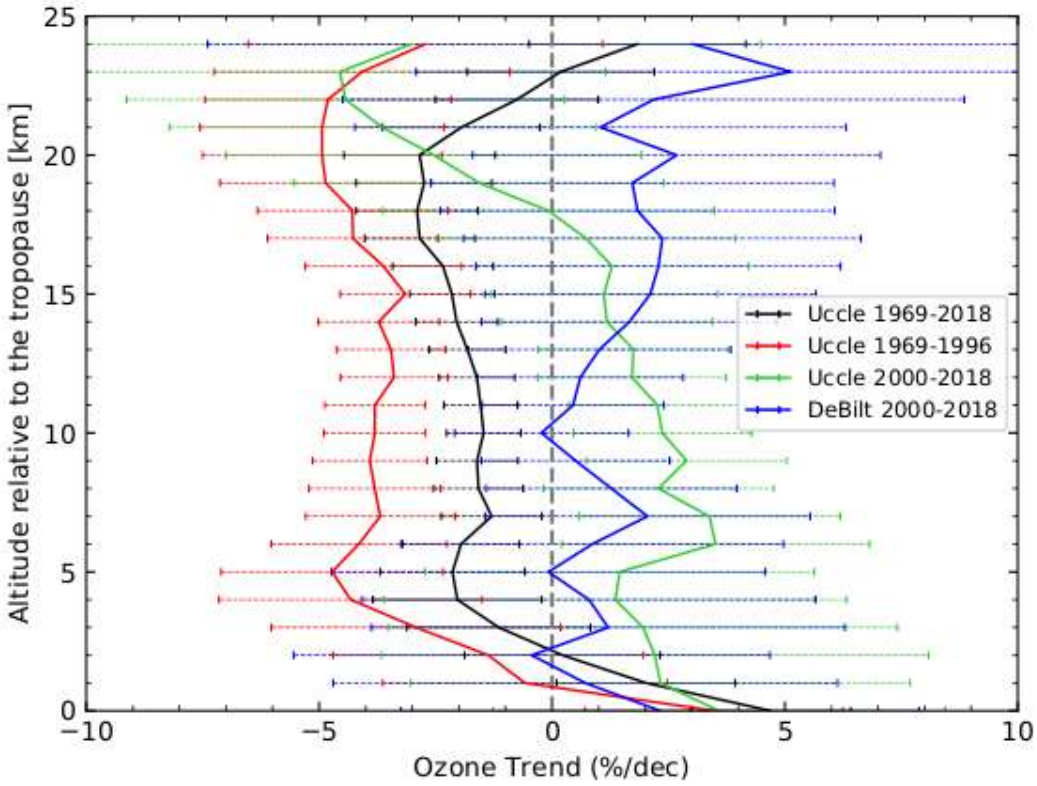

Figure 2. Vertical trends of stratospheric ozone concentrations at Uccle for different time periods and at De Bilt (2000-2018). The trends are calculated with the LOTUS multiple linear regression model, with an independent linear trend term, with the exception of the Uccle 1969-2018 time series, where one linear trend term is included in the model.

The Uccle ozonesonde series span a time period of 50 years (since 1969) and are, because of their homogeneity, a valuable dataset for vertical ozone trends assessment. The statistical model used to calculate trends is the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) multiple linear regression model (SPARC/IO3C/GAW, 2019). This model uses an independent linear trend (ILT) method as a trend term, which is based on two different, independent, unlinked trends to describe the ozone decrease until 1997 and the slow ozone increase since the early 2000s. Additionally, the LOTUS regression includes two orthogonal components of the QBO, the solar 10.7 cm flux, ENSO without any lag applied, and the GISS AOD (extended past 2012 by repeating the final available value from 2012 as the background AOD). The vertical ozone trends are shown in Fig. 2. From 1969 to 1997, stratospheric ozone concentrations decrease almost uniformly (and significantly) at a rate between -4 and -3 %/decade, except at the layers just above the tropopause. Since 2000, the stratospheric ozone concentrations rise at 2 to 3%/decade, but only significantly at the layers below and at the ozone maximum (from 6 to 13 km above the tropopause, or 17 to 24 km for an average tropopause height of 11 km at Uccle). As a consequence, the overall 1969-2018 stratospheric ozone vertical trends are negative (around -2%/decade). When we compare the post 2000 trends with these from the ozonesondes launched at De Bilt (The Netherlands), the overall stratospheric positive insignificant trends are found back at both stations, and also at the higher altitude levels at De Bilt. Both the Uccle and De Bilt time series do not show a significant decline in lower stratospheric (13-24 km) ozone amounts, as reported by Ball et al. (2018, 2019) for the periods 1998-2016 and 1998-2018 respectively, from multiple (merged) satellite measurements in the lower stratosphere between 60°N and 60°S.

2.2 Results from studies by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB)

BIRA-IASB is a coordinator of the SPARC/IO3C/GAW initiative on Long-Term Ozone Trends and Uncertainties in the Stratosphere (LOTUS, https://www.sparc-climate.org/activities/ozone-trends/ and http://lotus.aeronomie.be/), a follow-on of the SPARC/IO3C/IGACO-O3/NDACC SI2N initiative. BIRA-IASB has also contributed significantly to the 2018 WMO Scientific Assessment of Ozone Depletion (WMO 2018) as co-author of several chapters. .

BIRA-IASB has also contributed to the SPARC activity Towards Unified Uncertainty Reporting (TUNER, https://www.sparc-climate.org/activities/tuner) which aims at providing a complete and consistent data characterization in terms of uncertainty, resolution and content of a priori information, for the largest possible number of space-borne temperature and composition sounders.

The FTIR ozone data sets have been extended up to end of 2018, and collected by BIRA-IASB for the updated stratospheric trend studies published in Steinbrecht et al. (2017), in the SPARC/IO3C/GAW LOTUS Report (Petropavlovskikh et al., 2019) and in Chapter 3 of the 2018 Ozone assessment (WMO2018). These FTIR time-series have been used as well in the Tropospheric Ozone Assessment Report (TOAR), Chapter 2 (Tarasick et al., 2019) and Chapter 6 (Gaudel et al., 2018).

BIRA-IASB has been the coordinator of ESA's CCI Ozone Phase II project and its follow-on CCI+ Ozone, in which it contributes to the production and validation of homogenised total ozone data records from all European UV-visible nadir satellites and also some US nadir sounders: GOME, SCIAMACHY, GOME-2A/B/C, OMI, TROPOMI and the Suomi-NPP OMPS-nadir.

BIRA-IASB coordinates ECMWF's C3S Ozone project (2016-2019), and the ozone part of its current successor, which are to procure the Copernicus Climate Data Store (CDS) with ozone profile and column data records suitable for climate change research and monitoring and for long-term trend studies.

BIRA is involved in the Copernicus Climate Change Service for the development and delivery of climate data records from reference networks, in particular from NDACC (C3S-BARON).

BIRA-IASB has contributed to the GOMOS, MIPAS and SCIAMACHY Quality Working Groups (QWGs) aiming at the post-mission refinement of the Envisat satellite data products, at the improvement of the long-term stability of the data records, and at the production of Fundamental Climate Data Records for long-term ozone and other species from SCIAMACHY (FDR4ATMOS).

2.3 University of Liège (ULiège)

The Jungfraujoch FTIR observational data set from ULiège now covers more than 35 years. It is the longest available worldwide and hence is particularly appropriate for long-term trend investigations.

Recent relevant trend results derived from multi-decadal timeseries of organic chlorine source gases and stratospheric reservoirs have been included in the latest edition of the WMO assessment of ozone depletion, and more specifically in its Chapter 1 entitled "Update on Ozone-Depleting Substances (ODSs) and Other Gases of Interest to the Montreal Protocol" (see Figures 1-2, 1-13, 1-20 and Table 1-2).

An improved strategy for the retrieval of HCFC-22 ($CHClF_2$) has been developed, allowing for the first time to track from the ground the long-term evolution of this ODS in the troposphere and in the stratosphere (Prignon et al., 2019).

Jungfraujoch FTIR data have also been included in recent studies dealing with the ozone profile trend in the stratosphere (Steinbrecht et al., 2017) or of its abundance in the troposphere (Tropospheric Ozone Assesment Report, Gaudel et al., 2018).

2.4 Université Libre de Bruxelles (ULB)

In the last years, the ULB has been involved in the monitoring of global ozone distributions using IASI, both in terms of columns and vertical profiles. Time series are available from 2007, from 2012 and from 2019 onwards, for IASI-A, -B and –C, respectively.

2.4.1 Validation results

Based upon previous validation exercises (e.g. Boynard et al., 2016), we developed an improved version of the FORLI algorithm (v20151001). Several corrections (e.g. to emissivity integration, continua region, look-up-table – LUT- construction) have been brought. A bigger LUT range for O_3 and an updated version of the HITRAN spectroscopic database have also been used. That new reference FORLI algorithm brings considerable improvements for the O_3 retrievals above 20 km leading to a decrease of the bias in the total ozone by ~4-5%, on average (Boynard et al., 2018). On the contrary, the positive bias that was already reported from the previous validation is still observed (~20-40%) and requires further investigations, in particular the impact of the a priori.

The validation exercises of that reference FORLI-O_3 product has overall demonstrated a high degree of precision with excellent consistency between the measurements taken from the two IASI instruments on Metop-A and -B, as well as a good degree of accuracy with biases lower than 20% in the stratospheric layers (Boynard et al., 2018; Keppens et al. 2017). The validations have, however, reported a drift in the middle-upper stratospheric time series from comparison with O_3 sondes in the northern hemisphere (~3.53±3.09 DU.decade^{-1} on average over 2008–2016; Boynard et al., 2018). Further comparisons with CTM simulations (Wespes et al., 2019) have shown that it results from a pronounced discontinuity ("jump" on 15 September 2010) rather than from a progressive "instrumental" drift. This is verified by the absence of drift in the O_3 time series after the jump and is in line with the excellent stability of the Level-1 radiances of the three IASI instruments over the full period of measurements.The discontinuity is suspected to result from updates in level-2 temperature data from Eumetsat that are used as inputs into FORLI (see Hurtmans et al., 2012).

A recently updated version of FORLI (v20191122) which brings up a series of improvements (e.g. use of the latest available version of the Hitran database, time-varying CO_2 concentrations, corrections in the computation of absorbance look-up tables …) is now processing forward and backward and will then require a new validation exercise.

2.4.2 Results from trend studies

Many efforts were devoted to derive accurate trends in tropospheric and stratospheric O_3 levels using dedicated multivariate regression methods. Recently, eight years (January 2008 – March 2016) of daily O_3 observations in the troposphere (from ground to 300hPa) from IASI have been analyzed to identify the geophysical mechanisms conducting the O_3 variability (Wespes et al., 2017). Global patterns of the main geophysical parameters (including NAO, QBO and ENSO) adjusted by the regression model are obtained. They provide a meaningful view of the chemical and dynamical mechanisms driving the tropospheric O_3 variations in line with the current knowledge of these mechanisms. Based on on these results, the first global patterns of tropospheric trends were obtained and allowed us to identify negative trends in the Northern mid-latitudes (45°N-75°N) in summer which could be possibly associated with the decline of ozone precursor emissions (Wespes et al., 2018).

The trend study has been expanded to the stratospheric columns using a regression model adapted for the stratosphere with the use of appropriate drivers, in an effort to unambiguously discriminate anthropogenic trends from the various modes of natural variability. The results have verified the performance of the regression model to properly discriminate between natural and anthropogenic drivers of O_3 changes. The main conclusive results are summarized as follows:

(i) A significant O_3 recovery is categorically found in the two stratospheric layers (>~35°N/S in the MUSt and >~45°S in the LSt) as well as in the total column (>~45°S) during the winter/spring period, which confirms the healing in the Antarctic O_3 hole. These results verify the efficacy of the ban on O_3 depleting substances imposed by the Montreal protocol and its amendments, throughout the stratosphere and in the total column, from only one single satellite dataset for the first time.

(ii) A clear and significant speeding up (within 95%) in stratospheric and total O_3 recovery is measured at southern latitudes (e.g. from ~1.5±0.4 DU/yr over 2008-2017 to ~5.5±2.5 DU/yr over 2015-2017 in the LSt), which translate to trend values that would be categorically detectable in the next few years on an annual basis. It demonstrates that we are currently

progressing towards a substantial emergence in O_3 healing in the stratosphere over the whole year in the S.H.

(iii) The decline observed in LSt O_3 at northern mid-latitudes is unequivocal over the available IASI measurements in winter/spring of the N.H. The exact reasons for that decline are still unknown but O_3 changes in the LSt are estimated to be mainly attributable to dynamics which likely perturbs the healing of LSt and total O_3 in the N.H. A significant speeding up (within 95%) in that decline is measured in LSt and total O_3 over the last 10 years, but cannot be categorically confirmed yet.

It is of particular urgency to understand the causes of the decline for apprehending its possible impact on the O_3 layer and on future climate changes.

The activities on the tropospheric ozone data record within the first phase of TOAR (TOAR-I), which highlights strong discrepancies in tropospheric O_3 trends between satellite datasets, including IASI, came to an end in 2019. The IGAC Scientific Steering Committee has approved the second phase of TOAR (TOAR-II) that aims at identifying and understanding the sources of the biases in tropospheric O_3 trends, for another five years (2020-2024). A Satellite WG workshop is foreseen mid-2020 to plan the scientific activities during TOAR-II.

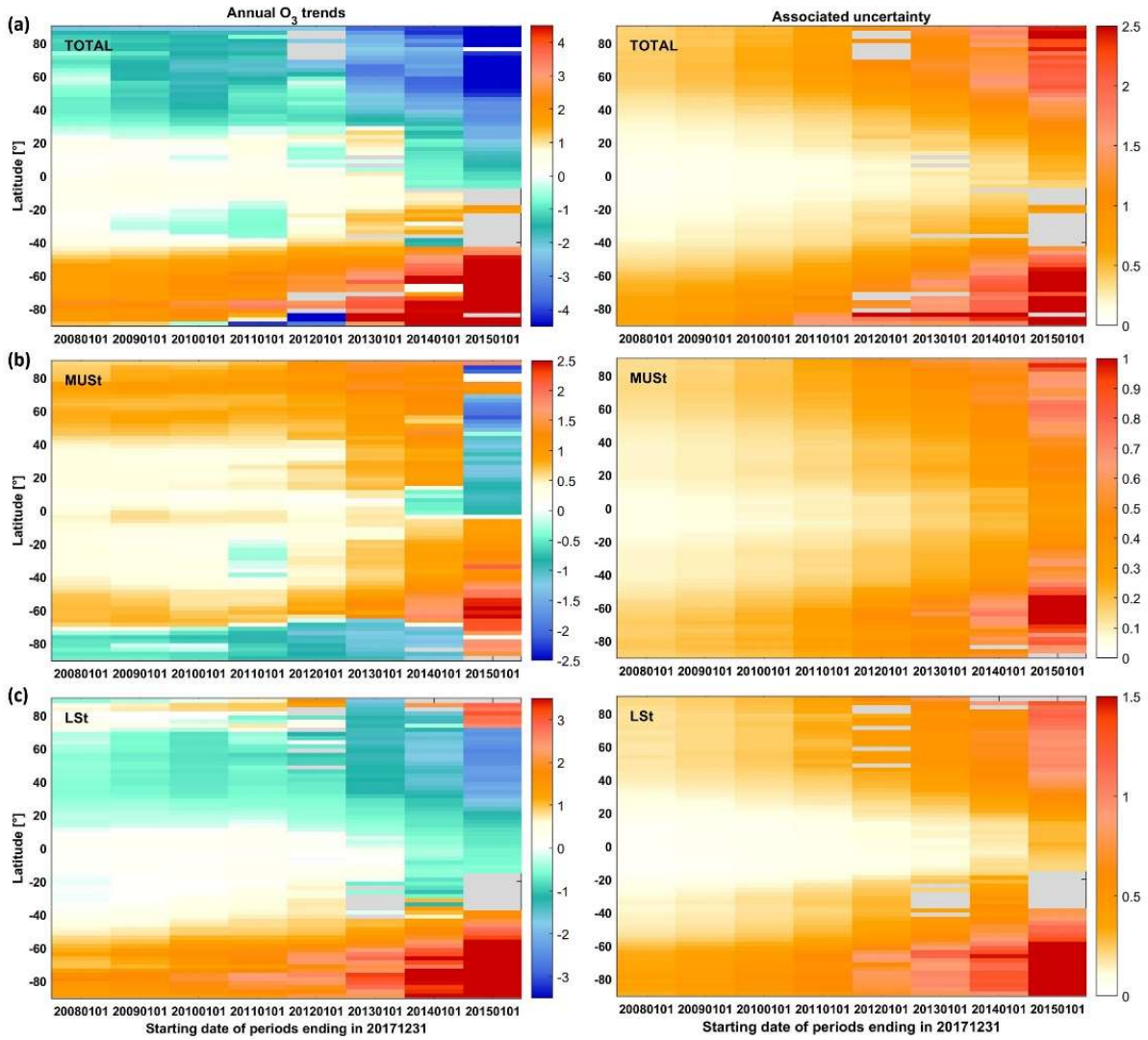

Figure 3. Evolution of estimated linear trend (DU/yr) and associated uncertainty accounting for the autocorrelation in the noise residuals (DU/yr; in the 95% confidence level) in (a) total, (b) MUSt and (c) LSt O_3 columns, as a function of the covered IASI measurement period ending in December 2017, with all natural contributions estimated from the whole IASI period (2008-2017). Note that the scales are different between the columns.

The inter-annual variability in CO and several volatile organic compounds over the IASI period is currently being investigated. For CO this is achieved with the MOPITT team; a paper has been submitted at the end of 2019.

3 THEORY, MODELLING AND OTHER RESEARCH

3.1 The Royal Meteorological Institute (RMI)

The Brewer data have been analysed for aerosol information in the UV. These AOD data at 320 nm are available now (*Cheymol and De Backer, 2003*). Special measurements with Brewer instrument #178 (and later also with #100 in Antarctica) were started to measure also the AOD at 340 nm (De Bock et al, 2010).

3.1.1 Satellite data validation and characterisation

RMI is partner in the Ozone SAF (Science application facility) of EUMETSAT. The main task here is the validation of the ozone profiles retrieved from satellite observations.

3.1.2 Ozone characterisation

The RMI is highly involved in the characterization and understanding of the ozonesonde instrument.

First of all, RMI is the lead author of the chapter on Standard Operation Procedures in the foreseen update of the WMO GAW report on Quality Assurance and Quality Control for Ozonesonde Measurements by Panel for Assessment of Standard Operating Procedures for Ozonesondes.

Secondly, the RMI participated as ozone expert in the Jülich OzoneSonde Intercomparison Experiment (JOSIE) in 2017, which was devoted to test all the different instrument methods used at sonde stations with experimenters who are associated with the tropical SHADOZ (Southern Hemisphere Additional Ozonesondes) network. As most of the SHADOZ stations operate with WMO-recommended solutions and preparation and calibration procedures also, the current WMO-recommended Standard Operating Procedures could be evaluated. Specific instrumental aspects examined in these tests were details of preconditioning, background current, response time, pump flow efficiency, and sensing solution strengths (SSTs). In addition to two WMO-recommended SSTs, two alternatives, one of which is employed at several SHADOZ stations, were included in the tests. For these alternatives, agreement of sonde ozone data with the vacuum chamber reference instrument in the tropical tropopause layer regions was improved. However, sensitivity to stratospheric ozone is reduced, so that total column ozone from these tests averaged 3% lower than the reference instrument.

Thirdly, in close collaboration with the Forschungszentrum Jülich, , we try to derive “calibration functions” to refer all ozonesonde measurements to a common reference instrument - the dual-beam UV absorption photometer at Jülich – after using the recent measurements of the decreasing ozonesonde pump efficiencies with pressure. Another research topic of this collaboration involves the study of the slow (20-25 minutes) reaction pathway in the ozonesonde cell, which was commonly named “the background current”, both from an experimental (a simulation chamber campaign with a changed composition of the sensing solution) and data correction strategy point of view.

3.2 The Royal Belgian Institute for Space Aeronomy (BIRA-IASB)

3.2.1 Modelling

(D33) BIRA-IASB has developed since many years now a 3D chemistry transport model (CTM) with a data assimilation system associated to it. The CTM is based on an advection system and a chemical solver accounting for around 200 stratospheric photo-chemical reactions. The CTM also includes heterogeneous reactions occurring at the surface or in the bulk of stratospheric aerosols and polar stratospheric clouds. Since 2017, we have augmented our CTM to be force different solar irradiance spectra. While in the past, our simulations were based on the so cold NRLSSI which

consider the solar iradiance at solar minimun, the current version allow us to use NRLSSI v2 which consider observation of the past or solar irrandiance spectra recommended for CMIP6 simulations.

The heterogneous reactions and the aerosol climatology have also been revised to more up-to-date values.

Using the assililation system, a reanalysis of Aura MLS observations has been carried out covering the period Sept 2004-Aug 2019 (Errera et al., ACP, 2019).

Studies of biogenic volatile organic compounds emissions and their dependence on short-term climate variability. Biogenic emission models accounting for land-use change and meteorological variability are evaluated in a tropospheric global model (IMAGES) against formaldehyde spaceborne (OMI) measurements. Inverse modelling techniques are applied to constrain the emissions of ozone precursors such as CO, NOx and volatile organic compounds.

3.2.2 Instrument developments

ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere): initiated as a national development of a limb sounding mission responding to the requirements resulting from the three last ORM Meetings in 2008, 2011 and 2014, respectively (*WMO GORMP Report No. 51, No. 53 and No. 54*): “Satellite observations of high vertical resolution profiles using limb viewing for O_3 and key molecules are required in order to more accurately understand the changes in O_3 as CFCs decline and climate change occurs.” (Annexe B). ALTIUS is presently implemented as an operational element of the ESA EarthWatch programme with a 2023/2024 target launch date.

(D33) Using its data assimilation system’s, BIRA-IASB has made an observations system simulation experiment (OSSE) to measure the value of future ALTIUS observation compared Aura MLS. The experiement show that ALTIUS is close to MLS and that all ALTIUS mode of observations – UV limb scatter, and occultations from the Sun, stars, planets and Moon – are necessary to provide a complete picture of the evolution of ozone during polar winter and spring.

MAX-DOAS instruments and associated data analysis algorithms. The MAX-DOAS technique has the capability of determining vertical distributions in the troposphere and lower stratosphere up to 35 km altitude.

3.2.3 Ground-based data retrieval algorithm developments

Similar harmonization work is being performed for UV-Vis measurements as part of the NDACC UV-Visible Working Group (UVVISWG) where a BIRA-IASB member is co-chair since 2004. These efforts including the development of a facility for MAXDOAS centralised processing and automated quality control are supported by ESA in the FRM4DOAS project (2016-2018).

3.2.4 Satellite data retrieval algorithm developments

Data retrieval algorithms and prototype data processors have been developed and implemented for the next generation of nadir and limb satellite sounders: Sentinel-5p (launched in 2017) and the Sentinel-4 and Sentinel-5 to be launched after 2023.

BIRA-IASB/B.USOC will host the data processing segment of the ALTIUS mission and will be responsible for the processing chains in near real time and in consolidation. BIRA-IASB will develop and prototype limb and occultation data for ozone (primary products) and several other trace gases (secondary products).

Development, validation and implementation of harmonised satellite data retrieval algorithms for ERS-2 GOME, Envisat SCIAMACHY, MetOp-A GOME-2, MetOp-B GOME-2 and Copernicus Sentinels 4/5/5p total O_3, NO_2, BrO, HCHO, SO_2…; data processing and dissemination.

Development, validation and implementation of satellite data retrieval algorithms for aerosols and trace gases from GOMOS.

Development, validation and implementation of retrieval algorithms for IASI/MetOp for mineral aerosols and CH_4 : data processing and dissemination.

3.2.5 Satellite data validation and characterisation

BIRA-IASB has continued the geophysical validation of satellite data records for O_3, NO_y, CH_4, CO, N_2O, H_2O, HNO_3…: GOME, SCIAMACHY, OMI, GOME-2, IASI, and 14 limb/occultation sounders including SCIAMACHY, GOMOS, MIPAS, ACE-FTS…. Validation studies are based on independent ground-based network data collected from network data archives like NDACC, SHADOZ, TCCON and WOUDC. In the reporting period it has designed, implemented and operated the automated Validation Data Analysis Facility (VDAF) performing the routine operations validation service of ESA's Mission Performance Centre (MPC) for the Copernicus Sentinel-5 Precursor mission. Validation of upcoming missions like the Copernicus Sentinel-4 (UVN) and Sentinel-5 (UVN and IASI-NG instruments) and ESA's Earth Watch mission ALTIUS are in preparation.

A multi-purpose simulator of global measurement systems for atmospheric composition with full metrology description has been built at BIRA-IASB (*Verhoelst et al., 2015*): *OSSSMOSE* (Observing System of Systems Simulator for Multi-mission Synergies Exploration). This versatile environment provides realistic simulations of the output of real and hypothetic global observing systems and of their data comparison. It combines various state-of-the-art components, such as multi-dimensional observation operators mapping in 2D/3D the real sensitivity of a measurement system to atmospheric gradients, cycles and trends. OSSSMOSE is used to investigate and quantify smoothing and sampling properties of ozone measurement systems and to close the error budget of data comparison (e.g., *Cortesi et al., 2007; Lambert et al., 2012; Verhoelst et al., 2012, 2015*).

BIRA-IASB contributes to the detection of a negative drift on IASI tropospheric ozone data (Boynard et al., 2018), and SCIAMACHY ozone column data, through IASI and SCIAMACHY validation with correlative data (sondes and FTIR for IASI, Brewer/Dobson/SAOZ for SCIAMACHY).

3.2.6 Validation of Copernicus Atmospheric Monitoring Service (CAMS) and Copernicus Climate Change Service (C3S) products

In the CAMS-84 project. BIRA-IASB is responsible for the validation of the CAMS data products using the NDACC and TCCON data.

BIRA-IASB is the coordinator of all ozone related validation activities In the C3S_312a_Lot4 Ozone (2016-2019) and C3S_312b_Lot2 O3-AER-GHG (2018-2020) procurement services feeding the Climate Data Store with satellite atmospheric composition data.

3.3 University of Liège (ULiège)

3.3.1 Trend studies

Numerous relevant long-term trend studies have been performed over the period under review here, on the basis of ground-based data recorded at Jungfraujoch and at other FTIR sites (see e.g. section 2.3) or using satellite products (inorganic chlorine and fluorine, organic chlorine and fluorine, source gases relevant to stratospheric and tropospheric ozone (HCl, $ClONO_2$, CFCs and HCFCs, CCl_4, C_2H_6, OCS, …).

3.3.2 Modelling

The 3-D Chemistry Transport Model GEOS-Chem, developed and maintained at Harvard University, is in operation at ULiège since 2013, in order to ease the interpretation of FTIR time series acquired at the Jungfraujoch and elsewhere. The more recent versions of this model natively allow modelling the stratosphere and a suite of ODSs.

3.4 Université Libre de Bruxelles (ULB/SQARES)

3.4.1 Laboratory experiments

The atmospheric spectroscopy group at ULB (SQUARES) has established expertise in the measurement of accurate absorption line parameters (positions, intensities and widths) for

atmospheric trace gases in the infrared (far-, mid- and near-) and visible ranges, using high-resolution Fourier transform spectroscopy. Analysis of spectra is carried out using software written in the laboratory. The contribution of ULB to international spectroscopic databases remains at the forefront.

3.4.2 Retrieval algorithm developments

The group has acquired a leading position for the atmospheric radiative transfer modelling in the thermal infrared and also for the development of atmospheric trace gases retrieval methods. It owns and maintains sophisticated algorithms, for research and operational applications in atmospheric chemistry and physics. They include:

- The Atmosphit line-by-line radiative transfer model, which allows simulation of spectra recorded under various geometries and/or with different instruments. Accurate and versatile, it has been used in most studies prior to IASI launch, and for IASI local analyses. A module using an advanced doubling-adding method to account for multiple scattering was coupled to *Atmosphit*, allowing simultaneous retrieval of gas and aerosol properties.
- The FORLI series of software specific to IASI (Hurtmans et al., 2012). These rely on fast radiative transfer calculations using look-up-table (LUT) approaches. The LUT compile absorbance spectra, pre-calculated on a given spectral range and on well-defined temperature/pressure/humidity grids. FORLI versions are currently in place for O_3, HNO_3, CO and in addition NH_3. The FORLI series allow NRT processing of the huge IASI data flow to provide global distribution of concentrations twice daily. The FORLI retrieval algorithms developed in the group are the official operational processors implemented in the EUMETSAT ground-segment to serve various users, notably the Copernicus Atmosphere Monitoring (CAMS) and Climate Change (C3S) services
- Radiance indexing schemes for IASI, which are used to track reactive species, among which SO_2, PAN, CH_3OH, HCOOH, and aerosols, including volcanic ash (e.g. Franco et al., 2018; Clarisse et al., 2019a; 2019b).

3.4.3 Satellite data retrievals

Development, upgrade and maintenance of the NRT processing chains for IASI-A, -B and –C, namely FORLI. Processing started by receiving of the calibrated L1C radiances from Eumetcast, which are transformed in suitable format and quality-flagged using available ancillary information (e.g. cloud coverage). The retrievals are performed on a large cluster of 24 nodes with a total of 357 threads. Large storage capabilities (above 230 TB) allow archiving of all data for scientific analyses, including long-term time series studies on global datasets.

Retrieved products from FORLI include O_3, HNO_3 and CO profiles on the global scale (cloud-free data). Every new FORLI algorithm development delivered to EUMETSAT is also validated with that implemented in the EUMETSAT CAF (Central Application Facility).

Additional products from the offline processing (BRESCIA-SO_2, ANNI-NH_3, ANNI-PAN …) are based on the calculation of hyperspectral radiance indices combined with an artificial neural network in some cases, to convert the spectral signature into columns using appropriate look-up-tables.

We have also developed a new global IASI Climate Product (*Donikis et al., 2015*): the ozone longwave radiative effect (LWRE) (in W/m^2), i.e., the radiative impact in the outgoing longwave radiation (OLR) flux due to absorption by ozone, for both tropospheric and total columns with respect to the retrieved FORLI-O_3 vertical distribution. This product opens perspectives for studying the impact of O_3 changes on the radiative forcing of climate at local and global scales. The derivation of trends in the O_3 LWRE is under development.

3.4.4 Satellite data validation and characterisation

ULB/SQUARES contributes to the validation activities of IASI chemistry products, in particular O_3, HNO_3, CO and SO_2 in the frame of the AC-SAF activities and of the O_3-CCI+ and C3S programs for O_3, but also NH_3 and other retrieved products.

ULB/SQUARES also continues cross-comparisons between satellites, in particular for CO and O_3.

4 DISSEMINATION OF RESULTS

4.1 Data reporting

- ***RMI***

The ozone data (columns and profiles) are regularly deposited in the WOUDC of WMO. Uccle is also affiliated to NDACC. Therefore the data are also made available in that network. In near real time the data are also distributed via NILU, where the data can be used for campaigns (e.g. Match campaigns to determine ozone losses in the polar and sub polar winter atmosphere, see Streibel et al, 2005). The data are also stored and used in databases for the validation of satellite data (EUMETSAT). Total ozone values are exchanged daily with the WMO ozone mapping centres in Canada and Greece for the production of daily ozone maps. The ozone profiles corrected according to the recommendations of the O3S-DQA activity are also distributed to this panel.

Data of the ceilometers are exchanged via the data-hub of the EUMETNET programme E-profile.

- ***BIRA-IASB***

NDACC FTIR and UV-visible data are submitted on a regular basis by BIRA-IASB to the NDACC Data Host Facility (DHF) established at NOAA NCEP (http://ndacc.org).

BIRA-IASB is deeply involved in the ESA CCI programme (Ozone, Aerosols, GHG, water vapour), providing high quality datasets for climate modelling applications and available on the CCI open data portal (http://cci.esa.int). Reprocessed satellite ozone data generated as part of the CCI Ozone project are also available publicly from the project site hosted at BIRA-IASB: http://www.esa-ozone-cci.org/

Satellite ozone data records and ground-based data records processed at BIRA-IASB as part of the C3S procurement are available on the Copernicus Climate Data Store hosted at ECMWF (https://cds.climate.copernicus.eu).

(D33) Reanalysis of Aura MLS observations are available here: http://strato.aeronomie.be/

- ***ULiège***

Time series of NDACC-relevant molecules (e.g., HCl, $ClONO_2$, HF, HNO_3, NO_2, O_3,) are archived routinely by ULiège at the NOAA Data Host Facility (Washington, DC, USA), with the ozone data mirrored to the WOUDC archive in Toronto. These data are available in the hdf format which provides the available vertical information and uncertainties on the retrieved products.

In addition, important results deduced by ULiège from Jungfraujoch observations have been included in successive editions of the scientific assessment of ozone depletion (UNEP/WMO), with ULg scientists involved as co-author or contributors in all recent volumes.

- ***ULB***

Datasets produced by the ULB are documented in the scientific literature.

Operational dissemination by ULB/SQUARES of the FORLI-CO, -O_3, -HNO_3, BRESCIA-SO_2 are occuring within the AC-SAF (data processed at EUMETSAT-CAF and disseminated through EUMETCAST system). This has started in 2017 with CO, followed by SO_2 in 2018 and O_3 and HNO_3 both expected in the course of 2020. The ANNI-NH_3 product will be also dessiminated through EUMETCAST in the future.

Archives of the IASI retrieval datasets generated by ULB/SQUARES (FORLI-O_3, -CO, -HNO_3, BRESCIA-SO_2, ANNI-NH_3 and other products) for IASI-A, -B and -C are made available to the user's community in NetCDF (v4) format from the French Aeris data portal at: http://iasi.aeris-data.fr/. IASI CO distributions of profiles are distributed in NRT by ULB to ECMWF in the frame of the Copernicus Atmosphere Monitoring Service (CAMS). Satellite ozone data records processed as part of the C3S procurement are available on the Copernicus Climate Data Store hosted at ECMWF.

Spectroscopic information obtained by ULB/SQUARES is disseminated through various channels.

4.2 Information to the public

- ***RMI***

Daily UV forecasts are produced and disseminated with the weather forecasts. They are also available at the internet (www.meteo.be).

Ozone and UV data of Uccle were also used in yearly reports on the environment (successive MIRA reports).

- ***BIRA-IASB***

Relevant information is available on different web pages hosted by BIRA-IASB:

- CCI Ozone website, including documentation and data: http://www.esa-ozone-cci.org/
- NDACC Satellite Working Group website, with catalogues and relevant information on atmospheric composition satellites: http://accsatellites.aeronomie.be
- Sentinel-5 Precursor TROPOMI data quality assessment (http://mpc-vdaf.tropomi.eu)
- Ozone monitoring and research activities on the BIRA-IASB website: http://www.aeronomie.be/en/topics/naturalhazards/ozone-bira-iasb.htm
- Article on "BIRA-IASB monitors effect of Montreal Protocol": http://www.aeronomie.be/en/topics/globalchange/montrealprotocol.htm

A new website for UV radiation and indexes monitoring is under development at BIRA-IASB.

BIRA-IASB publishes press releases on ozone related subjects and activities.

BIRA-IASB contributes to WMO Ozone Depletion Assements, to the LOTUS stratospheric ozone trend report, and to the Tropospheric Ozone Assessment Report (TOAR).

BIRA-IASB contributes to WMO Antarctic Ozone Bulletins and WMO Arctic Ozone Bulletins (http://www.wmo.int/pages/prog/arep/gaw/ozone).

BIRA-IASB disseminates relevant information to the public through lessons and seminars in most of the major Belgian universities, through large public events like the Annual Open Doors organised at BIRA-IASB premises, through participation in public exhibitions at the Planetarium in Brussels and the Euro Space Centre in Redu.

Lectures about the history of ozone research was organised at BIRA-IASB for non-scientific and scientific personal in French and Dutch.

4.3 Relevant scientific papers

A list of relevant scientific papers published or submitted by the reporting teams after the issue of the Belgian National Report for the 10th WMO/UNEP Ozone Research Managers Meeting is provided in ANNEX D.

5 PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

Projects and collaborations involving the four institutes are listed in ANNEX E.

6 IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 10TH OZONE RESEARCH MANAGERS MEETING

6.1 Overarching goals

- *Goal (2) – Maintain and enhance existing observation capabilities for climate and ozone layer variables*

RMI continued the ozone observing program with spectroscopic ozone column and UV measurements and 3 times per week ozone profile measurements with balloons. Also the ceilometer measurements are continued.

6.2 Research needs

(i) Chemistry-climate interactions and monitoring the Montreal Protocol

- *Specific recommendation (4) – Ozone in climate models*

ULB/SQUARES has undertaken several projects in partnership with BIRA-IASB focusing on the link between chemistry and climate, where, in particular, both FORLI-O_3 and O_3 LWRE are key products to evaluate the evolution of O_3 and its radiative forcing in climate models.

BIRA-IASB coordinates the Data Assimilation activity of the international programme Stratosphere/Troposphere Processes and their Role in Climate (SPARC).

BIRA-IASB participates to the SPARC Reanalysis Intercomparison Project (S-RIP) with a focus on the use of chemical tracers to better understand how the past changes of stratospheric circulation are represented in modern reanalyses.

BIRA-IASB participates to the validation and development of the global model used for the Copernicus Atmosphere Monitoring Service (CAMS) with a strong focus on stratospheric ozone.

BIRA-IASB continuously improves its data assimilation system BASCOE and the chemical transport model associated with it, which includes detailed microphysics description.The Near-Real-Time analyses of stratospheric composition generated by BASCOE are often used in the WMO Antarctic Ozone Bulletins and for validation of the ozone forecasts delivered by the CAMS.

- *Specific recommendation (7) – Trends in ozone*

ULB/SQUARES continues the retrieval/measurement of ozone columns and profiles from IASI, and applies state-of-art statistics to the FORLI-O_3 data sets to retrieve accurate trends (cf. Section 2.1).

ULB/SQUARES also actively contributes to other international ozone trend assessment initiatives, namely, the O_3-CCI+ and the second phase of TOAR, which aims at understanding biases between trends derived from O_3 datasets and at improving confidence in trend estimates.

RMI continues the measurement of ozone columns and profiles, and applies state-of-art statistics to the data sets to retrieve trends (cf. Section 2.1).

BIRA-IASB conducts studies of ozone variabilities and trends, using ground-based and satellite data. RMI is part of the Ozondesonde Data Quality Assessment Working Group and with conducts studies of ozone variabilities and trends, using those ozonesonde data.

BIRA-IASB also actively contributes to other international ozone trend assessment initiatives, namely, LOTUS (a SPARC Activity coordinated by BIRA-IASB, aiming at improving confidence in trend estimates), the 2018 WMO Assessment of Ozone Depletion, the Tropospheric Ozone Assessment Report (TOAR).

- *Long-term recommendation (1) – Constructing data records*

ULB/SQUARES is deploying efforts to develop a climate version of FORLI which will provide homogeneous IASI-O_3 record by using ERA-5 reanalysis as new input parameters for the temperature and humidity profiles.

BIRA-IASB coordinates ESA's CCI Ozone project Phase II (2014-2017) and CCI+ (2019-2021), in which RMI is a partner, which aims at improving ozone data products from European satellites in order to provide harmonised ozone data records suitable for climate change studies. This project includes specific effort on the improvement of ozone profile data in the upper troposphere and lower stratosphere, to improve our evolving understanding of the

coupling and exchange in this particular altitude region. BIRA-IASB is also responsible for the operational generation of ozone Climate Data Records (CDRs) in support of the Copernicus Climate Change Service (C3S), service started in the C3S_312a_Lot4 project (2016-2018) and continued in the C3S_312b_Lot2 project (2018-2020).

In C3S-BARON, BIRA-IASB was responsible for the development and delivery of ozone data records from NDACC, and auxillary data for trend studies (solar cycle, QBO, …).

- *Long-term recommendation (2) – Data quality*

RMI participated as referee in intercomparison campaigns of ozone sondes; regular calibration of the Brewer spectrophotometers were performed.

(ii) Processes influencing stratospheric evolution and links to climate

- *Recommendation (5) – Stratospheric aerosols*

BIRA-IASB actively participated in the ESA Aerosol_cci project, and this activity is currently continued in the framework of the Copernicus Change Change Services (C3S). This work focuses on the production of stratospheric aerosol time series based on the GOMOS experiment on ENVISAT. The development and improvement of time series of extinction and size information is of high importance to provide reference datasets to the climate modelling community. Currently, the large uncertainties and the poor agreement of size information derived from different techniques is a major issue impacting atmospheric chemistry and climate modelling, that has to be better understood. This requires progresses in the improvement of the retrieval algorithms and of aerosol characterisation. Combined with precursor work on the SAGE II experiment (1984-2005), these times series also offer useful datasets for aerosol studies, e.g. in the framework of geoengineering.

(iii) UV Changes and other impacts of ODS changes

- *Recommendation (1) – Factors affecting UV*

RMI studies the effects of aerosol on UV radiation.

6.3 Systematic observations

- *Key Recommendation (1) – Monitoring of temperature, winds, trace-gas profiles, especially dynamical tracers (N_2O, SF_6), ozone and water vapour, to support assessment of expected changes in global meridional BDC and unexpected events like the recent break of the QBO*

ULB/SQUARES is progressing on the identification of the causes of the bias that characterizes the FORLI-O_3 measurements in the UTLS region. Retrievals with new sets of a priori matrices have been tested on a restricted IASI number of Level-1C radiances, co-located with O_3 sonde stations for validation purpose. It tends to identify the a priori as a main cause of the bias in the UTLS FORLI-O_3 profile that was reported earlier (Boynard et al., 2018).

The ozone and water vapour profiles obtained simultaneously with the RMI balloon-borne ozonesondes. Data are archived and are available.

- *Key Recommendation (2) – Continuation of ground-based stations with long-term records*

ULiège's primary aim will be to maintain the operation of the FTIR instrumentation at the Jungfraujoch station.

RMI continues the observations of the ozone layer at Uccle, and in Antarctica during the manned period of the Princess Elisabeth station.

Efforts have been made by BIRA-IASB to maintain operation of existing instrumentation, and to increase the use of more sophisticated instrumentation, mainly FTIR spectrometers and UV-visible instruments. BIRA-IASB has continued operation of its FTIR and UV-visible instruments which contribute to the NDACC and TCCON global monitoring networks.

- *Key Recommendation (3) – Continuation of limb emission and infrared occultation observations from space*

RMI is a partner in the EUMETSAT O3SAF, and is responsible for the validation of the operational ozonesonde profiles and aerosol products of the GOME2 instruments on board of the meteorological satellites.

The work performed at BIRA-IASB on GOME/SCIAMACHY/OMI/GOME-2/TROPOMI total ozone retrieval algorithms is a response to the requirement to continue the key baseline set of solar backscatter UV observations. In particular, the development of the GODFIT-3 direct fitting algorithm has led to improvements needed to expand capabilities at high latitudes and high solar-zenith angles (*Lerot et al., 2014*).

In anticipation of the upcoming gap in limb viewing satellites, BIRA-IASB has proposed the new satellite mission ALTIUS, a limb scattering and occultation satellite instrument addressing directly the 7ORM requirements, reiterated at 8ORM, 9ORM and 10ORM, for limb viewing observations of high vertical resolution profiles of ozone and key ozone related parameters that are critical for understanding the science behind changes in ozone in the context of changing climate – see ANNEX B. This instrument concept combines the technique of limb scattering observation with an imaging capacity when operating on the day side. At the terminator and in the eclipse phase, the spectrometer would be used in solar and stellar occultation modes respectively. This instrument is designed to infer from UV-visible-NIR radiance measurements from the upper troposphere to the mesosphere the vertical distribution of ozone, NO_2, BrO, H_2O, OClO, aerosols and PSCs… In 2016, the ALTIUS mission was accepted by the ESA-Earth Observation programme board as an element of the EarthWatch programme and definitely approved at the last ESA ministerial council in Dec 2016. The instrument and the ground segment are in development, with a launch targeted in 2023.

A PICo-satellite for Atmospheric and Space Science Observations (PICASSO) is an ESA project led by BIRA-IASB, in collaboration with VTT Technical Research Centre of Finland Ltd, Clyde Space Ltd. (UK), Centre Spatial de Liège (BE) and the Royal Observatory of Belgium – see ANNEX B. PICASSO is a three-unit CubeSat, for which VTT will develop the main payload,Visible Spectral Imager for Occultation and Nightglow (VISION). VISION will primarily target the observation of the Earth's atmospheric limb during orbital Sun occultation. By assessing the radiation absorption in the Chappuis band for different tangent altitudes, the vertical profile of the ozone is retrieved. A secondary objective is to measure the deformation of the solar disk so that stratospheric and mesospheric temperature profiles are retrieved by inversion of the refractive ray-tracing problem. PICASSO has now passed the Critical Design Review. Its launch, foreseen initially for February 2020, has been postponed due to delays associated with the COVID-19 pandemic.

- *Key Recommendation (4) – Maintenance of regular, long-term monitoring in key regions for troposphere stratosphere exchange*

ULB/SQUARES ensures the maintenance of the processing chains for IASI-A, -B and –C with the updated FORLI version, allowing long-term time series studies on the global datasets.

BIRA-IASB has maintained the additional ground-based instruments previously deployed in the Tropics: NDACC/TCCON certified FTIR instruments on Reunion Island (Indian Ocean), and NDACC certified (MAX)DOAS UV-visible instruments on Reunion Island and in Bujumbura (Burundi). It has deployed a new FTIR instrument at Porto Velho (Brazilian Amazonian forest) in July 2016.

RMI is taking steps to start an ozone sounding program in Nigeria, in an African region with very few ozone observations from the ground.

- *Key Recommendation (8) – Implementation of new and cost-effective instruments for ozone and trace gases, as well as data analysis protocols, including further progression with network harmonisation*

RMI participates in the efforts of homogenizing ozone profile data records.

- *Other systematic observations*

ULB/SQUARES has expanded IASI data dissemination to a variety of users, notably the Copernicus Atmosphere Monitoring (CAMS) and Climate Change (C3S) services.

ULB/SQUARES verifies the consistency between the FORLI datasets retrieved from IASI-A, -B, and -C. Every new FORLI algorithm development comes with the reprocessing of the whole IASI dataset for consistency purposes.

ULB/SQUARES is also deploying efforts to provide homogenized IASI datasets through the development of a climate version of FORLI.

RMI continues the UV observations with Brewer spectrophotometers in Uccle and in Antarctica.

6.4 Data archiving and stewardship

- *Key Recommendation (1) – Develop robust automated data submission with centralised processing and QA schemes*

In the frame of the CAMS-84 NDACC-based validation project for the Copernicus Atmosphere Monitoring Service (CAMS), data archiving of NDACC and TCCON observations has been accelerated for a set of stations, data being now submitted within 1 day to 1 month after acquisition. Tools for the evaluation of the quality and consistency of NDACC data files have also been developed. Procedures and tools that have been developed for NORS and CAMS-84 are being extended to other NDACC key species.

Similarly, data archiving of EUBREWNET, NDACC, SHADOZ, WOUDC and other ozone and related observations have been accelerated and quality assured in order to meet operational requirements of the routine validation service operated at BIRA-IASB on behalf of ESA's Copernicus Sentinel-5 Precursor Mission Performance Centre (S5P MPC).

- *Key Recommendation (3) – Encourage data providers to submit to existing databases*

ULiège performs regular data archiving at NDACC.

RMI archives the data regularly in the well-established network databases at WOUDC and NDACC. It also submitted homogenized ozonesonde data to the database set up within the O3SDQA Working Group. It submits Brewer data to the database created within the framework of the COST action ES1207 EUBREWNET.

- *Key Recommendation (6) – Enhanced linkage among data centres*

BIRA-IASB is ECMWF's prime contractor coordinating the collaborative project Production of Essential Climate Variable Datasets based on Earth Observations (Ozone), Ref. C3S_312a_Lot4, to populate the European Copernicus Climate Change Service (C3S) Data Store with Level 3 data products.

BIRA-IASB provides advice to the definition and improvement of ESA's Validation Data Centre operated at NILU (EVDC, https://evdc.esa.int/), which interconnects several data centres for the purpose of harmonised satellite validation.

- *Other data archiving and stewardship activities*

ULB/SQUARES stores raw IASI L1C and L2 data locally so that reprocessing of historical IASI data with an improved FORLI version can easily be performed. Through collaborations with LATMOS, ULB/SQUARES archives continuously the in-house IASI retrieved datasets (FORLI-O_3, -CO, -HNO_3, BRESCIA-SO_2, ANNI-NH_3 and other products) into the Aeris portal at: http://iasi.aeris-data.fr/.

The backprocessing of the whole IASI FORLI datasets with the last v20191122 is ongoing and will be archived on the Aeris portal in the future.

In addition to submitting them to WOUDC and NDACC, RMI stores raw data and metadata locally so that reprocessing of historical data is easily established.

6.5 Capacity building

- *Key Recommendation (2) – Provide training opportunities for station operators in developing countries*

RMI will provide the hardware, equipment, and training to the National Space Research and Development Agency of Nigeria to launch ozonesondes at Abuja. The exploitation of this dataset will be done in close collaboration between the partners.

BIRA-IASB provides training to the local operators of the new Porto Velho site in Brazil, and hosted a second Chinese PhD student for training on NDACC and TCCON operations and data analysis and validation procedures.

- *Other capacity building activities*

The relocation of the unused Dobson instrument from Uccle to Kyev is explicitly mentioned on p. 38 of the WMO report of the 8th session N° 53.

In response to the need to further develop methods and tools for a better-integrated use of complementary data with different scale, resolution etc., BIRA-IASB has developed the multi-purpose simulator of global measurement systems for atmospheric composition with full metrology description (*Verhoelst et al., 2015*): OSSSMOSE (Observing System of Systems Simulator for Multi-mission Synergies Exploration). This versatile environment provides realistic simulations of the output of real and hypothetic global observing systems and of their data comparison. It combines various state-of-the-art components, such as multi-dimensional observation operators mapping in 2D/3D the real sensitivity of a measurement system to atmospheric gradients, cycles and trends. OSSSMOSE has been applied with success to the validation of Envisat and MetOp to close the error budget of data comparisons (e.g., *Cortesi et al., 2007; Lambert et al., 2012; Verhoelst et al., 2012, 2015*). OSSSMOSE is also being used for optimisation studies and gap analysis of measurement systems in the GAIA-CLIM project and implemented partly in the Virtual Observatory being built at EUMETSAT. - See Section 3.2.6.

7 FUTURE PLANS

7.1 Royal Meteorological Institute (RMI)

Continuation of the observations at Uccle (ozone column, ozone profile, Spectral UVB, aerosol) and at the Antarctic station (Ozone column, Spectral UVB and aerosol).

Continuation of the automatic lidar ceilometer observations

Analysis of the data obtained at the Belgian Antarctic station.

Participation in the validation and quality assurance of satellite observations (AC SAF CDOP-4 of EUMETSAT and Ozone CCI of ESA).

The RMI has recently signed a Memorandum of Understanding with the National Space Research and Development Agency of Nigeria to launch ozonesondes at Abuja, Nigeria. The hope is to have the first launches there at the end of 2020.

The RMI will take the lead in the homogenization of the European ozonesonde station time series, which is lagging behind for some stations in comparison with e.g. the tropical, American and Canadian networks. Use of these homogenized data for trend analysis and validation of satellite retrievals of ozone.

At the occasion of the International Polar Year 2007, the Belgian government decided to build a new scientific summer station at Utsteinen, East Antarctica and committed the International Polar Foundation to design and build this new base.

A Brewer ozone spectrophotometer was installed mid-January 2011 and was able to measure until 14 February 2011. It measured the total column amount of ozone and the UV radiation in the UV-A and UV-B bands. It was successfully set up for the first time. It was mounted on the northern roof of

the station. It needs sun and regular maintenance for operation and was therefore de-installed at the end of the season. First analyses of the data show that it made very good and interesting measurements of total ozone and the UV index at Utsteinen. Since then the instrument was operational during each manned period at the station.

Besides this, a suite of aerosol instruments are in use at the station, some of which are also operational, under remote control, during the unmanned (winter) period.

7.2 Royal Belgian Institute for Space Aeronomy (BIRA-IASB)

Preparation of a large scale Sentinel-5 Precursor Cal/Val campaign to be organised in 2020-2021. For this campaign, both ground-based and aircraft experiments will be deployed in synergy. These will build on preparatory airborne and ground-based activities developed as part of the successive AROMAT, AROMAT-2, CINDI-2, AROMAPEX and RAMOS campaigns, most of them coordinated by BIRA-IASB.

Development of a centralised and automated processing system for UV-visible MAXDOAS observations to be hosted at the ESA Cal/Val facilities, in support of multi-mission programmes (FRM4DOAS project, 2016-2021).

BIRA-IASB has developed the instrument concept of Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) – see ANNEX B and Section 6.3. This instrument consists of a limb viewing atmospheric sounder designed to operate on board a micro-satellite like the PROBA platform. This instrument combines the technique of limb scattering observation with an imaging capacity when operating on the day side. At the terminator and in the eclipse phase, the spectrometer will be used in solar and stellar occultation modes respectively. This instrument is designed to infer from UV-visible-NIR radiance measurements from the upper troposphere to the mesosphere the vertical distribution of ozone, NO_2, BrO, CH_4, H_2O, OClO, aerosols and PSCs… BIRA-IASB is the PI of this instrument, which has now received definite approval as an element of the EarthWatch programme at the last ESA ministerial council in Dec 2016 and is being developped.

A PICo-satellite for Atmospheric and Space Science Observations (PICASSO) is an ESA project led by BIRA-IASB, in collaboration with VTT Technical Research Centre of Finland Ltd, Clyde Space Ltd. (UK), Centre Spatial de Liège (BE) and the Royal Observatory of Belgium – see ANNEX B and Section 6.3. PICASSO is a three-unit CubeSat, for which VTT will develop the main payload,Visible Spectral Imager for Occultation and Nightglow (VISION). VISION will primarily target the observation of the Earth's atmospheric limb during orbital Sun occultation. By assessing the radiation absorption in the Chappuis band for different tangent altitudes, the vertical profile of the ozone is retrieved. A secondary objective is to measure the deformation of the solar disk so that stratospheric and mesospheric temperature profiles are retrieved by inversion of the refractive ray-tracing problem. PICASSO will be launched on VEGA return flight in 2020.

The Tropospheric Monitoring Instrument (TROPOMI) aboard ESA's Copernicus Sentinel-5 Precursor satellite was aunched in October 2017. Since April 2018 it acquires measurements of the troposphere down to the boundary layer and quantify emissions and transport of anthropogenic and natural trace gases and aerosols, which impact stratospheric ozone air quality and climate. BIRA-IASB is one of the key TROPOMI level-2 algorithm developers, being responsible for the prototyping of three important products: ozone, SO_2 and HCHO. BIRA-IASB is also the coordinator of its operational validation service

Continued participation and/or coordination of validation and quality assurance of satellite observations in the context of the EUMETSAT AC-SAF CDOP-2/3, ESA Multi-TASTE Phase F, ESA Ozone_cci and CCI+ (ozone and water vapour), C3S_312a_Lot4, ESA Aerosol_cci, EXPANSION (ESA Living Planet Fellowship), MIPAS and SCIAMACHY Quality Working Groups Phase-F, and EU FP7 QA4ECV.

7.3 University of Liège (ULiège)

The continuation of the NDACC observations at the Jungfraujoch station remains the primary objective of the team.

7.4 Université Libre de Bruxelles (ULB)

On the remote sensing side, IASI-related activities will be strengthened through the participation of ULB researchers in international programs, including the continuation of the ESA Climate Change Initiative (O_3-CCI+), the EUMETSAT SAF (Satellite Application Facility) on Atmospheric Composition Monitoring and the C3S programs.

The NRT FORLI processing chain for IASI-A, -B and -C are being upgraded with the improved FORLI v20191122 that is planned to be implemented in the future at the EUMETSAT CAF (Central Application Facility) for wider dissemination of the IASI L2 products to the user's community.

The group will continue to contribute to various international efforts for providing long-term quality-assured information on essential climate variables, e.g. in the frame of the O_3-CCI+ and C3S programs.

The group will foster activities with IASI in the context of chemistry and climate, including O_3-HNO_3 correlations; link to O_3 and precursor emissions in the troposphere; STE; O_3 long-wave radiative effect.

The group will pursue its activities around the preparation of the future infrared components of the Sentinel 4 and 5, via the active contribution to the IASI-NG and IRS-MTGS mission advisory groups.

8 NEEDS AND RECOMMENDATIONS

There is an urgent need to secure financial support for laboratory spectroscopic activities supporting investigations of the terrestrial atmosphere.

There is a need for technical staff to maintain the preparation and execution of balloon soundings.

There is also a need for structural logistical, technical and financial support of the activities at the Antarctic station Princess Elisabeth.

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ANNEX A. LONG-TERM TIME SERIES OF GROUND-BASED MEASUREMENTS

ULiège, BIRA and RMI are involved in instrument operation at twenty-eight stations located in various parts of the world and at different altitudes (Table A 1), including the ten stations belonging to the Meteo-Wing network of the Belgian Defence, which are operated by RMI and are equipped with ceilometers providing aerosol backscatter profiles from the ground to 7 km altitude. Detail of the station networks, of the instruments and platforms, of the observation record duration, of the nature of the species observed and physical quantity retrieved, and of which institute is involved is provided in Table A 2 while Table A3 provides the complete list of species monitored with the FTIR instrument operated by ULiège at the Jungfraujoch.

Table A 1. Geolocation of ground-based stations and type of data collected. Col = column(s); Prof = profile(s); Aer = aerosol properties; UV = UV radiation.

Station	Country / Continent	Latitude	Longitude	Altitude a.s.l.	Type of data			
Beauvechain (*)	Belgium	50.78°N	4.77°E	108 m			Aer	
Bujumbura	Burundi	3°S	21°E	774 m	Col	Prof	Aer	
Casteau (*)	Belgium	50.52°N	4.01°E	80 m			Aer	
Chièvres (*)	Belgium	50.59°N	3.81°E	56 m			Aer	
Diepenbeek	Belgium	50.9°N	5.4°E	42 m			Aer	
Elsenborn (*)	Belgium	50.46°N	6.22°E	560 m			Aer	
Florennes (*)	Belgium	50.25°N	4.6°E	280 m			Aer	
Harestua	Norway	60.2°N	10.8°E	596 m	Col	Prof		
Humain	Belgium	50.2°N	5.25°E	240 m			Aer	
Houthalen-Helchteren (*)	Belgium	51.02°N	5.37°E	57 m			Aer	
Jungfraujoch	Switzerland	46.55ºN	7.98ºE	3580 m	Col	Prof	Aer	
Kleine-Brogel (*)	Belgium	51.17°N	5.47°E	58 m			Aer	
Koksijde (*)	Belgium	51.1°N	2.4°E	8 m			Aer	
La Réunion	France DOM/TOM	20.9°S	55.5°E	10 m	Col	Prof		
Le Port, La Réunion	France DOM/TOM	20.56°S	55.17°E		Col			
Mol (**)	Belgium	51.19°N	5.11°E	27 m				UV
Mount Maïdo, La Réunion	France DOM/TOM	21°S	55.3°E	2200 m	Col			
Mount Rigi (**)	Belgium	50.5°N	6.1°E	674 m				UV
Observatoire de Haute Provence (OHP)	France	43.94°N	5.71°E	650 m	Col	Prof		
Porto Velho	Brazil	8.77°S	63.87°W	87 m	Col	Prof		
Princess Elisabeth[1] (**)	Antarctica	71°S	23°E	1397 m	Col			UV
Redu (**)	Belgium	50°N	5.15°E	325 m				UV
Schaffen (*)	Belgium	51°N	5.06°E	95 m			Aer	
Semmerzake (*)	Belgium	50.95°N	3.67°E	35 m			Aer	
Uccle[2] (**)	Belgium	50.8°N	4.35°E	100 m	Col	Prof	Aer	UV
Virton (**)	Belgium	49.57°N	5.53°E	226 m				UV

[1] Station n° 499 in the WOUDC list. It is operational during the manned periods in the austral summer.

[2] A complementary NDACC station, Uccle is Staion n° 053 in the WOUDC list.

Station	Country / Continent	Latitude	Longitude	Altitude a.s.l.	Type of data
Xianghe[3]	PR of China	39.75°N	116.96°E	46 m	Col Prof Aer
Zeebrugge	Belgium	51.3°N	3.2°E	3 m	Aer

(*) Part of the Belgian Meteo-Wing military network.

(**) While being completely refurbished, the UV observation network is currently down. It will be completed by a new station in Oostende (the old station in Oostende has been dismantled).

Table A 2. Long-term time series of measurements at ground-based stations.

Station	Network	Technique	Start	End	Species	Physical quantity	Belgian institutes involved
Jungfraujoch	NDACC Alpine	FTIR	Early '80	/	*Detail in Table A3*	total & partial columns, vertical profile	ULiège BIRA
		SAOZ UV-Vis DOAS	1990	/	O_3, NO_2	column	BIRA
		MAXDOAS	2010	/	BrO, NO_2, O_3	stratos. vertic. profile	BIRA
					NO_2, H_2O, O_3, H_2CO	tropospheric abundance	
					aerosol	tropospheric AOD	
Harestua	NDACC Arctic	UV-Vis DOAS	1994	/	O_3, NO_2, OClO, BrO	column	BIRA
					NO_2, BrO	stratos. vertic. profile	
Observatoire de Haute Provence (OHP)	NDACC Alpine	UV-Vis MAXDOAS[4]	Summer 1998	/	O_3, NO_2, BrO	column	BIRA
					NO_2, BrO	stratos. vertic. profile	
			2000	/	NO_2, H_2CO	tropospheric abundance	
La Réunion Saint-Denis	NDACC SH tropical	FTIR (Bruker 120M)	May 2009[5]	Dec 2011	O_3, halogenated and nitrogenated source and reservoir gases, volatile organic compounds, …	total & partial columns, vertical profile	BIRA
	TCCON & NDACC[6]	FTIR (Bruker 125HR)	Sep 2011	/	As above + CO_2, CH_4	column	BIRA
					O_3	total & partial columns, vertical profile	
	/	UV-Vis MAXDOAS	Aug 2004	Jul 2005	O_3, NO_2, BrO, H_2CO, CHOCHO	column, tropospheric abundance	BIRA

[3] Approximately 50 km East of Beijing. This area is not strongly affected by local emissions but still largely under the influence of pollutants transported from three surrounding major cities: Beijing, Tianjin and Tangshan.

[4] Initially a standard UV-Visible DOAS instrument, upgraded with off-axis capability (MAXDOAS) in 2000.

[5] Initially FTIR observations were made during campaigns in Sept.-Oct. 2002, Aug.-Nov. 2004 and May-Nov. 2007. During the first FTIR campaign in 2002, simultaneous measurements at sea level and at high altitude (2200 m asl) were performed, allowing inferring columns in the boundary layer/low troposphere, via a differential approach.

[6] The instrument is switched regularly between the TCCON Mode (greenhouse gas measurements in the near-IR) and the NDACC mode (measurements of O_3 and related key species). The instrument got the official certification of being affiliated to the Total carbon Column Observing Network (TCCON) in summer 2012. As the evolution of the stratospheric ozone layer is influenced by climate changes, these measurements are relevant indirectly for understanding ozone in the future.

Station	Network	Technique	Start	End	Species	Physical quantity	Belgian institutes involved
La Réunion Mount Maïdo	NDACC SH tropical	FTIR (Bruker 125HR)[7]	Feb 2013	/	O_3, halogenated and nitrogenated source and reservoir gases, volatile organic compounds	total & partial columns, vertical profile	BIRA
La Réunion Le Port	/	MAXDOAS/ direct-sun	Apr 2016	/	O_3, O_3-related key species	column, tropospheric abundance[8]	BIRA
Porto Velho	/	FTIR (Bruker 125M)	Jul 2016	/	O_3, halogenated and nitrogenated source and reservoir gases, volatile organic compounds, …	total & partial columns, vertical profile	BIRA
Xianghe	/	UV-Vis MAXDOAS	Feb 2010[9]	/	NO_2, O_3, H_2CO, SO_2, HONO, BrO, CHOCHO, H_2O	tropospheric and/or stratospheric column	BIRA[10]
					NO_2, H_2CO, SO_2, CHOCHO	tropospheric vertic. profile	BIRA
					NO_2, BrO	stratos. vertic. profile	BIRA
					aerosol	AOD	BIRA
	/	FTIR (Bruker 125HR)	Jun 2018	/	O_3 + HCHO, CO_2, CH_4	total & partial columns, vertical profile	CAS[11], BIRA
Bujumbura	/	UV-Vis MAXDOAS	Nov 2013	/	O_3, NO_2, HCHO, CHOCHO, SO_2, BrO, H_2O	column	BIRA
					NO_2, BrO	stratos. vertic. profile	BIRA
	/	CIMEL sun photometer	Nov 2013	/	aerosol	AOD	BIRA
Uccle	NDACC NH Mid-lat.	Mini-MAXDOAS [12]	Apr 2011	/	NO_2	tropospheric column	BIRA[13]
					aerosol	AOD	
	WOUDC Station 053	Brewer n°16 [14]	1983	/	O_3	column[15]	RMI
					UV	spectral irradiance[16]	
			2001	/	O_3	column	RMI

[7] Solar absorption in the mid-IR.

[8] These observations will be exploited in cooperation with the Univerity of Colorado which will install another MAXDOAS system at the Maido site (2200 m asl) in January 2017. The combination of both systems will allow for better separation of the boundary layer, free-troposphere and stratospheric composition.

[9] Following a campaign based in Beijing (July 2008 to April 2009).

[10] Six years of observations are now available allowing for the study of a number of trace gases (NO_2, O_3, H_2CO, SO_2, HONO, BrO, CHOCHO, and H_2O) and aerosols in the troposphere and/or the stratosphere. These measurements are being exploited in support of various projects, serving in particular the validation of tropospheric measurements from recent satellite sensors (GOME-2, OMI and SCIAMACHY) and various modelling projects dealing with the determination of trace gas emissions in China.

[11] CAS (Chinese Academy of Sciences) is owning and operating the FTIR instrument at Xianghe. BIRA collaborates with CAS for the exploitation of the data.

[12] Time resolution : approximately 20 minutes.

[13] In support of the Copernicus Atmosphere Monitoring Service (CAMS) and for satellite validation purposes.

[14] Single monochromator, refurbished with new electronics in 2017.

[15] Daily.

[16] Several scans per day, number depending on the time the sun is above the horizon

Station	Network	Technique	Start	End	Species	Physical quantity	Belgian institutes involved
		Brewer n°178 [17]			UV	spectral irradiance	
		Dobson n°40 [18]	1971	May 2009	O_3	column	RMI
		Balloon-borne ozone-sondes[19]	1969 [20]	/	O_3	vertical profile[21]	RMI
Uccle	EUMETNET E-Profile	Automatic Lidar Ceilometer		/	aerosol	backscatter profile (0-14 km)	RMI
Zeebrugge							
Diepenbeek							
Humain							
Beauvechain	Meteo-Wing (Belgian Defence)	ceilometer		/	aerosol	backscatter profile (0-7 km)	RMI
Casteau							
Chièvres							
Elsenborn							
Florennes							
Houthalen-Helchteren							
Kleine-Brogel							
Koksijde							
Schaffen							
Semmerzake							
Princess Elisabeth[22]	WOUDC Station 499	Brewer n°100 [23]	Jan 2011	/	O_3	column	RMI
					UV	spectral irradiance	
	(*)	UV-B, UV-A sensors, pyranometer	2012	/	UV	global solar spectral irradiance, broadband data, filter radiometer data, sunshine duration	BIRA
Mol	(*)	UV-B, UV-A sensors, pyranometer	1995	/	UV	global solar spectral irradiance, broadband data, filter radiometer data, sunshine duration[24]	BIRA
Mount Rigi							
Redu							
Uccle							
Virton							

(*) No more contribution to the EUVDB European Database since 2016.

[17] Double monochromator.

[18] In agreement with WMO-GAW the instrument is now loaned to the University of Kiev (Ukraine) and is operational there.

[19] Three times per week.

[20] Ozone profile data in the period 1969-1997 were obtained with Brewer-Mast sensors. ECC ozone sensors have been used since 1997. Special care is taken to ensure the homogeneity of the time series, not only between the two types of ozone sensors, but also between soundings using one single type of sensor.

[21] Resolution: a few hundred metres.

[22] The Antarctic station is operational during the manned periods in the austral summer

[23] Put at RMI's disposal by KNMI (The Netherlands).

[24] Plus associated cloud and meteorological parameters.

Table A 3. Molecules currently studied in FTIR solar spectra recorded at the Jungfraujoch [25]

Reference gas:		N_2
Minor constituents:		CO_2, N_2O, CH_4, CO, *O_3*
Trace constituents:	Halogenated species:	*HCl*, *$ClONO_2$*, *HF*, *COF_2*,
		CCl_2F_2, $CHClF_2$, CCl_3F, CH_3CClF_2, CCl_4, CF_4, SF_6, CH_3Cl
	Nitrogenated species:	*NO*, *NO_2*, *HNO_3*, *$ClONO_2$*, NH_3
	Others:	H_2O, C_2H_6, C_2H_2, C_2H_4, HCN, OCS, H_2CO, H_2CO_2, CH_3OH
		Isotopologues of CO, CH_4, H_2O, *O_3*

[25] Species typed *in italic* are primarily present in the stratosphere, while the other ones are tropospheric source gases.

ANNEX B. SATELLITE OBSERVATIONS

ULiège, ULB and BIRA-IASB are involved in several satellite missions relevant to atmospheric ozone and connected issues, the detail of which is provided below.

B.1 Column measurements of ozone and other gases/variables relevant to ozone loss

ULiège, ULB and BIRA-IASB are involved in several satellite missions measuring the total column of ozone and of ozone relevant species (halogens, NOy, BrO, HCFC, CFC…).

- ***Royal Belgian Institute for Space Aeronomy (BIRA-IASB)***

- Global Ozone Monitoring by Occultation of Stars (GOMOS), on board of ESA's Envisat, measured the vertical profile of O_3, NO_2, NO_3, aerosols, OClO and other trace gases from August 2002 till April 2012 (end Envisat mission). BIRA-IASB is a co-proposer of the instrument, an expert support laboratory (ESL) certified by ESA, and has been active in the development of retrieval algorithms (IPF, AerGOM) and validation of O_3, NO_2, aerosols, OClO and temperature data products.
- Global Ozone Monitoring Experiment-2 (EUMETSAT GOME-2), aboard EUMETSAT MetOp-A platform since October 2006 and MetOp-B platform since September 2012, measures the column of O_3, NO_2, BrO, SO_2, OClO and other trace gases. Partner of the EUMETSAT Satellite Application Facility on Atmospheric Composition (AC-SAF), BIRA-IASB plays a key role in scientific developments, evolution and geophysical validation of the operational GOME-2 Data Processor for the column of ozone, NO_2, BrO, H_2CO and SO_2 established at DLR (Germany) as part of the AC-SAF *(Loyola et al. 2011; Lerot et al. 2010b; Lerot et al. 2014; Koukouli et al. 2014)*.
- Tropospheric Moniroting Instrument (TROPOMI), launched in October 2017 on board of the Copernicus Sentinel-5 Precursor mission (S-5p). Member of the S-5p Mission Advisory Group, BIRA-IASB is involved in scientific developments and evolution of the operational algorithms for the column of ozone, NO_2, H_2CO, CO, CH_4 and SO_2. BIRA-IASB host and operate parts of the ground-segment for data processing, and it is the coordinatior and host of the Validation Data Analysis Facility (VDAF) of the S-5p Mission Performance Centre (MPC) for all data products.
- Copernicus Sentinel-4 and Sentinel-5, planned for after 2023. Member of the Sentinel-4/5 Mission Advisory Group, BIRA-IASB is involved in scientific developments, evolution and geophysical validation of the operational algorithms for the column of ozone, NO_2, H_2CO, CO, CH_4 and SO_2.

- ***Université Libre de Bruxelles (ULB)***

The Atmospheric Spectroscopy group (Service de Chimie Quantique et Photophysique) at ULB is heavily involved in the IASI/MetOp satellite mission, being member of its Science Working Group (ISSWG-2), under auspice of CNES and EUMETSAT. IASI is a sounder that measures the thermal infrared radiation of the Earth/atmosphere in nadir geometry (*Hilton et al., 2012*), at fairly high spatial (12 km diameter circular pixel on-ground) and spectral (0.5 cm^{-1}) resolutions (*Clerbaux et al 2009*).

The IASI mission consists of a series of three identical infrared nadir-looking sounders (IASI-A, -B and -C), each providing high-resolution global daily maps of numerous species, amongst which ozone throughout the troposphere and the stratosphere. Launched successively in 2006, 2012 and 2018 onboard the meteorological Metop platforms, IASI is part of the EPS system.

As compared to UV sounders but also precursor infrared sounders (IMG and TES), IASI has the advantage of high spatial and temporal sampling, providing global measurements twice daily, once in the morning and once in the evening. The small pixel allows capturing fine concentration variations of several trace gases. The ULB group has set-up, in collaboration with the French LATMOS, a near-real time processing chain for IASI. Of particular relevance here are:

- Ozone total columns distributions, which are retrieved global twice a day, in near-real time using FORLI-O_3. The reference version (v20151001) has undergone validation against a series of independent observations (GOME-2, Dobson, Brewer, SAOZ and ozonesondes data) on the global scale for the two IASI instruments (Boynard et al., 2018). The added value of IASI exceptional frequency sampling has been demonstrated to be of particular importance for monitoring medium to long-term changes in global ozone concentrations (Wespes et al., 2019). FORLI-O_3 is being implemented in the EUMETSAT Central Application Facility and is expected

to become the operational processing chain for IASI O_3. FORLI-O_3 v20151001 is also the reference algorithm for the work performed under the O_3-CCI+ and the C3S programs.

- Nitric acid total columns distributions, which have an important role in regulating the ozone hole, and a sensitive species to monitor its development. The first characterization and validation of the FORLI-HNO_3 vertical profile product with FITR instruments at 6 stations has been previously published (Ronsmans et al., 2016). Analysis of the IASI HNO_3 variations with a focus on the Polar Regions and the influence of PSCs has also been reported (Ronsmans et al., 2018). FORLI-HNO_3 is being implemented in the EUMETSAT Central Application Facility and is expected to become the operational processing chain for IASI HNO_3.
- Aerosols from various types, including volcanic ash and sulfuric acid droplets (Clarisse et al., 2013). Note that BRESCIA-SO_2 is implemented in the EUMETSAT Central Application Facility since 2018.
- In addition a series of column measurements of tropospheric species, strongly involved in the ozone budget by being ozone precursors, are provided. These include in particular CO and volatile organic compounds (e.g. Franco et al., 2018). FORLI-CO is implemented in the EUMETSAT Central Application Facility since 2017.

➢ ***University of Liège (ULiège)***

ULiège is involved in the Canadian ACE satellite mission (Bernath et al., 2005), which includes an FTIR instrument on operation from space since early 2004. ULiège contributes to the scientific exploitation of the ACE-FTS data, especially for ODS substances.

B.2 Profile measurements of ozone and other gases/variables relevant to ozone loss

ULB and BIRA are involved in several satellite missions measuring the vertical distribution of ozone and of ozone relevant species (halogens, NOy, BrO, HCFC, CFC…).

➢ ***Royal Belgian Institute for Space Aeronomy (BIRA-IASB)***

- Global Ozone Monitoring by Occultation of Stars (GOMOS), on board of ESA's Envisat, measured the vertical profile of O_3, NO_2, NO_3, aerosols, OClO and other trace gases from August 2002 till April 2012 (end Envisat mission). BIRA-IASB is a co-proposer of the instrument, an expert support laboratory (ESL) certified by ESA, and has been active in the development of retrieval algorithms (IPF, AerGOM) and validation of O_3, NO_2, aerosols, OClO and temperature data products.
- Tropospheric Moniroting Instrument (TROPOMI), launched in 2017 on board of the Copernicus Sentinel-5 Precursor mission (S-5p). Member of the S-5p Mission Advisory Group, BIRA-IASB is involved in scientific developments and evolution of the operational algorithms for the vertical distribution of ozone. BIRA-IASB coordinates the ozone profile and tropospheric ozone validation for TROPOMI and operates the Validation Data Analysis Facility (VDAF) of ESA's S-5p Mission Performance Centre (MPC).
- Copernicus Sentinel-4 and Sentinel-5, planned for after 2023. Member of the Sentinel-4/5 Mission Advisory Group, BIRA-IASB is involved in planning the geophysical validation of the operational algorithms for the vertical distribution of ozone.
- Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS): national development of a limb viewing satellite instrument responding to the requirements resulting from the 7th, 8th and 9th ORM Meetings in 2008, 2011 and 2014, respectively (*WMO GORMP Report N° 51, N° 53 and N° 54*): "Satellite observations of high vertical resolution profiles using limb viewing for O_3 and key molecules are required in order to more accurately understand the changes in O_3 as CFCs decline and climate change occurs." In 2016, the ALTIUS mission was accepted by the ESA-Earth Observation programme board as an element of the EarthWatch programme and definitely approved at the last ESA ministerial council in December 2019. The instrument and its ground segment are now in development and implementation phase.
- PICASSO - A PICo-satellite for Atmospheric and Space Science Observations is an ESA project led by BIRA-IASB, in collaboration with VTT Technical Research Centre of Finland Ltd, Clyde Space Ltd. (UK), Centre Spatial de Liège (BE) and the Royal Observatory of Belgium. PICASSO

is a three-unit CubeSat, for which VTT will develop the main payload,Visible Spectral Imager for Occultation and Nightglow (VISION). VISION will primarily target the observation of the Earth's atmospheric limb during orbital Sun occultation. By assessing the radiation absorption in the Chappuis band for different tangent altitudes, the vertical profile of the ozone is retrieved. A secondary objective is to measure the deformation of the solar disk so that stratospheric and mesospheric temperature profiles are retrieved by inversion of the refractive ray-tracing problem. PICASSO is on way toward a launch in 2020.

- ***Université Libre de Bruxelles (ULB)***

- The Atmospheric Spectroscopy group at ULB/SQUARES tackles several chemistry-related activities around the IASI/MetOp satellite mission. The researchers take active part in the IASI Sounder Science Working Group (ISSWG-2), under auspice of CNES and EUMETSAT, for IASI and preparation of IASI on EPS-SG. In addition to providing information on total columns (see above), IASI has also profiling capabilities at least equal if not superior to most instrument currently in operation. With the FORLI processing chain set-up at ULB, the following products are available in near-real-time:
  - Ozone vertical profiles, which are retrieved in 40 layers of 1km thickness starting from the ground, with 3-4 independent pieces of information. Upper stratospheric, middle-low stratospheric, UTLS and tropospheric contributions are well decorrelated. The maximum sensitivity of IASI to the ozone profile extends from the mid-troposphere to the lower stratosphere, and the product is thus of high relevance for monitoring the vertical structure of the ozone hole, the contribution of tropospheric ozone to climate, as well as the impact of ozone in the lowest layers on air quality.
  - Nitric acid vertical profiles. The vertical information is low with only one level of information on the vertical profile and negligible sensitivity near the surface in most cases but the retrieval of vertical profiles improves on the columns measurements by accounting for changes in tropopause height. Vertical profiles are available in NRT. The maximum sensitivity is in the upper troposphere/lower stratosphere (10-20km). A partial de-correlation between tropospheric and stratospheric HNO_3 is possible in the best cases.
- In addition to IASI, the ULB researchers are involved SCISAT-1 ACE-FTS Science Team, although their active contribution has decreased in the last years due to their large involvement in IASI. They have contributed to several profile studies with ACE-FTS.

ANNEX C. CALIBRATION / VALIDATION ACTIVITIES

C.1 Ground-based and balloon-borne instrument calibration

- ***RMI***

Before the transfer to Ukraine, the Dobson instrument nr 40 was refurbished and calibrated at the Regional Calibration Centre of WMO in Hohenpeißenberg in 2009-2010. It turned out that the instrument has been very stable since the last calibration. Therefore no reprocessing of the data set at Uccle was necessary.

The Brewer instruments #016 and #178 were compared with the travelling reference instrument #017 in 2006 and 2008. In 2010 the instruments were calibrated in Uccle together with Brewer #100 (before it was sent to Antarctica) against Brewer reference instrument #158. The cosine response of Brewer #178 was measured in co-operation with BIRA in 2011. Other calibrations against reference instrument #158 took place in 2012, 2014, 2016 and 2018. The results of the calibrations are always immediately implemented, and recalculation of ozone values are done if needed.

The ozone sondes are carefully prepared and calibrated with a reference instrument in the laboratory before launch. A correction procedure is applied to minimise the inhomogeneity that could have been introduced at the change of the sonde type in 1997. The ozonesonde data are corrected according to the standard operating procedures and algorithms from the Ozone Sonde Data Quality Assessment (O3S-DQA) activity. In a more global context, the RMI participated in an international 4-week campaign (Jülich OzoneSonde Intercomparison Experiment in 2017) to compare different ozonesonde measurements in a simulation chamber with a reference instrument, to study the impact of different preparation procedures and sensing solution strengths. Additionally, the RMI and Forzungcentrum Jülich set up another intercomparison campaign in September 2018 with a modified sensing solution composition. The UV-B calibration of the Brewer instruments was checked with 1000W lamps in 2006, 2008, 2010, 2012, 2014, 2016 and 2018 during the calibration visits. In 2004 the special comparative observations were performed with a travelling reference UV instrument of the Joint Research Centre (JRC in Ispra) in the frame of the Qasume project (Gröbner et al, 2004). All the 1000W calibrations were consistent with the calibrations based on the monthly tests with 50W lamps within the expected errors.

- ***BIRA-IASB***

Different calibration facilities are available at the BIRA-IASB for the radiometric characterization (for example: angular response, relative spectral response, wavelength scales,…) and absolute calibration (using standard of spectral irradiance) of pyranometers, filter radiometer and spectroradiometer. The spectral range is 200-3000 nm.

A facility for electro-optical characterization of detectors in the VIS and NIR is available at BIRA-IASB (MAJIS project).

The BIRA-IASB MAX-DOAS instruments have participated to several calibration/intercomparison campaigns, e.g., the CINDI-2 campaign in Cabauw (NL) in September 2016 (Kreher et al., 2019).

The calibration of the BIRA-IASB FTIR instruments at La Réunion is verified on a daily basis by doing HBr (for NDACC) and HCl (for TCCON) cell measurements. BIRA-IASB also participates in the data processing standardisation procedures that are on-going in the frame of the NDACC Infrared Working Group and the TCCON network.

- ***ULiège***

Calibration of the Jungfraujoch FTIRs is performed according to NDACC recommendations, in order to characterize the instrument performance and stability. This is done by regularly recording HBr cell measurements. Also, N_2 (whose vertical distribution and concentration are well known) absorption features are further used to check the instrumental consistency, in particular for time periods for which regular cell measurements are unavailable.

C.2 Calibration / validation activities in the context of satellite missions and data retrieval

ULB participates in the AC-SAF activities in CDOP-2 and CDOP-3. In this framework, it plays a key role in the implementation of algorithms (including for FORLI-O_3, -HNO_3, -CO, BRESCIA-SO_2 and ANNI-NH_3) at the EUMETSAT Central Application Facility, and on the quality assurance of the retrieved products.

Based upon previous validation exercises of FORLI-O_3 (v20151001) using independent measurements (cf. Section 2.4.1 and Annex B), an updated version of FORLI retrievals has been developed (v20191122). The IASI dataset using the updated FORLI algorithm is now processing forward and backward at ULB.

An improved version of the SO_2 retrieval method has been developed in parallel and it will be ready by 2020.

For FORLI retrievals (O_3, CO and HNO_3) as well as for BRESCIA-SO_2 comparison between the processing chains operating in parallel at ULB and at EUMETSAT is being performed in the frame of the AC-SAF.

ULB is strengthening its calibration/validation activities within the O3-CCI+ program for which constructing long-term data records of stratospheric and tropospheric ozone profiles is the major requirement. This is also further reinforced by dedicated validation activities in the frame of the second phase of the TOAR project (TOAR-II) that has been approved for another five years (2020-2024).

C.3 Product and validation harmonisation, quality standards

BIRA-IASB has contributed to the international implementation of the global Quality Assurance framework for Earth Observation (QA4EO, http://qa4eo.org/) for the GEOSS, an effort coordinated by the CEOS WGCV. At European level it is active in the system engineering for the Copernicus Atmospheric Monitoring Service (CAMS) and the Copernicus Climate Change Service (C3S), where it ensures coordination and harmonisation of the data quality strategy between, on one hand, Copernicus pioneering projects of the EC (MACC-II/III, PASODOBLE, EVOSS, QA4ECV, GAIA-CLIM) and ESA (CCI-ozone, CCI-GHG), and on the other hand, ECMWF sponsored procurement of CAMS (CAMS-84) and C3S (C3S-ozone). In particular, BIRA-IASB coordinates stratospheric ozone validation activities in the CAMS-84, CCI-ozone and C3S-ozone procurement projects, including organisation of NDACC data provision on a rapid delivery basis (less than 1 month after acquisition) for the validation of the CAMS and C3S products.

In the EU projects FP7 QA4ECV (2014-2018) and H2020 GAIA-CLIM (2015-2018), BIRA-IASB coordinated the development, implementation and application of a Quality Assurance system (Nightingale et al., 2018) for atmospheric Essential Climate Variables (ECVs). Thioseprojects aimed at developing a robust generic system for the QA of satellite and in-situ retrieval algorithms and multi-decadal data records that can be applied virtually to all ECVs in a prototype for future sustainable services in the frame of the Copernicus Climate Change Service (C3S). Multi-use tools and SI/community reference standards are publicly available. More details on http://www.qa4ecv.eu/ and http://www.gaia-clim.eu and in Nightingale et al. (2018).

BIRA-IASB is involved in the harmonisation of data products from NDACC and TCCON, especially regarding uncertainty budget evaluations. Developments for better traceability to standards are ongoing.

ANNEX D. LIST OF RELEVANT SCIENTIFIC PAPERS

Only publications issued or submitted after the Belgian Report for the 10th WMO/UNEP Ozone Research Managers Meeting (ORM10) are listed below.

D.1 Peer reviewed papers, books

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D.2 Doctoral thesis

De Bock, V.: Analysis and interpretation of Aerosol Optical Depth values retrieved from a Brewer spectrophotometer at Uccle, Belgium (Unpublished doctoral dissertation) Université libre de Bruxelles, Faculté des Sciences – Chimie, Bruxelles, 2018.

ANNEX E. PROJECTS AND COLLABORATION

Only projects and collaborations that are ongoing or have been running after the issue of the Belgian National Report for the 10th WMO/UNEP Ozone Research Managers Meeting are listed in the top three tables below. A list of agency and programme acronyms is provided in Table E 4.

Table E 1. Projects in partnership.

Table E 2. Participation to working groups and collaborative initiatives.

Table E 3. Membership of international organisations and committees.

Table E 4. Acronyms of agencies, programmes, working groups.

Table E 1. Projects in partnership.

Acronym / Title / Objective / URL	Agency / Programme	Start	End	Belgian partners
ACCROSS - Atmospheric Composition and Circulation investigated with meteorological Reanalyses, Observational datasets and models for the Study of the Stratosphere and its changes	F.R.S. - FNRS	2016	2021	ULiège
AC-SAF - Satellite Application Facility on Atmospheric Composition Monitoring	EUMETSAT	2017	2021	ULB BIRA
AEROCLOUD BELARE field campaign to monitor solar UV-VIS global irradiance in Antarctica	BELSPO	2014	2020	RMI BIRA KU Leuven
Aerosol_CCI Phase II http://www.esa-aerosol-cci.org/	ESA CCI	2014	2018	BIRA
BACCHUS - Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding http://www.bacchus-env.eu/	EU FP7	2013	2017	BIRA (PI)
B-ACSAF - Belgian Contribution to the AC SAF activities (see AC-SAF below)	ESA, BELSPO PRODEX	2017	2021	ULB
CAMS-84 - Global and regional a posteriori evaluation and quality assurance	ECMWF	2015	2018	BIRA
CLIMB - How do aerosol-CLoud Interactions influence the surface Mass Balance in East Antarctica?	BELSPO	2019	2021	RMI
C3S-BARON (C3S_311a_Lot3) - Baseline And Reference Observations Network for C3S	ECMWF C3S	2017	2020	BIRA
C3S_Ozone (C3S_312a_Lot4) - Production of Essential Climate Variable Datasets based on Earth Observations (Ozone) – to feed the C3S Data Store (CDS) with Level 3 data	ECMWF C3S	2016	2018	BIRA (prime contractor)
CDOP-3 - Continuous Development and Operation 3	EUMETSAT	2017	2022	BIRA
ECVs-C3S_312a_Lot5 - Copernicus Climate Change Service, Atmospheric composition		2016	2018	BIRA ULB
ECVs-C3S_312b_Lot2 - Copernicus Climate Change Service, Atmospheric composition		2019		ULB BIRA
EXPANSION – ESA Living Planet Fellowship	ESA	2016	2018	BIRA
GAIA-CLIM - Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring http://www.gaia-clim.eu/	EU H2020	Mar 2015	Feb 2018	BIRA
GAW-CH 4 - FTIR measurements at the Jungfraujoch	WMO GAW	2018	2021	ULiège

Acronym / Title / Objective / URL	Agency / Programme	Start	End	Belgian partners
IASI-Flow - Infrared Atmospheric Sounding with IASI and Follow-on missions	ESA, BELSPO PRODEX	2019	2021	ULB
Ozone_CCI+ http://www.esa-ozone-cci.org/	ESA CCI	2019	2022	BIRA (coordinator) ULB
QA4ECV - Quality Assurance system for Essential Climate Variables http://www.qa4ecv.eu/	EU FP7	2014	2018	BIRA ULB
Sentinel-5 Precursor Mission Performance Centre (S5P MPC) Validation Data Analysis Facility (http://mpc-vdaf.tropomi.eu)	ESA, BELSPO PRODEX	2016	2021	BIRA
TROVA	BELSPO PRODEX	2016	2018	BIRA

Table E 2. Participation to working groups and collaborative initiatives.

Working group / Initiative	Belgian partners
ECUVM	BIRA
ESA Quality Working Groups (GOMOS, MIPAS, SCIAMACHY, Sentinel-5p)	BIRA
ESA Sentinel-5 Precursor Validation Team (S5PVT)	BIRA
ESA Satellite validation projects	RMI
EUBREWNET - A European Brewer Network – ESSEM COST Action ES1207 http://www.eubrewnet.org/cost1207/	RMI
EUMETNET E-profile programme to exchange data from lidar-ceilometers	RMI
EUMETSAT Satellite validation projects	RMI
JOSIE - Jülich Ozonesonde Intercomparison Experiment (Oct-Nov 2017)	RMI
LOTUS - Long-term Ozone Trends and Uncertainties in the Stratosphere – SPARC Activity http://www.sparc-climate.org/activities/ozone-trends/	RMI
Science and processing teams of several satellite missions	BIRA, ULB
SPARC / IO3C / IGACO / NDACC (SI2N) assessment of trends in the vertical distribution of ozone	BIRA, RMI
SPARC / IO3C / GAW (LOTUS) Long-term Ozone Trends and Uncertainties in the Stratosphere https://www.sparc-climate.org/activities/ozone-trends/	BIRA, RMI
SPARC Towards Unified Error Reporting (TUNER) activity https://www.sparc-climate.org/activities/tuner/	BIRA
STCE (Support of the ozone research programme)	RMI
TOAR - Tropospheric Ozone Assessment Report – IGAC Activity http://www.igacproject.org/TOAR	ULB
TOPROF – COST Action to use aerosol profile information from lidar-ceilometers	RMI
WCCOS - collaboration with the Forschungszentrum Jülich (FZJ) to sustain the World Calibration Centre for Ozonesondes hosted at FZJ (Forschungszentrum Jülich)	RMI

Table E 3. Membership of international organisations and committees.

International organisation / International committee	Belgian members
ACTRIS BE to build a National Facility for ins situ aerosol observations	RMI
Atmospheric Chemistry Experiment (ACE) Science Team	ULiège, ULB
ASOPOS	RMI

International organisation / International committee	Belgian members
Committee on Earth Observation Satellites (CEOS) Virtual Constellation for Atmospheric Composition (AC-VC)	BIRA, ULB
Committee on Earth Observation Satellites (CEOS) Working Group on Cal/Val (WGCV)	BIRA
EUBREWNET Management Committee (COST ES1207 - A European Brewer Network)	RMI
EUMETNET General Assembly	RMI
EUMETNET Policy and Finance Advisory Committee (PFAC)	RMI
EUMETNET Scientific and Technical Advisory Committee (STAC)	RMI
EUMETSAT Council	RMI
EUMETSAT O3MSAF Project Team	RMI
EUMETSAT O3MSAF Steering Group	RMI
EUMETSAT O3MSAF Validation Team	RMI
EUMETSAT Policy Advisory Committee	RMI
EUMETSAT Scientific and Technical Group	RMI
GEOS-Chem Carbon Gases & Organics working group	ULiège
GEOS-Chem Stratosphere	ULiège
IASI Conference Scientific Committees	ULB
IASI Sounder Science Working Group–II	ULB
International Scientific Station Jungfraujoch and Gornergrat (ISSJG) Astronomic Commission	ULiège
Mission Advisory Group for Sentinel-5p TROPOMI, Sentinel 4, Sentinel 5 and ALTIUS	BIRA
NDACC-Infrared working group	ULiège
NDACC steering committee	ULiège
WMO GAW Brewer sub-committee	RMI

Table E 4. Acronyms of agencies, programmes, working groups.

AC-SAF	EUMETSAT Satellite Application Facility on Atmospheric Composition
ACTRIS	European Research Infrastructure for the Observation of Aerosol, Clouds and Trace Gases
ASOPOS	Panel for the Assessment of Operating Procedures for Ozone Sondes
BELSPO	Belgian Science Policy
BELSPO PRODEX	BELSPO's PROgramme de Développement d'EXpériences scientifiques
BELSPO SSD	BELSPO's Science for a Sustainable Development programme
CEOS	Committee on Earth Observation Satellites
COST	European Cooperation in Science and Technology
ECMWF	European Centre for Medium-Range Weather Forecasts
ECUVM	European Conference on Solar UV Monitoring
C3S	European Union's Copernicus Climate Change Service
ESA	European Space Agency
ESA CCI	ESA's Climate Change Initiative
EU FP7	European Union's Seventh Framework Programme
EU H2020	European Union's Horizon 2020 research and innovation programme
F.R.S. - FNRS	Fonds National de la Recherche Scientifique, entité francophone
IAMAS	International Association of Meteorology and Atmospheric Sciences
IGAC	International Global Atmospheric Chemistry

IGACO	Integrated Global Atmospheric Chemistry Observations
IO3C	International Ozone Commission
IPCC	Intergovernmental Panel on Climate Change
IUGG	International Union of Geodesy and Geophysics
JOSIE	Jülich Ozonesonde Intercomparison Experiment
MPC	Mission Performance Centre
O3MSAF	EUMETSAT Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring
OSSSMOSE	Observing System of Systems Simulator for Multi-mission Synergies Exploration
QA4EO	Quality Assurance framework for Earth Observation
S5P	Sentinel-5 Precursor
SADDU	SCIAMACHY Algorithm Development and Data Usage
SCIAVALIG	SCIAMACHY Validation and Interpretation Group
SPARC	Stratosphere-troposphere Processes And their Role in Climate (WCRP's core project)
SSAG	SCIAMACHY Science Advisory Group
STCE	Solar Terrestrial Centre of Excellence
UNEP	United Nations Environment Programme
WCCOS	World Calibration Center for Ozone Sondes
WCRP	World Climate Research Programme
WGCV	Working Group on Calibration and Validation
WMO	World Meteorological Organisation
WMO GAW	WMO's Global Atmosphere Watch

ANNEX F. CONTACT DETAILS OF BELGIAN INSTITUTES AND SCIENTISTS INVOLVED IN OZONE RELATED RESEARCH

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