National Report of Belgium

for the 12th WMO/UNEP Ozone Research Managers Meeting

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Contents

FOREWORD

This report compiles contributions provided by four Belgian research performing organisations (RPO), whose contact details are found in ANNEX B

- the Institute of Astrophysics and Geophysics of the University of Liège (ULiège),
- the Royal Meteorological Institute (RMI) and
- the Royal Belgian Institute for Space Aeronomy (BIRA-IASB).
- the Service de Chimie Quantique et Photophysique of the Université Libre de Bruxelles (ULB) *(– no update received since ORM11 report.)*

1. OBSERVATIONAL ACTIVITIES

The past and current observations conducted under the responsibility of the Belgian RPO are summarized in Table 1.1 below.

Table 1.1 Status of observations conducted under the responsibility of the Belgian RPO. RI stands for European Research Infrastructure.

Station (Lat, Lon, Altitude)	Network / RI[1]	Technique[2]	Start – End Date[3]	Species	Physical quantity	Responsible RPO
Jungfraujoch 46.6N, 8.0E, 3580 masl	NDACC / ACTRIS	FTIR (120HR)	Mid-1980 →	N2, CO2, N2O, CH4, CO, O3 HCl, ClONO2, HF, COF2, CCl2F2, CHClF2, CCl3F, CH3CClF2, CCl4, CF4, SF6, CH3Cl, NO, NO2, HNO3, ClONO2, NH3, H2O, C2H6, C2H2, C2H4, HCN, OCS, H2CO, H2CO2, CH3OH, Isotopologues of CO, CH4, H2O, O3	vertical profile or total column concentrations	ULiège
		ZS DOAS (SAOZ)	1990 →			BIRA-IASB
		MAXDOAS	2010 →	BrO, NO2, O3 ; NO2, H2O, O3, H2CO; aerosol	stratospheric.profile; tropospheric column; tropospheric AOD	BIRA-IASB
Harestua	NDACC	ZS DOAS	1994 →	O3, NO2, OClO, BrO;	total column;	BIRA-IASB

[1] NDACC: Network for the Detection of Atmospheric Composition Change; TCCON: Total Carbon Column Observing Network; ACTRIS: Aerosol, Clouds and Trace Gas Research Infrastructure. Currently ACTRIS covers only O3, NO2, HCHO, C2H6 and NH3.

[2] FTIR: Fourier-transform infrared spectrometry; ZS or MAX-DOAS: Zenith Sky or Multi-Axis Differential Optical Absorption Spectroscopy in UV-Visible.

[3] The indicated time period may include interruptions due to instrument failures, etc.

Station (Lat, Lon, Altitude)	Network / RI[1]	Technique[2]	Start – End Date[3]	Species	Physical quantity	Responsible RPO
60.2N, 10.8E, 596 masl				NO_2, BrO	stratospheric.profile	
Observatoire de Haute Provence (OHP) 43.9N, 5.7E, 650 masl	NDACC	ZS DOAS	summer 1998 →	O_3, NO_2, BrO; NO2, BrO	column; stratospheric profile	BIRA-IASB
		MAXDOAS	2000 →	O_3, NO_2, BrO; NO2, BrO; NO_2, H_2CO	column; stratospheric profile; tropospheric column	BIRA-IASB
La Réunion Maido -21.1N, 55.4E, 2155 masl	NDACC/ACTRIS	FTIR (125HR)	Feb. 2013[4] →	HCl, HF, CO, CH4, HNO3, O3, NO2,N2O, C2H6, HCN, H2CO, CCL2F2, CCL3F, CHF2CL, NO, SF6, C2H2, CH3OH, HCOOH, NH3, OCS	vertical profile or total column concentrations	BIRA-IASB
La Réunion Saint-Denis -20.9N, 55.5E 85 masl	NDACC	FTIR-1 (120M)	May 2009[5] - Dec. 2011	HCl, HF, CO, CH4, HNO3, O3, NO2, N2O, C2H6, HCN, H2CO, CCL2F2, CCL3F, CHF2CL, NO, SF6, C2H2, CH3OH, HCOOH, NH3, OCS	vertical profile or total column concentrations	BIRA-IASB
	NDACC ; TCCON	FTIR-2 (125HR)[6]	Sept. 2011 – Dec. 2013	HCl, HF, CO, CH4, NO2, N2O, C2H6, HCN, H2CO, C2H2, OCS + CO2	vertical profile or total column concentrations	BIRA-IASB
	TCCON	FTIR-2 (125HR)	2014 →	CO2, CO, CH4, N2O, HF, H2O, HDO	total column	BIRA-IASB
	NDACC/ACTRIS	MAXDOAS	Aug. 2004 – July 2005	O_3, NO_2, BrO, H_2CO; CHOCHO	total column; tropospheric profile	BIRA-IASB
La Réunion Le Port -20.9N, 55.3E, 50 masl	/	MAXDOAS	April 2016 - 2017	O_3, O3-related key species	column, tropospheric abundance	BIRA-IASB
Porto Velho -8.5N, -63.5E, 83 masl	/	FTIR-1 (120M)	July 2016 – July 2017	HCl, HF, CO, CH4, NO2 N2O, C2H6, HCN, H2CO, C2H2, OCS	vertical profile, partial or total column concentrations	BIRA-IASB
	/	FTIR-1 (120M)	May 2019 –	HCl, HF, CO, CH4, HNO3, O3,	vertical profile, partial or total	BIRA-IASB

[4] Starting with campaign in Sept.-Oct. 2002

[5] Starting with campaigns in Sept.-Oct. 2002, Aug.-Nov. 2004, May-Nov. 2007

[6] Switching between NDACC mode in mid-Infrared (MIR) and near-infrared (NIR) solar absorption observations.

Station (Lat, Lon, Altitude)	Network / RI[1]	Technique[2]	Start – End Date[3]	Species	Physical quantity	Responsible RPO
			Dec 2019	NO2 N2O, C2H6, HCN, H2CO, CCL2F2, CCL3F, CHF2CL, C2H2, CH3OH, HCOOH, NH3, SF6, OCS, isoprene	column concentrations	
	/	FTIR-2 (125HR)	May 2023 →	as above + CO2	vertical profile or total column concentrations	BIRA-IASB
Xianghe 39.8N, 117.0E, 50 masl	/	MAXDOAS	Feb. 2010[7] →	NO2, O3, H2CO, SO2, HONO, BrO, CHOCHO, H2O; aerosol	vertical profile, partial or total column concentrations; AOD	BIRA-IASB/IAP[8]
	TCCON	FTIR (125HR)	June 2018 →	O3, HCHO, CO2, CH4, N2O, HF, H2O, HDO, NO2	vertical profile or total column concentrations	IAP[9]/BIRA-IASB
Bujumbura 3.4N, 29.4E, 774 masl	/	MAXDOAS	Nov. 2013 →	NO2, O3, H2CO, SO2, HONO, BrO, CHOCHO, H2O	vertical profile, partial or total column concentrations	BIRA-IASB
		CIMEL sunphotometer	Nov. 2013 →	aerosol	AOD	BIRA-IASB
Uccle/Brussels 50.8N, 4.4E, 100 masl	NDACC	mini-MAXDOAS	Apr. 2011 →	NO2	tropospheric column	BIRA-IASB
	WOUDC station 053	Brewer n°16[10]	1983 →	O3; UV	total column; spectral irradiance	RMI
		Brewer n°178[11]	2011 →	O3; UV	total column; spectral irradiance	RMI
		Dobson n°40[12]	1971 - May 2009	O3	total column	RMI
		O3 sondes (balloon-borne)	1969 →	O3	vertical profile	RMI
	PGN	PANDORA	March 2020 →	O3, NO2, HCHO AOD	total column, lower tropospheric columns	BIRA-IASB RMI
		UV-B, UV-A Pyronameters, multichannel filters radiometer, spectroradiometer		UV	Global solar UV irradiance: (i) λ integrated, (ii) spectral measurements. UV index	BIRA-IASB
	AERONET	CIMEL sunphotometer	July 2006 →	aeroiol	AOD, H2O, Angstrom coeff.	BIRA-IASB
Princess Elisabeth	WOUDC station 499	Brewer n°100[14]	Jan. 2011 →	O3; UV	total column; spectral irradiance	RMI

[7] Following a campaign in Beijing from July 2008 to April 2009.
[8] BIRA-IASB collaborates with the Institute of Atmospheric Physics (Chinese Academy of Sciences) at Beijing
[9] The Institute of Atmospheric Physics (Chinese Academy of Sciences) at Beijing owns the FTIR instrument and operates it in collaboration with BIRA-IASB
[10] Single monochromator, refurbished with new electronics in 2017.
[11] Double monochromator.
[12] In agreement with WMO-GAW the instrument is now loaned to the University of Kiev (Ukraine) and is operational there.
[14] Put at RMI's disposal by KNMI (The Netherlands).

Station (Lat, Lon, Altitude)	Network / RI[1]	Technique[2]	Start – End Date[3]	Species	Physical quantity	Responsible RPO
station (Utsteinen) -71.9N, 23.3E, 1396 masl[13]		UV-B, UV-A sensors, pyronameter	2012 →	UV	global solar spectral irradiance, broadband data, filter radiometer data, sunshine duration	BIRA-IASB
	AERONET	CIMEL sunphotometer	Feb. 2009 →	aerosol	AOD, H2O, Angstrom coeff.	BIRA-IASB RMI
		MAXDOAS	Dec. 2015 → ?	O3, NO2, …	column tropospheric profile	BIRA-IASB
Redu 50.0N, 5.2E, 359 masl Virton 49.6N, 5.5E, 209 masl Oostende 51.2N, 2.9E, 7 masl		UV-B, UV-A Pyronameters, multichannel filters radiometers	1995 →	UV	Global solar irradiance, broadband UV data, UV index [15]	BIRA-IASB

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

The timeseries of concentrations (total columns, vertical profiles) of ozone, ozone depleting substances (ODS), ozone precursors, aerosol, long- and short-lived climate pollutants and UV spectral irradiances, doses and UV index values are retrieved from the raw observations by the responsible RPO and made available to the community through local data repositories and webpages or via the data portals of the networks to which they are affiliated (NDACC, WOUDC, ACTRIS, TCCON,…) or direct contact with responsible scientists.

- Results of the observations in Uccle can be found at https://ozone.meteo.be/research-themes/Ozone

The UV index derived from the measurements with the Brewer ozone spectrophotometers is displayed in near-real time on the RMI website for the public. RMI publishes also UV index forecasts for Uccle (10 days) and for Belgium (5 days).

A paper on the fifty years of balloon-borne ozone profile measurements at Uccle, with a short history, the scientific relevance, and the achievements in understanding the vertical ozone distribution has been published by Van Malderen et al. (ACP, 2021).

- Results of the observations carried out by BIRA-IASB can be found at https://www.aeronomie.be/index.php/nl/node/757 or https://www.aeronomie.be/nl/observational-model-data

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

[15] Plus associated cloud and meteorological parameters.

- Results of the observations carried out by ULiège can be found at https://www.girpas.uliege.be/cms/c_5466059/en/geophysical-data

The responsible RPO also publish news items on their website and social media channels on ozone and UV related subjects and activities.

Ground-based FTIR data are often exploited in the context of a network-wide effort, e.g., for trend and process studies, further using satellite and model products (inorganic chlorine and fluorine, organic chlorine and fluorine, source gases relevant to stratospheric and tropospheric ozone (HCl, $ClONO_2$, HF, COF_2, CFCs, HCFCs, HFC-134a, CCl_4, N_2O, C_2H_6, OCS, …).

Some data are provided as reference climate data records on the Copernicus Climate Data Store, while some time series are included in important international scientific assessments (WMO).

➢ see section 5.

3. THEORY, MODELLING AND OTHER RESEARCH

3.1 The Royal Meteorological Institute (RMI)

3.1.1 Satellite data validation and characterisation

RMI is partner in the Atmospheric Composition SAF (Science Application Facility) of EUMETSAT. The main task here is the validation of the ozone profiles retrieved from satellite observations (GOME-2 and IASI).

3.1.2 Ground-based data retrieval algorithm developments

The RMI took the lead in the follow-up of the Ozonesonde Data Quality Assessment (O3S-DQA) activity, aiming at the homogenization of the ozonesonde records, but now embedded in the activities of the HEGIFTOM (Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements) Focus Working Group of the second phase of Tropospheric Ozone Assessment Report (TOAR-II). This ozonesonde reprocessing activity corrects for biases due to changes in instruments, in solution strengths, in operating procedures, generates the raw data, and estimates the ozone partial pressure uncertainties.

RMI developed, in close collaboration with Forschungszentrum Jülich, a new ozonesonde data processing method that corrects for time constants in the data and refers all ozonesonde data to the reference instrument for the global ozonesonde network, i.e. the photometer in the environmental simulation chamber in Jülich (Smit et al., ACP, 2024).

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

3.2.1 Modelling

BIRA-IASB has developed since many years now a 3D chemistry transport model (CTM) with a data assimilation system associated to it (namely the Belgian Assimilation System for Chemical ObsErvations - **BASCOE**). 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 irradiance at solar minimum, the current version allow us to use NRLSSI v2 which consider daily observation of the past or solar irradiance spectra recommended for CMIP6 simulations. Surface emissions of ozone depleting substances and other long-lived species have been implemented following the CMIP6 recommendations. The heterogeneous reactions and the aerosol climatology have also been revised to more up-to-date values. Using the assimilation system, a reanalysis of Aura MLS observations has been carried out covering the period Sept 2004-Aug 2019 (Errera et al., ACP, 2019). In the CAMS2_35 project, BIRA-IASB is involved in the revision of the stratospheric coupling between aerosols and chemistry, and is in charge of the implementation of a new approach for the BASCOE photolysis calculations, including tests of their impact on the stratospheric ozone. This new approach is based on an online computation of the photolysis rates, and includes a careful optimisation for speed and accuracy of the photolysis code. The chemistry of BASCOE has been included in the Copernicus Atmospheric Monitoring System (CAMS) which is now running operationally since June 2023.

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 and maintenance.

ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere), was initiated as a national 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 O3 and key molecules are required in order to more accurately understand the changes in O3 as CFCs decline and climate change occurs.” ALTIUS is presently implemented as an operational element of the ESA EarthWatch programme with a 2026 target launch date. ALTIUS will deliver NRT stratospheric O3 concentration profiles, and consolidated products (O3, NO2, aerosols, water vapor, temperature). Other species are still under investigation (BrO, OClO, NO3), pending their feasibility in solar/lunar occultations. The primary L2 products (O3 NRT and consolidated), and most of the secondary products are important for studying the coupling between climate and stratospheric ozone.

Using its data assimilation system’s, BIRA-IASB has made an observations system simulation experiment (OSSE) to measure the value of future ALTIUS observations compared to Aura MLS. The experiment shows 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.

Since end 2023, the proposed **CAIRT** (Changing Atmosphere Infra-Red Tomography) ESA Earth Explorer 11 (EE11) mission entered in Phase A, in competition with another EE11 candidate. This mission has been proposed in order to achieve a step change in our understanding of the coupling of atmospheric circulation, composition and regional climate. The CAIRT concept proposes to perform limb infra-red tomography of the atmosphere from the troposphere to the lower thermosphere (about 5 to 115 km altitude) with a 400 km swath and high spatial and spectral resolution to provide a three-dimensional picture of atmospheric structure at unprecedented scales. BIRA-IASB is contributing to CAIRT with its middle-atmosphere modelling expertise and by running dedicated OSSE experiments.

Upgrading, maintenance and calibration of the ground-based instruments (FTIR, DOAS, ozonesondes, Brewer, UV radiometers, PANDORA, sunphotometers,,…) and their accessories (solar trackers, meteo station, …) requires a continuous and resource-intensive effort. The lack of spare parts or trained personnel causes gaps in the observations.

3.2.3 Ground-based data retrieval algorithm developments

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.

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 centralized processing and automated quality control (FRM4DOAS) are supported by ESA in the successive FRM4DOAS projects (2016->) and ACTRIS.

BIRA-IASB is strongly involved in the development of new harmonized retrieval strategies, e.g., for HCHO, ozone and NO2 from NDACC FTIR observations. It consists of using updated a priori information, new micro-windows, new spectroscopic parameters and a new regularization method. After reprocessing according to the new retrieval strategies – which is a network-wide effort -, the data will be labelled as version 'IRWG2023'. The IRWG2023 version of the ozone data acquired by BIRA-IASB and ULiège is already publicly available at the NDACC DHF.

In the NDACC network and ACTRIS RI, It has been accepted that central data processing systems (CDPS) are the way forward in order to ensure a more rapid and intra-network consistent data delivery. BIRA-IASB is leading the development and implementation of the CDPS 'FRM4DOAS' for the DOAS-type observations and the FTIR CDPS for the FTIR observations. Both CDPS are running in a pre-operational state.

3.2.4 Satellite data retrieval algorithm developments

- 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 O3, NO2, BrO, HCHO, SO2…; 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 (dust), CH4 and N2O vertical profiles or total columns: data processing and dissemination. The dust product is also available on the Climate Data Store (Copernicus Climate Change Service or C3S). The IASI dust processing will be implemented at EUMETSAT in 2024.
- BIRA-IASB/B.USOC will host the payload data ground segment of ESA's ALTIUS mission and will be responsible for running the O3 (NRT and consolidated product) retrieval chains. BIRA-IASB is responsible for the development of the L2 processing chains of ALTIUS in all its observation modes (limb-scattered light, and occultations). The primary scientific objective is the retrieval of NRT and consolidated stratospheric O3 concentration profiles. Algorithms are optimized for the specifics of the ALTIUS mission (high vertical resolution). They are also tested on existing satellite datasets (OMPS-LP, GOMOS, SAGE-III, etc).

3.2.5 Satellite data validation and characterisation

BIRA-IASB has continued the geophysical validation of satellite data records acquired by the satellite constellations for ozone, air quality and greenhouses gases monitoring and, namely, for data records of O3, NOy, CO2, CH4, CO, N2O, H2O, HNO3. Validation studies are based on independent ground-based network data collected from network data archives like NDACC, PGN, SHADOZ, TCCON and WOUDC. BIRA-IASB leads: (i) the operational validation service for Sentinel-5 Precursor TROPOMI in the context of the ESA/Copernicus Atmosphere Mission Performance Cluster (ATM-MPC), (ii) the routine validation service for GOME-2 and IASI trace gases data in the context of the EUMETSAT AC SAF, and (iii) the development of the operational validation service for the ESA/BELSPO ozone profiling mission ALTIUS (launch in 2026). BIRA-IASB is also involved in the preparation of the validation of future missions like the Copernicus Sentinel-4 (UVN), Sentinel-5 (UVNS) and CO2M missions, and the MetOp-SG IASI-NG instruments.

BIRA-IASB is in charge of the validation of several sensors within the ESA CCI+ ozone and ozone precursors project: CO and NH3 (IASI A/B/C), HCHO (SCIAMACHY, GOME, GOME 2 A/B/C, OMI, TROPOMI).

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

In the CAMS2-82 project. BIRA-IASB is responsible for the validation of the CAMS data products using the NDACC and TCCON data. It manages the rapid delivery of reference data through the CAMS2-27 project.

3.2.7 Involvement in a project under the Metrology Partnership Programme (EMP)

21GRD02 BIOSPHERE project: Impact of increased cosmic rays, UV radiation and fragility of ozone shield on the biosphere and our health (see Table 5.1)

3.3 University of Liège (ULiège)

3.3.1 Modelling

The 3D CTM GEOS-Chem implemented at ULiège is mainly used for research focusing on the troposphere. For studies dealing with stratospheric species, ULiège collaborates with BIRA-IASB and uses BASCOE results, or with ULeeds and uses TOMCAT/SLIMCAT simulations, allowing for the interpretation of the ground-based measurements and their trends.

3.3.2 Ground-based data retrieval algorithm developments

As co-chair of the InfraRed Working Group (IRWG) of NDACC, ULiège coordinates the various activities of this group, including the revision, improvement, and harmonization of the retrieval strategies, for all mandatory targets of the IRWG. This effort has recently been focusing on ozone (see section 3.2.3), C_2H_6, HCl, HF, $ClONO_2$ and CO, and new products are being produced and delivered to the NDACC-DHF. In addition, ULiège has completely revised the Jungfraujoch CFC-11 time series which now extends back in time until the mid-1980s. Also, a retrieval strategy has been developed to retrieve the most abundant HFC (HFC-134a) from the Jungfraujoch solar spectra. This halocarbon is a CFC substitute

targeted by the Kigali Amendment (2016) to the Montreal Protocol.

3.4 Université Libre de Bruxelles (ULB/SQARES)

No update received since ORM2011 report

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 O3, HNO3, CO and in addition NH3. 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 SO2, PAN, CH3OH, 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 O3, HNO3 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-SO2, ANNI-NH3, 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/m2), 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-O3 vertical distribution. This product opens perspectives for studying the impact of O3 changes on the radiative forcing of climate at local and global scales. The derivation of trends in the O3 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 O3, HNO3, CO and SO2 in the frame of the AC-SAF activities and of the O3-CCI+ and C3S programs for O3, but also NH3 and other retrieved products.

ULB/SQUARES also continues cross-comparisons between satellites, in particular for CO and O3.

4. DISSEMINATION OF RESULTS

4.1 Under the responsibility of the Belgian partners

Apart from the dissemination of local data and results via the RPO's data repositories and Webpages (see Section 2), data are disseminated through collaborative efforts.

4.2 Through collaborative efforts

See table 5.1 in Section 5.

4.3 Relevant scientific papers

A list of relevant scientific papers published or submitted by the reporting teams since the submission of the national report to the 11th WMO/UNEP Ozone Research Managers Meeting is provided in Annex A.

5. PROJECTS, COLLABORATIONS, TWINNING AND CAPACITY BUILDING

Table 5.1 Overview of relevant ongoing activities / projects with Belgian involvement.

Research project or initiative / Scientific Service **(funder; start-end dates if relevant)**	**Belgian partners (role in the activity)**	**Tasks of Belgian partners**	**Objectives/ Major results / outcomes of initiative**	**Webpages / data archive/ link to outreach material/; References (publications/ assessments/ reports…)**
Copernicus – EU programme – Phase 2 (2023-2027)				
Copernicus Atmosphere Monitoring Service (CAMS) -2				
CAMS2-27	BIRA-IASB (coordinator) ULiège (contributor)	rapid delivery of QA/QC-ed target NDACC data	availability of QA/QC-ed NDACC reference data in due time for validation of CAMS products.	cams27.aeronomie.be
CAMS2-82	BIRA-IASB (partner)	contribute to quarterly validation reports	validation of CAMS products against reference data	https://global-evaluation.atmosphere.copernicus.eu/ https://atmosphere.copernicus.eu/quality-assurance
CAMS2-35	BIRA-IASB (partner)	integration of BASCOE model in IFS	IFS model extension with stratospheric chemistrty	
Copernicus Climate Change Service (C3S) -2				
C3S2_311_lot2 (Sept. 1, 2021 – Aug. 31 2025)	BIRA-IASB (partner)	Provision of NDACC FTIR and DOAS records for O3, CO, CH4, NO2 and HCHO.	Provision of ground-based reference climate data records to the Climate Data Store (CDS)	https://climate.copernicus.eu/access-observations-baseline-and-reference-networks
C3S2_312a_lot2	BIRA-IASB (partner)	Provision of ... and IASI dust records	Provision of satellite climate data records to the Climate Data Store (CDS) for ozone, aerosol and greenhouse gases	
ESA Climate Change Initiative + (CCI+) – Climate Space Programme				
CCI+ O3 precursors & aerosol (2022-2025)	BIRA-IASB (coordinator)	data provision, validation, …	developing long-term climate data records of the GCOS Precursors for Aerosol and Ozone: NO2, SO2, CO, HCHO, NH3	https://climate.esa.int/en/projects/precursors-for-aerosols-and-ozone/about/
CCI+ O3 (2010 → 2022-2025)	BIRA-IASB (coordinator) RMI ULB	data provision, validation, …	generation of multi-decadal time series of harmonised and consistent ozone data suitable to assess long-term changes in the total ozone column, the tropospheric ozone column as well as its vertical	https://climate.esa.int/en/projects/ozone/

Research project or initiative / Scientific Service **(funder; start-end dates if relevant)**	**Belgian partners (role in the activity)**	**Tasks of Belgian partners**	**Objectives/ Major results / outcomes of initiative**	**Webpages /** **data archive/ link to outreach material/;** **References (publications/ assessments/ reports…)**
			distribution across the UT/LS and stratosphere.	
EUMETSAT AC-SAF CDOP4	BIRA-IASB RMI ULB (all are contributors)	see https://cdop.aeronomie.be/index.php?option=com_content&view=article&id=29&Itemid=149	Operations, Production and validation reports of METOP data products https://acsaf.org/opreps.php https://cdop.aeronomie.be/index.php?option=com_cdop&view=cdop&Itemid=151 https://cdop.aeronomie.be/ProjectDir/documents/Internal/GDP-UPAS%20versions%20table.pdf	https://cdop.aeronomie.be/ https://acsaf.org/
SPARC LOTUS	BIRA-IASB (theme lead) IRM-KM (contributor)	homogenisation of ozone data records; stratospheric ozone trend analyses;	Assessment of stratospheric ozone trends and their uncertainties based on long-term data records from multiple satellites and ground-based observations	https://lotus.aeronomie.be/ https://www.sparc-climate.org/activities/ozone-trends/ https://lotus.aeronomie.be/index.php/publications
TOAR-II (2020-2024)				https://igacproject.org/activities/TOAR/TOAR-II; https://bg.copernicus.org/articles/special_issue10_1256.html
HEGIFTOM (Tropospheric ozone trends from ground-based measurements)	RMI (co-lead) BIRA-IASB (contributor)	Ground-based ozone profile data evaluation and harmonization	Evaluation and harmonization of ozone profile datasets from ozone-sondes, FTIR, Brewer/ Dobson Umkehr, Lidar and IAGOS, for improved trend analysis	http://hegiftom.meteo.be
OPT (Ozone Precursors in the Tropics).	BIRA-IASB	responsible for the trends of ozone & ozone precursors HCHO and CO from the global FTIR network	address knowledge gaps in understanding ozone variability and changes throughout the tropical troposphere and the exchange between the tropics and extratropics.	https://igacproject.org/opt-focus-working-group

Research project or initiative / Scientific Service **(funder; start-end dates if relevant)**	**Belgian partners (role in the activity)**	**Tasks of Belgian partners**	**Objectives/ Major results / outcomes of initiative**	**Webpages / data archive/ link to outreach material/; References (publications/ assessments/ reports…)**
DORA (BELSPO, 2023-2025)	BIRA-IASB (coordinator)	analyze ozone trends in the Arctic using ground-based data (FTIR and sondes)	Representativeness of the ground-based data in the Arctic. Ozone recovery detection in the Arctic.	https://dora.aeronomie.be/
BECCM-O3: Building a benchmarking service for Chemistry-Climate Models with sustainable satellite records of ozone, its radiative effects, and related tracers (2023-2033)	BIRA-IASB ULB (promotors of the BECCM-O3 national FEDtWIN project)	All tasks of the project	build a benchmarking activity for the atmospheric components in Chemistry-Climate Models (CCMs) using three new satellite datasets (including IASI data) that focus on ozone and a few related tracers. This will guide the modellers in improving the processes that drive stratospheric composition in their CCMs, thanks to creative analyses of the O3, N2O and HCl variabilities and the attribution of a grading score for each investigated diagnostic.	https://www.belspo.be/belspo/FED-tWIN/fiche_en.stm?prfid=2021045
Scientific Assessment of ozone depletion 2022 (GAW report n° 278);	BIRA-IASB (Ch. 3) ULIège (Ch. 1)	contributing author; co-author and contributing author	Regular assessment of the state of atmospheric ozone	https://ozone.unep.org/science/assessment/sap
Report on unexpected emissions of CFC-11 (WMO-No. 1268; 2021),	ULiège	Contributor	Dedicated report aiming at investigating the unexpected emissions of CFC-11	https://ozone.unep.org/system/files/documents/SAP-2021-report-on-the-unexpected-emissions-of-CFC-11-1268_en.pdf
WMO-GAW QA-SAC for ozone-sondes	RMI (PI of Quality Assurance Science Activity Centre)	maintain and develop quality assurance for worldwide ozonesonde measurements	WMO GAW Report on ozonesonde measurement principles and best operational practices	https://ozone.meteo.be/projects/qasac https://community.wmo.int/en/activity-areas/gaw/research-infrastructure/qaqc/central-facilities; https://library.wmo.int/records/item/57720-ozonesonde-measurement-principles-and-best-operational-practices
21GRD02 BIOSPHERE (EURAMET's Metrology Partnership programme	BIRA-IASB RMI (partners)	BIRA-IASB: management of 4 ground-based intercomparison campaigns for simultaneous	Impact of increased cosmic rays, UV radiation and fragility of ozone shield on the biosphere and our health	https://euramet-biosphere.eu/

Research project or initiative / Scientific Service **(funder; start-end dates if relevant)**	**Belgian partners (role in the activity)**	**Tasks of Belgian partners**	**Objectives/ Major results / outcomes of initiative**	**Webpages /** **data archive/ link to outreach material/;** **References (publications/ assessments/ reports…)**
(EMP).		measurements of solar UV irradiance, secondary cosmic rays (SCR) and atmospheric species (ozone, etc.); modelling of SCR; outreach RMI: partcipation to campaigns		
COST Action HARMONIA (2022-2026)	RMI; BIRA-IASB (Members of management committee)	Exploitation of ground-based photometer measurements; dust aerosol retrievals from IASI	Improve and homogenize aerosol retrievals using mainly solar and sky but also lunar and star photometers from different networks.	https://www.cost.eu/actions/CA21119/

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 11TH OZONE RESEARCH MANAGERS MEETING

Below, we limit ourselves to specific actions that have not yet been mentioned above or are part of the above projects.

6.1 Research needs

(1) Improve understanding of global emissions of ozone-depleting substances and related
(2) Concentrations and climate effects of HFC
(3) Aviation, rockets and climate intervention

6.2 Systematic observations

(1) Assure and increase funding for continuous observations, analyses and curation of data.

Continuation of the observations at Uccle (ozone column, ozone profile, Spectral UVB, aerosols) and at the Antarctic station (ozone column, Spectral UVB, aerosols).
RMI financed a post-doc researcher to implement the ozonesonde homogenization at 8 remaining sites (mostly EU).

(2) Continue efforts for supporting ongoing and new observations of ozone, GHG, ODS, HFCs, VSLS, aerosols, related chemical composition, and meteorological parameters on national and global scales, especially in Article 5 countries. Support from the VCTF is needed. Therefore, the delegates recommend increasing funding for the VCTF.0

RMI has signed a MoU with the National Space Research and Development Agency of Nigeria to launch ozonesondes at Abuja, Nigeria. A project proposal for funding (hydrogen generator !) to the VCTF is being prepared.

(3) Open access to observation data (including metadata and calibration information) is required for intercomparability of networks and data analyses. Stations need to be supported to provide such data.

Total ozone and UV data from Brewer measurements are sent to WOUDC, NDACC and EuBrewNet (eubrewnet.aemet.es) data bases. On the EuBrewNet data base also metadata and calibration information can be found.
Uccle ozonesonde data are sent to WOUDC and NDACC; the reprocessed, homogenized ozonesonde data for all sites is made available at the HEGIFTOM ftp-server.

(4) Data analyses are critical for interpretation of observations, driving future research and informing policy makers.

Analysis of all the past Jülich Ozone Sonde Intercomparison Experiment (JOSIE) campaigns data, to develop new methodology for ozonesonde data processing.

(5) Provide support for the long-term curation of the archived data, requiring active collaboration between data providers, data archives and data users.
(6) Develop common tools, formats and centralized processing for the near-real time ozone data submission to improve forecasts.

RMI and BIRA are involved in defining a new GEOMS-HDF template for ozonesondes, in agreement with the WMO GAW Report No. 268 recommendations, in close collaboration with the EVDC. Tools for conversion to this new data format will be developed, distributed and central processing will be proposed as an option. All these steps will enable near-real time data submission to the EVDC and NDACC.
total ozone and UV data from Brewer measurements are sent to EuBrewNet in near-real time and the Uccle data are shared by EuBrewNet with ESA. Validation data centre

(evdc.esa.int).

(7) Encourage the twinning of observation stations in Article 5 and non-Article 5 countries (see further recommendations under “capacity building”).

(8) Identify extra financial sources to support regional network calibration and data homogenization initiatives (such as calibration of the South America Brewer instruments, reprocessing Indian ozonesonde records, operational software upgrades).

RMI is willing to share their expertise in the O3S-DQA for the reprocessing of Indian ozonesonde records, and to support an intercomparison campaign with Indian-type ozonesondes with the reference ozone photometer in the Jülich environmental simulation facility.

BIRA-IASB is managing the integration of NDACC and the Pandonia Global Network (PGN) in the European Research Infrastructure ACTRIS, focusing on aerosol, clouds and trace gases, especially the short-lived climate pollutants, ozone and ozone precursors like NO2 and HCHO, in order to ensure better sustainability of the long-term systematic observations and FAIR data archiving and dissemination. Also NDACC as a whole is moving forward to FAIR data dissemination.

6.3 Gap filling

6.4 Data archiving and stewardship

6.5 Capacity building

RMI employees teach courses on “Ozone” (as part of the course “Physical Meteorology”) and on “Remote Sensing” ozone retrieval in the Postgraduate Studies in Weather and Climate Modeling at Ghent University.

RMI is actively involved in the organization of webinars and (regionally organized) online meetings for/with ozonesonde operators, PIs, and data users. Those webinars and meetings should improve the implementation of the ozonesonde preparation and processing guidelines of the WMO-GAW Report No. 268.

BIRA-IASB has contributed to a webinar on Atmospheric chemistry and physics: the ozone on May 3, 2023 - https://climate.copernicus.eu/climate-situ-data-measurements-applications, outreach events organized by ESA about S5P or the CCI project results, etc.

and 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 organized at BIRA-IASB premises (most recent one in 2022), through participation in public exhibitions at the Planetarium in Brussels, the Eurospace Centre in Redu and Astropolis in Oostende.

7. FUTURE PLANS

Continuation of ongoing activities and projects as listed in Table 5.1

And **in particular:**

4.4 Royal Meteorological Institute (RMI)

Maintain the observations of ozone and UVB at Uccle and the Belgian Antarctic station.

RMI will lead the TOAR-II Special Issue paper on the tropospheric ozone column trends derived from the harmonized ground-based data.

RMI will publish the evaluation of the homogenization of the European ozonesonde time records.

RMI will test the implementation of the new ozonesonde processing methodology in the global network.

In its role of QA-SAC for ozonesondes, RMI will organize JOSIE campaigns, in collaboration with Forschungszentrum Jülich, to monitor the ozonesonde quality, and will develop a near real-time tool for data archiving and quality control.

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

BIRA-IASB intends to maintain the systematic observations that contribute to NDACC (and TCCON) and to affiliate (or support the affiliation of) additional instruments to NDACC; e.g., the FTIR at Porto Velho and at Xianghe. Procuring the required funding remains an issue.

It coordinates the Third Cabauw INtercomparison of DOAS-like Instruments (CINDI-3) that will take place in the Netherlands in May-June 2024. CINDI-3 is a community-wide intercalibration campaign of ground-based UV-Visible DOAS instruments measuring the atmospheric column and profile of NO2 and O3, complemented by mobile-DOAS observations and an exhaustive range of measurements of aerosols and other trace gases of interest like BrO and H2O. The campaign also includes an airborne component. CINDI-3 is organised under the joint umbrella of the ACTRIS RI, ESA and NDACC. Conducted as a semi-blind intercomparison campaign with an external referee, CINDI-3 aims at the intercalibration of atmospheric trace gas UV-Visible remote-sensing systems in view of consolidating the international participation to ACTRIS and NDACC, and of establishing Fiducial Reference Measurements (FRM) suitable for the validation of current and future satellite missions of the CEOS Air Quality and Ozone constellations..

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4.6 University of Liège (ULiège)

The continuation of the NDACC observations at the Jungfraujoch station remains the primary objective of the team. This will include the replacement of the instrumentation (spectrometer and sun-tracker) in 2024-2025.

4.7 Université Libre de Bruxelles (ULB)

No update received since ORM2011 report

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 (O3-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 O3-CCI+ and C3S programs.

The group will foster activities with IASI in the context of chemistry and climate, including O3-HNO3 correlations; link to O3 and precursor emissions in the troposphere; STE; O3 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, and for radiometric laboratories that ensure full radiometric characterization and calibration of instruments involved in solar UV and trace species mesurements.

There is still a need for structural logistical, technical and financial support including technical staff, to maintain and secure instrument operation and scientific exploitation. In some instances, having access to a stock of spare parts for 'standard' instruments would reduce the gaps in the observational timeseries.

As Kipp & Zonen does not longer produce Brewer spectrophotometers, an international assessment of which instruments might provide a long-term, very stable, alternative for total ozone and UV time series should be initiated.

The loss of aging profiling satellite missions having provided global long-term observations of not only the ozone profile but also profiles of ozone-relevant trace gases is a threat to data assimilation activities and associated studies of global changes. The development and implementation of data continuity missions targeting the vertical distribution of source and reservoir species and other diagnostics of ozone and climate change (HCl, ClO, BrO, HNO_3, N_2O, CFCs, $ClONO_2$…) is still an urgency.

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ANNEX A. LIST OF RELEVANT SCIENTIFIC PAPERS

Only publications issued or submitted after the Belgian Report for the 11th WMO/UNEP Ozone Research Managers Meeting (ORM10) are listed below.

A.1 Peer reviewed papers, books

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A.2 Doctoral theses

Minganti, Daniele: Evaluating the stratospheric circulation and its variability in a Chemistry-Climate Model with reanalyses and observations of nitrous oxide, PhD Thesis, Université de Liège, pp. 1-272, 2022.

Prignon, Maxime: Stratospheric circulation changes: investigations using multidecadal observations and simulations of inorganic fluorine, PhD Thesis, Université de Liège, pp. 1-157, 2021

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

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Dr. C. Servais - Christian.Servais@uliege.ac.be (FTIR Instrumentation development and improvement (electronic, optic, remote control…), maintenance and observations)

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Dr. Alexander Mangold - Alexander.Mangold@meteo.be (PI for Brewer ozone and UV observations, MC member of COST action HARMONIA)

Dr. Roeland Van Malderen - Roeland.VanMalderen@meteo.be (PI for WMO-GAW QA-SAC for ozonesondes, chair of the TOAR-II FWG HEGIFTOM, NDACC Sondes Working Group representative, member of WMO-GAW expert team on Atmospheric Composition Measurement Quality (ET-ACMQ))

Dr. ir. Andy Delcloo - Andy.Delcloo@meteo.be (Validation of satellite ozone data, Member of project team of AC SAF of EUMETSAT)

Ms. Natacha Pezzetti - Natacha.Pezzetti@meteo.be (Retrieval of aerosol optical parameters from Brewer observations and work on UV index and forecast))

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Dr. Martine De Mazière - Martine.DeMaziere@aeronomie.be , lead of IR observations team at BIRA-IASB dealing with satellite and ground-based remote sensing measurements of the atmospheric composition, with infrared spectrometric techniques, implementation and testing of retrieval algorithms to invert observations into geophysical data, remote-sensing instrument developments, satellite data validation, FTIR CDPS in ACTRIS. She is co-chair of NDACC and lead of reactive trace gases remote sensing component in ACTRIS.

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Dr. Jean-Christopher Lambert - J-C.Lambert@aeronomie.be (Satellite and ground-based remote sensing of the atmospheric composition, coordinator of Copernicus operational

validation services (Sentinel-5p ATM-MPC, CCI/CCI+ ozone, C3S2_312b ozone); current member of Sentinel-4/5 and ALTIUS Mission Advisory Groups, of Sentinel-5p Quality Working Group and of EUMETSAT AC-SAF team; former member of the International Ozone Commission (2008-2016); Co-chair of the NDACC Satellite Working Group and of the CEOS Working Group on Cal/Val / Atmospheric Composition).

Dr. Daan Hubert – Daan.Hubert@aeronomie.be (Coordinator of SPARC/IO3C/GAW activity LOTUS, coordinator of CCI+ ozone project, active in C3S2_312b procurement service, Sentinel-5p tropospheric ozone validation coordinator).

Dr. Michel Van Roozendael - Michel.VanRoozendael@aeronomie.be (Satellite and ground-based remote sensing measurements of the atmospheric composition, implementation and testing of retrieval algorithms to invert radiance observations into geophysical data, remote-sensing instrument developments, data validation, member of EUMETSAT O3M-SAF project team, coordinator of the ESA CCI and ECMWF C3S procurement O3 projects, Co-chair of the NDACC UVVIS Working Group, member of several satellite Mission/Science Advisory Groups).

Dr. Quentin Errera - Quentin.Errera@aeronomie.be (stratospheric modelling, chemical data assimilation, reanalysis of long-term atmospheric data records, leader of the SPARC Data Assimilation activity).

Dr. Simon Chabrillat - Simon.Chabrillat@aeronomie.be (stratospheric modelling, chemical data assimilation, chemical weather, Stratospheric Ozone Service of the Copernicus Atmosphere Monitoring Service CAMS).

Dr. Jean-François Müller - Jean-Francois.Muller@aeronomie.be (Global tropospheric ozone modelling, inverse source/sink modelling).

Dr. Christine Bingen - Christine.Bingen@aeronomie.be (stratospheric aerosol retrievals and characterization).

Dr. David Bolsée - David.Bolsee@aeronomie.be (Ground- and space-based measurement of ultraviolet solar radiation: UV-B).

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