

GAW Report No. 322

Izaña Atmospheric Research Center

Activity Report 2023-2024

Joint publication of State Meteorological Agency (AEMET)
and World Meteorological Organization (WMO)

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VICIPRESIDENCIA
TERCERA DEL GOBIERNO
MINISTERIO
PARA LA TRANSICIÓN ECOLÓGICA
Y EL RETO DEMOGRÁFICO



Agencia Estatal de Meteorología

Cover photograph: Izaña Observatory (Photo credit: Conchy Bayo-Pérez)

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Izaña Atmospheric Research Center

Activity Report 2023–2024

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*At IARC during 2023–2024

March 2026

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This sixth edition of the Izaña Atmospheric Research Center
Activity Report is dedicated to the memory of

Dr Emilio Cuevas Agulló

*“Izaña: El lugar donde encontrar las respuestas
The place to find the answers”*

Foreword

In the summer of 1996, as a young post-doctoral scientist at the Consiglio Nazionale delle Ricerche, I had the privilege of participating in the 2nd Aerosol Characterization Experiment (ACE-2) international field campaign. Aircraft, research vessels and ground stations worked together across the Atlantic, and at the heart of this global effort stood the Izaña Observatory on Mount Teide. I still remember cycling up from the coast to reach the station for the first time — perhaps an unconventional arrival, especially for Dr Emilio Cuevas-Agulló, its long-standing director at the time, but one that marked the beginning of a lasting connection with this remarkable site.

Since its inauguration in 1916, the Izaña Observatory, now a Global Station of the World Meteorological Organization Global Atmosphere Watch (WMO GAW) Programme, has maintained uninterrupted meteorological and climatological observations. As one of the 40 WMO GAW Global Stations, it provides invaluable long-term records: more than a century of meteorological data, four decades of continuous greenhouse gas measurements, and >30 years of ozone, radiation, aerosol and water vapour observations. These sustained, high-quality measurements are the result of extraordinary scientific rigor and long-term institutional commitment.

Naturally, as a recognized centre of excellence, the Izaña Atmospheric Research Center (IARC), became a key contributor to European research infrastructures within ACTRIS and ICOS. Izaña's crucial role in long-term carbon cycle monitoring and for atmospheric observations was then reinforced. In fact, its global relevance was also demonstrated in November 2022, when the eruption of Mauna Loa forced the partial shutdown of the Mauna Loa Observatory after lava flows cut access roads and power supply.

Then, as a natural counterpart of Mauna Loa in the WMO GAW network of Global Stations, Izaña served as a critical reference site, helping to ensure continuity in global carbon dioxide (CO₂) monitoring at a time when the iconic Keeling Curve risked interruption. Its stable, high-quality long-term data, but also the skills of the AEMET personnel, and their dedication to research, were essential to preserving the integrity of global trend analyses, a powerful reminder that resilient global networks depend on trusted, high-quality stations.

Beyond the IARC observation programme, the Izaña Observatory and the AEMET staff play a vital role as a regional hub for capacity development. Through training activities, calibration services and technical cooperation, it supports specialists and institutions in Northern and Western Africa, Europe and beyond. By strengthening regional expertise in atmospheric composition monitoring, IARC contributes directly to global observation quality and to more equitable access to scientific knowledge.

In August 2023, devastating wildfires reached the slopes of Izaña itself. Thanks to rapid emergency response, the observatory was spared and most measurement programmes continued. The anomalies recorded during this period now provide valuable insight into the atmospheric impacts of extreme wildfire events — once again demonstrating the irreplaceable value of continuous observations.

At a time when urgent climate and environmental action depend on the best available science, IARC stands as a pillar of international cooperation, trust and long-term commitment. I would like to express my sincere gratitude to the staff of IARC and AEMET for their exceptional dedication and service to the global scientific community.

Nearly thirty years after my first ascent to Izaña, I remain convinced that this station embodies the spirit of sustained, collaborative science — science that serves society and strengthens global solidarity in understanding our changing atmosphere.



Dr Paolo Laj

*Chief, Global Atmosphere Watch Programme
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Tribute to Dr Emilio Cuevas Agulló

We would like to pay a sincere tribute for the outstanding professional and scientific career of Dr Emilio Cuevas Agulló (1961–2026), the pioneering atmospheric scientist and former Director of the Izaña Atmospheric Research Center, who retired in August 2023. The Izaña Observatory as we know it today is due to the vision and leadership of Dr Emilio Cuevas.

Emilio profoundly shaped atmospheric composition monitoring and research, covering a wide range of subject areas: meteorology, atmospheric dynamics, global greenhouse gases, climate science and the study of climate change in the Canary Islands, tropospheric and stratospheric ozone, radiation and aerosol research, with a particular emphasis on Saharan dust.

Emilio graduated with a Physics degree and Master's degree in Atmospheric Physics from the Complutense University of Madrid in 1986. He joined AEMET in 1987 and was assigned to the Izaña Observatory in 1989, transforming it from a mountain observatory into a world-leading WMO Global Atmosphere Watch global station.

He obtained his doctorate in 1996 from the Complutense University of Madrid, with a thesis entitled: "Study of the Behaviour of Tropospheric Ozone at the Izaña Observatory (Tenerife) and its relationship with Atmospheric Dynamics".

Under Emilio's leadership, international collaboration in atmospheric research and development expanded in many areas, contributing as a key station to multiple global networks and initiatives. As the first Spanish member of the International Ozone Commission (2000–2007), he represented Spain at meetings of the Vienna Convention for the Protection of the Ozone Layer. He highlighted the strategic importance of Izaña as a global centennial station, modernizing its mission, overseeing a major refurbishment and redesign of the observatory and pioneering high-quality observations of greenhouse gases, ozone, radiation, aerosols and water vapour, while strengthening calibration activities and recognizing the crucial role of ground stations such as Izaña in satellite evaluation and validation.

Emilio was a key and influential player in the initiation and development of the WMO Sand and Dust Storm Warning and Advisory System launched in 2007; as recognized by the WMO in July 2025 ([International Recognition Award](#) Presented to Dr Emilio Cuevas).

Dr Emilio Cuevas was also instrumental in Spain becoming a member of the Integrated Carbon Observation System (ICOS). He worked tirelessly to ensure Spain's integration into the network, a goal finally realized in 2021 and was the National Network Focal Point for ICOS-Spain until his retirement.





Throughout his professional life, Dr Emilio Cuevas was also a keen supporter of capacity-building programmes, such as key initiatives to strengthen observational capacity in Northern and Western Africa. For example, in September 2006, the WMO GAW Tamanrasset-AEMET twinning station was installed in Algeria, providing much needed data over the last two decades in a region with sparse measurements.

Emilio always recognized the importance of communicating the work of Izaña to the public as well as to the scientific community. He commissioned the documentary, “Izaña, the place to find the answers” (available in [Spanish](#) and [English](#)) to commemorate the Izaña Observatory centenary; it summarizes the work conducted at Izaña and the atmospheric challenges currently faced.

In 2016, the Izaña Observatory celebrated its 100-year anniversary with numerous activities, coordinated by Emilio and IARC staff in conjunction with AEMET. The Official Centenary Ceremony, held on 8 April 2016 at Izaña Observatory was attended by representatives of world meteorological authorities including the WMO President and Secretary-General, the Director Generals of ECMWF and EUMETSAT, the Director of the Group on Earth Observations, the Executive Director of EUMETNET, the AEMET president and the Directors of 16 national meteorological services in Europe; providing a testament to his leadership and international stature.



Emilio had a keen interest in technological projects and innovation in measurement techniques, initiating long-term collaborations with various companies on instrument development. This led to Izaña Observatory becoming a WMO Measurement Lead Centre for Aerosols and Water Vapour Remote Sensing Instruments where new methodologies are developed, tested and validated. His work also led to Izaña becoming one of the two NASA AERONET absolute calibration centers.

Emilio was a key collaborator on many projects involving science conducted in the Teide National Park. For example, he instigated the collaboration of IARC in “TeideLab” an initiative involving Teide National Park and one of its projects, the “Teide Clouds Laboratory”, which started in 2015.

Emilio was also strongly committed to the protection of the natural environment, initiating a project to reclaim land near the Izaña Observatory for the Corona Forestal Natural Park, restoring native vegetation and significantly improving the Observatory’s measurement conditions, he also introduced solar energy projects to enable the Observatory to become self-sufficient in energy.

He was always aware of the importance of the human factor in maintaining and operating a Research Centre such as Izaña, and of the crucial input that each and every person contributes to the work of such a centre, both past and present. Emilio always acknowledged the role of his colleagues and predecessors at Izaña, recognizing in his

own words in the Izaña Observatory Centenary celebration in 2016 that “Today’s successes are the fruit of past efforts”. He was also keenly involved in curating, recovering and documenting the history of the Izaña Observatory.

Emilio had an ability to motivate, enthuse and encourage others. During his career he co-supervised eight PhD theses and numerous Master theses and was an inspiration to the generation of scientists and staff who had the privilege of working or collaborating with him.

The legacy of Dr Emilio Cuevas is of his scientific leadership, dedication, enthusiasm and vision, as well as his passion for delivering science for society and for innovation in research and development. Under his stewardship, IARC’s activities in research and development regarding state-of-the-art measurement techniques, calibration and validation, and international cooperation have given it an outstanding reputation in weather, climate and atmospheric science and established the Izaña Observatory as a reference global station. His work placed Izaña, the Canary Islands and Spain firmly on the international stage.

On 1 January 2026, Izaña Observatory reached its 110-year anniversary, its unparalleled long-term data series form part of his legacy. We give special thanks to Dr Emilio Cuevas, for all his years of service to IARC and to science and to society. He will be greatly missed and remembered with deep fondness by all.



Executive summary

This report summarizes the activities of the Izaña Atmospheric Research Center (IARC) during 2023–2024. IARC, part of the State Meteorological Agency of Spain (AEMET), is a site of excellence in atmospheric science, operating four observatories on Tenerife, Canary Islands, including the Izaña Observatory (IZO) at 2 373 m a.s.l., a WMO Centennial Station, which on 1 January 2026, celebrated its 110-year anniversary.

IARC's mission is to conduct high-quality, long-term observations and research on atmospheric composition, climate change, air quality, and related phenomena. As a WMO Global Atmosphere Watch (GAW) Global Station and a key node in multiple international networks, IARC provides critical data and expertise to the scientific community, policymakers and society.

IARC's activities cover various key aspects: long-term measurements; national and international cooperation programmes; quality assurance; specific measurement campaigns; instrument development; satellite evaluation and validation; training and capacity-building.

Key achievements and activities (2023–2024)

Long-term atmospheric monitoring

The Izaña Observatory (i.e. IZO) is a multi-platform or “super site” where multiple measurement techniques are hosted. There are currently >150 instruments at IZO.

Meteorology The Izaña Observatory now has 110 years of meteorological and atmospheric data, the oldest uninterrupted climate series in the Canary Islands; an invaluable dataset for climate change studies. The 2024 annual mean temperature (12.1 °C) at IZO was the highest ever recorded since measurements began in 1916. The rate of rise in annual mean temperature at IZO has increased slightly to 0.16 °C/decade and the total annual sunshine duration series has also maintained a significantly increasing trend of 42.5 h/decade.

Greenhouse gases IARC continued its uninterrupted, high-precision measurements of greenhouse gases (GHG) CO₂, CH₄, N₂O, CO and SF₆, contributing to two complementary networks: the WMO GAW network and the European Research Infrastructure Integrated Carbon Observation System (ICOS). The Izaña 40-year CO₂ record (1984–2024) shows a persistent annual increase, with recent acceleration (up to +3.4 ppm/year in 2024). In 2024, the maximum average monthly mole fraction was 427.45 ppm (recorded in May), an increase of 3.59 ppm with respect to the previous maximum, 423.86 ppm, observed in May 2023.

Reactive gases and ozonesondes IARC maintains continuous, high-quality measurements of surface O₃, NO_x and SO₂ at IZO and the Santa Cruz Observatory (SCO, 52 m a.s.l.) to characterize the physicochemical reactions and transport processes within the mixed layer and in the free troposphere, since 1987. These surface measurements are complemented by the vertical profile and total ozone column content through a weekly ozone sounding, conducted continuously since 1992.

Total ozone column and ultraviolet radiation The main scientific objective of this programme is to obtain the Total Ozone Column (TOC) and ultraviolet (UV) spectral radiation with the greatest possible precision and long-term stability. This programme began in 1991 with measurements taken by a Brewer spectroradiometer. Currently IARC maintains, and shares with Environment and Climate Change Canada (ECCC), the Brewer world ozone reference at IZO. TOC is also measured by FTIR, ozonesondes and Pandora spectrometer instruments.

Fourier Transform Infrared Spectroscopy (FTIR) IARC currently operates in parallel, two ground-based high-resolution (HR) FTIR spectrometers at IZO, through a long-lasting collaboration of >25 years with the Karlsruhe Institute of Technology (KIT) Germany. In August 2022, a new IFS 125HR spectrometer, owned by AEMET, was installed at Izaña to replace the previous equipment owned by KIT. The HR FTIR measurements provide high-precision, total column content and vertical profiles of key atmospheric trace gases including the main greenhouse gases.

Aerosols Due to the complexity of aerosol measurement and characterization, this programme is divided into two thematic areas: 1) In situ aerosol measurement, for determining mass, concentration, chemical composition, size distribution, and optical properties, in collaboration with the Institute of Natural Products and Agrobiology - CSIC; and 2) Remote measurement techniques for column aerosol characterization by solar and lunar photometry and Lidar, in collaboration with the University of Valladolid (UVa) Atmospheric Optics Group, the Spanish Institute for Aerospace Technology (INTA), Cimel (France) and NASA. Column aerosol measurements using photometry and Lidar are performed from both IZO and SCO, allowing detailed, long-term characterization of the vertical structure of the Saharan Air Layer in this region.

Radiation IARC has been part of the Baseline Surface Radiation Network (BSRN) of the World Radiation Monitoring Centre (WRMC) since 2009, in close

collaboration with UVA. It provides a full suite of radiometric parameters at IZO, SCO, the Botanic Observatory (BTO, 114 m a.s.l.) and Teide Peak Observatory (TPO, 3 555 m a.s.l.).

Water vapour Precipitable water vapour is currently evaluated at IZO by six independent measurement techniques to monitor its spatiotemporal distribution, long-term trends and its relationship with aerosols in nucleation processes. These techniques include a high precision microwave radiometer, Global Navigation Satellite System technique, FTIR, lunar and solar photometers, an EKO MS-711 spectroradiometer and twice daily radiosondes managed by the Meteorological Centre of Santa Cruz de Tenerife (AEMET).

In addition to the long-term meteorological measurements, IARC's meteorology and forecasting group provides support to all measurement programmes. It is responsible for monitoring weather conditions at IZO and at the other observatories. Specialized forecasts are provided from meteorological resources and from the implementation and operation of high-resolution numerical weather prediction models and other advanced meteorological applications.

National and international cooperation

As well as maintaining the core measurement programmes, IARC actively participates in monitoring and research activities within international networks associated with GAW, such as **NDACC** (Network for the Detection of Atmospheric Composition Change), **BSRN**, **TCCON** (Total Carbon Column Observing Network), **AERONET** (Aerosol Robotic Network), **E-PROFILE** (EUMETNET Profiling) and **MPLNET** (Micro Pulse Lidar Network).

IARC collaborates closely with >20 national institutions, universities and technological companies throughout Spain and with >60 other organizations in Europe and worldwide. Two long-term collaborations are with INTA on Differential Optical Absorption Spectroscopy (DOAS) measurements at IZO since 1993 and with the Autonomous University of Barcelona on the Aerobiology programme at IZO and SCO since 2004.

IARC participates in two key European Research Infrastructure Consortia (ERIC): **ACTRIS** (Aerosol, Clouds and Trace Gases Research Infrastructure) and **ICOS** (Integrated Carbon Observation System). IARC participates in ACTRIS as a National Facility (NF) for in situ aerosol measurements and as a Central Facility (CF) for the calibration of remote sensing instrumentation.

IARC coordinates the activities of **ICOS-Spain**, and provides GHG data (CO₂, CH₄, N₂O and CO) from IZO since November 2022. During 2023 and 2024, three new stations were incorporated, and progress was made in the

certification process of the six stations currently comprising the network. The Izaña Atmospheric Station was the first atmospheric ICOS station established and certified in Spain, in May 2023.

COCCON-Spain This project started in 2023 with the aim of addressing the existing gap in atmospheric GHG observations in Spain by implementing a network of stations for GHG columnar measurements at a national scale (initially consisting of fourteen stations throughout Spain). It is coordinated by IARC along with support from KIT and ESA. During 2024, all the portable EM27/SUN spectrometers that will form part of this network were received at the Izaña Observatory.

IARC manages a global network of Brewer spectroradiometers, **EUBREWNET** (European Brewer Network) for real-time observations of column ozone, SO₂, UV and AOD, which started in 2013 and currently includes > 80 instruments in 57 countries worldwide. It provides Fiducial Reference Measurements which are invaluable for evaluation and validation of satellite measurements.

IARC continued its collaboration with the **WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) initiative**. IARC staff have supported the **WMO GAW Tamanrasset** site in Algeria since its implementation in 2006, now covering a period of 20 years. Also, IARC is contributing to build capacity in the region of **Northern Africa, Middle East and Europe (NAMEE)**, through the training activities coordinated through the WMO Barcelona Dust Regional Center, i.e. the WMO SDS-WAS NAMEE Regional Center.

Other national and international initiatives in which IARC participated in 2023–2024 were **ATMO-ACCESS**, **BREWEB**, **CarbonSurvey**, **CREWS**, **GASPOF**, **HARMONIA**, **KADI**, **Mac-Clima**, **MAPP** and **RESPIRE**.

Quality assurance and calibration activities

IARC is involved in various key quality assurance activities. It hosts the **GAW Regional Brewer Calibration Center for Europe (RBCC-E)**. The RBCC-E is the WMO GAW Central Calibration Laboratory (CCL) for Total Ozone in collaboration with ECCC. One of the World Optical Depth Research and Calibration Center Precision Filter Radiometer reference instruments is also maintained at IZO.

Following the volcanic eruption at Mauna Loa Observatory (MLO, Hawaii) in late 2022, which disrupted operations, IZO hosted the world reference Brewer and Dobson spectrophotometers for absolute ozone calibration campaigns in collaboration with ECCC

and NOAA (USA). During 2023–2024, 49 Brewer spectroradiometers were calibrated by IARC.

IARC plays an important role as a center of absolute calibration in other networks such as AERONET. In 2023–2024, IARC provided AERONET calibration of reference photometers from NASA and PHOTONS-LOA (France). Between Jan 2023 and April 2024, six NASA master photometers were calibrated. One NASA reference photometer is still located at IZO and serves as a link between the two absolute calibration centers of AERONET. In addition, during the period 2023–2024, >50 sun-photometers were calibrated by IARC in the framework of AERONET, ACTRIS and CARSNET.

Measurement campaigns

IARC was involved in the following measurement campaigns in 2023–2024:

- Testing of new solar spectrometer for CO₂ monitoring based on Laser Heterodyne Radiometry, field campaign at IZO, July 2023.
- Absolute ozone world reference calibration campaigns at IZO in August 2023 and September 2024.
- The 18th RBBC-E intercomparison campaign, El Arenosillo (Spain), September 2023.
- First Ibero-American Campaign for Brewer Spectrophotometer Calibration and Intercomparison, Santa Maria (Brazil), February–March 2024.
- Fifty Calitoo sun-photometers were calibrated at IZO as part of the WMO Measurement Lead Centre (MLC) for Aerosols and Water Vapour Remote Sensing Instruments programme in May 2024.
- Third Cabauw INtercomparison of UV-Vis DOAS Instruments (CINDI-3), (Kingdom of the Netherlands), May–June 2024.
- The 19th RBBC-E intercomparison campaign, Davos (Switzerland), August 2024.
- Calibration campaign of BSRN pyranometers and pyrhelimeter in IZO in summers 2023 and 2024.

Instrument development

During 2023–2024, various activities involving instrument development were carried out, some of them within the framework of the **WMO MLC for Aerosols and Water Vapour Remote Sensing Instruments**: 1) The Langley ratio method was developed, a new approach for transferring photometer calibration from direct sun measurements; 2) A methodology required to retrieve aerosol properties from ground-based Fourier transform spectra was developed within the MAPP project; 3) The performance of a compact dual-wavelength depolarization elastic lidar was evaluated and 4) Collaboration in the development of the Lunar Irradiance Model of ESA (LIME).

Satellite evaluation and validation

IARC participated in the following satellite evaluation activities in 2023–2024: 1) Validation of Sentinel-4 and 5 TOC using Brewer, Dobson and UV-visible/SAOZ; 2) Validation of Sentinel 5 Level 2 surface UV radiation product; 3) PACE-OCI Validation Plan, Ultraviolet Aerosol Index and AOD; 4) New methodologies for estimating NO₂ and CH₄ emission fluxes from space-based platforms and validation of new satellite products, from TROPOMI, the Greenhouse gases Observing SATellite and the Orbiting Carbon Observatory-2; 5) NO₂ and Formaldehyde validation using NDACC and complementary FTIR and UV-Vis DOAS data and 6) Validation of Sentinel-5P CH₄ and CO with TCCON data.

Training and capacity-building

In May 2023, four 2-year AEMET postgraduate training scholarships were initiated at IARC. IARC participated in various capacity-building activities during 2023–2024, including operator training in South America, a WMO training school for sun-photometer operators and Brewer calibration in North Africa (held at IZO) and various WMO SDS-WAS online training workshops.

Scientific publications and outreach

During 2023–2024, IARC participated in 37 published articles in the SCI (Science Citation Index) and in >80 papers presented at conferences or workshops.

On behalf of IARC and collaborating organizations, we are pleased to present this sixth edition **Izaña Atmospheric Research Center Activity Report: 2023–2024**.

Izaña Observatory is a site which combines excellent “free troposphere” conditions and pristine skies for most of the year. It is invaluable to the global scientific community due to these environmental conditions and due to the extensive measurement programmes, the multiple measurement techniques operated there and the highly skilled and dedicated personnel.

As the Izaña Observatory celebrates its 110-year anniversary, this report summarizes the main activities undertaken, not only at the Observatory itself, but also by IARC in providing atmospheric monitoring, research, quality assurance activities, national and international collaboration, satellite validation and cutting-edge development in many fields. These wide-ranging activities have consolidated IARC and its pivotal role both nationally and internationally.

This report highlights the long-term commitment by IARC to providing high-quality atmospheric composition and meteorological data, to underpin the best available science, essential for both the public and decision-makers.



1 Organization

The Izaña Atmospheric Research Center ([IARC](#)) is part of the Department of Planning, Strategy and Business Development of the State Meteorological Agency of Spain ([AEMET](#)). AEMET is an Agency of the Spanish Ministry for the Ecological Transition and the Demographic Challenge ([MITECO](#)).

2 Mission and background

IARC conducts observations and research related to atmospheric constituents that have impact on climate (greenhouse gases, reactive gases and aerosols), may cause depletion of the global ozone layer or play key roles in air quality from local to global scales. The IARC is an Associated Unit of the Spanish National Research Council (CSIC) through the Institute of Environmental Assessment and Water Research ([IDAEA](#)). The main goal of the Associated Unit “Group for Atmospheric Pollution Studies” is to perform air quality research in both rural and urban environments.

IARC has contributed to the World Meteorological Organization (WMO) Global Atmosphere Watch Programme ([GAW](#)) since its establishment in 1989. The main objectives of the GAW Programme are to provide data and other information on the chemical composition and related physical characteristics of the atmosphere, its changes and the drivers of these changes. These are required to improve our understanding of the behaviour of the atmosphere and its interactions with the oceans and the biosphere, as well as supporting impact assessments. The GAW surface global network integrates a number of WMO research and monitoring activities in the field of atmospheric environment.

The IARC also contributes to the Network for the Detection of Atmospheric Composition Change ([NDACC](#)). NDACC is an international network for monitoring atmospheric composition using remote measurement techniques. Originally, NDACC was created to monitor the physical and chemical changes in the stratosphere, with special emphasis on the evolution of the ozone layer and the substances responsible for its destruction known as Ozone Depleting Substances. The current objectives of NDACC are to observe and to understand the physicochemical processes of the upper troposphere and stratosphere, and their interactions, and to detect long-term trends of atmospheric composition. IARC also makes an important contribution to the WMO through the WMO Integrated Observing System ([WIGOS](#)) and by hosting the [WMO Measurement Lead Centre for Aerosols and Water Vapour Remote Sensing Instruments](#).

Izaña Observatory was inaugurated in its present location on 1 January 1916, initiating uninterrupted meteorological and climatological observations, which constitutes a 110-year record in 2026. In 1984, the observatory became a station of the WMO Background Atmospheric Pollution Monitoring Network (BAPMoN). In 1989, BAPMoN and GO3OS (Global Ozone Observing System) were integrated under the GAW network. Izaña Observatory is one of 40 GAW Global stations (Figure 2.1). GAW Global stations serve as centres of excellence and perform extensive research on atmospheric composition change. IZO is a key example of such a research facility.



Figure 2.1. WMO GAW global stations

3 Facilities and summary of measurements

IARC manages four observatories in Tenerife (Figure 3.1, Table 3.1): 1) Izaña Observatory (IZO); 2) Santa Cruz Observatory (SCO); 3) Botanic Observatory (BTO); and 4) Teide Peak Observatory (TPO).



Figure 3.1. Location of IARC observatories on Tenerife

Table 3.1. IARC observatories

Observatory	Latitude	Longitude	Altitude (m a.s.l.)
IZO	28.309°N	16.499°W	2 373
SCO	28.473°N	16.247°W	52
BTO	28.411°N	16.535°W	114
TPO	28.270°N	16.639°W	3 555

3.1 Izaña Observatory

The Izaña Observatory (IZO) is located on the island of Tenerife, Spain, roughly 300 km west of the African coast. The observatory is situated on a mountain plateau, 15 km north-east of the volcano Teide (3 715 m a.s.l.) (Figures 3.2 and 3.3). The local wind regime at the site is dominated by north-westerly winds. Clean air and clear sky conditions generally prevail throughout the year. IZO is normally above a temperature inversion layer, generally well established over the island, and below the descending branch of the Hadley cell.



Figure 3.3 Izaña Observatory (2 373 m) with the volcano Teide (3 715 m) to the left of the image



Figure 3.2. Image of Izaña Observatory

Image credit: ICOS-ERIC

The station offers excellent conditions for trace gas and aerosol in situ measurements under “free troposphere” conditions, and for atmospheric observations by remote sensing techniques. The environmental conditions and pristine skies are optimal for calibration and validation activities of both ground-based and space-borne sensors. Due to its geographic location, it is particularly valuable for the investigation of dust transport from Africa to the North Atlantic, long-range transport of pollution from the Americas, and large-scale transport from the tropics to higher latitudes.

The IZO facilities consist of three separate buildings: the main building, inaugurated in 1916; the aerosols lab, a small nearby building of the same period which was renamed “Joseph M. Prospero Aerosols Laboratory” on 8 April 2016; and the technical tower, completely rebuilt in early 2000, which hosts most of the instruments. Details of the IZO measurement programme are given in Table 3.2.

The main building is a two-storey building with a total area of 1 420 m², which hosts the following facilities: office space, dining room, kitchen, library, conference hall with audio-visual system, meeting room, engine rooms, a mechanical workshop, and an electronics workshop. In addition, there is residential accommodation available for visiting scientists (seven double en-suite rooms). The technical tower is a seven-storey building with a total area of 900 m². It includes 20 laboratories distributed among the different floors (Table 3.3, Figure 3.8). All the laboratories are temperature controlled.

Table 3.2. Izaña Observatory (IZO) measurement programme

Parameter	Start date	Present instrument	Data frequency
Greenhouse gases and carbon cycle			
CO ₂	Jun 1984	CRDS Picarro G2401 (Primary instrument) NDIR Licor 7000 (Secondary instrument)	2" 1"
CH ₄	Jul 1984	CRDS Picarro G2401	2"
N ₂ O	Jun 2007	GC-ECD Agilent 8890 OA-ICOS Los Gatos Research 913-0015	15' 4"
SF ₆	Jun 2007	GC-ECD Agilent 8890	15'
CO	Jan 2008	CRDS Picarro G2401 OA-ICOS Los Gatos Research 913-0015	2" 4"
Greenhouse gases and carbon cycle (ICOS)			
CO ₂ , CH ₄ and CO	Nov 2022	CRDS Picarro G2401	2"
CO and N ₂ O	Nov 2022	OA-ICOS Los Gatos Research 907-0015	5"
In situ reactive gases			
O ₃	Jan 1987	UV Photometry Teco 49-i (New Primary instrument) Teco 49-C (Secondary instrument) Thermo Scientific 49i (installed in Dec 2022) Thermo Scientific 49i (installed in Dec 2022, moved to SCO in 2025)	1' 1' 1' 1'
CO	Nov 2004– June 2019	Non-dispersive IR absorption Thermo 48C-TL	1'
SO ₂	Jun 2006	UV fluorescence Thermo 43C-TL Thermo Scientific 43i(installed May 2023) Thermo Scientific 43i(installed May 2023)	1' 1' 1'
NO-NO ₂ -NO _x	Jun 2006	Chemiluminescence EcoPhysics CraNOx II	1'
Total ozone column and UV			
Column O ₃ Column SO ₂	May 1991 Sept 2022	Brewer Mark-III #157 (Primary Reference) Brewer Mark-III #183 (for developments) Brewer Mark-III #185 (Travelling Reference) Brewer Mark-III #256 (Secondary Reference) Brewer Mark-III #257 (Secondary Reference) Brewer Mark-III #258 (Secondary Reference)	~100/day ~100/day ~100/day ~100/day ~100/day ~100/day
Spectral UV: 290–365 nm	May 1991 Sept 2022	Brewer Mark-III #157 (Primary Reference) Brewer Mark-III # 183 (for developments) Brewer Mark-III #185 (Travelling Reference) Brewer Mark-III #256 (Secondary Reference) Brewer Mark-III #257 (Secondary Reference) Brewer Mark-III #258 (Secondary Reference)	~30' ~30' ~30' ~30' ~30' ~30'
Spectral UV: 290–450 nm	May 2021	BTS	2 min

Parameter	Start date	Present instrument	Data frequency
Total Ozone Column and UV (Pandora)			
Column O ₃	Oct 2011 Dec 2022	Pandora 101 Pandora 121	10' 10'
Column SO ₂	Dec 2019 Dec 2022	Pandora 101 Pandora 121	10' 10'
Column NO ₂	Dec 2019 July 2022 Dec 2022	Pandora 101 Pandora 209 Pandora 121	10' 10' 10'
Fourier Transform Infrared Spectroscopy (FTIR)			
Greenhouse gases, reactive gases, and O ₃ depleting substances (O ₃ , HF, HCN, HCl, ClONO ₂ , C ₂ H ₆ , HNO ₃ , CH ₄ , CO, CO ₂ , N ₂ O, NO, NO ₂ , H ₂ O, HDO, OCS)	Jan 1999 May 2007 Aug 2022	Fourier Transform Infrared Spectroscopy Bruker IFS 120/5HR (co-managed with KIT) Middle infrared (MIR) solar absorption spectra Near infrared (NIR) solar absorption spectra Bruker IFS 125HR SN149	3 days/week (weather permitting)
Greenhouse gases, and reactive gases (CO ₂ , CH ₄ , CO, H ₂ O)	May 2018 Mar 2021	Bruker EM27/SUN SN85 Bruker EM27/SUN SN143	1 day/week (weather permitting)
In situ aerosols			
Chemical composition of particulate matter: PM _T ⁽¹⁾ PM ₁ ⁽²⁾ PM _{2.5} PM ₁₀	Jul 1987 Aug 2010 Apr 2002 Jan 2005	High-volume sampler custom built/MVC™/MCZ™ Concentrations of soluble species by ion chromatography (Cl ⁻ , NO ₃ ⁻ and SO ₄ ²⁻) and FIA colorimetry (NH ₄ ⁺), major elements (Al, Ca, K, Na, Mg and Fe) and trace elements by ICP-AES and ICP-MS were determined at CSIC	8h sampling at night
Number of particles > 3 nm	Nov 2006 ⁽³⁾	TSI™, UCPC 3025A	1'
Number of particles > 2.5 nm	Dec 2012	TSI™, UCPC 3776	1'
Number of particles > 10 nm	Dec 2012	TSI™, CPC 3010	1'
Size distribution: 10–400 nm	Nov 2006 ⁽⁴⁾	TSI™, class 3080 + CPC 3772	5'
Size distribution: 10–800 nm	Jan 2024	TSI™, class 3080 + CPC 3750-10	5'
Size distribution: 0.7–20 μm	Nov 2006	TSI™, APS 3321	10'
Absorption coeff. (PM ₁₀) at 637 nm	Nov 2006	Thermo™, MAAP 5012	1'
Attenuation (PM ₁₀) at 370, 470, 520, 590, 660, 880 and 950 nm	Jul 2012 Feb 2022	Magee™, Aethalometer AE31-HS Magee™, Aethalometer AE33	1'
Scattering coeff. (PM ₁₀) at 450, 550 and 700 nm	Jun 2008	TSI™, Integration Nephelometer 3563	1'
Scattering coeff. (PM ₁₋₁₀) and phase function at 470, 529 and 621 nm	Jun 2023	Air Photon, Inverse Multi-Angle Polarimeters with polarization (IMAP) 100	1'
Scattering coeff. (PM ₁₀) at 450, 525 and 635 nm	Oct 2024	Ecotech, Integration Nephelometer Aurora 3000	1'
PM ₁₀ mass concentration	Jun 2016	Thermo, BETA 5014i	5'
PM _{2.5} and PM _{2.5-10} mass concentrations	Jun 2016	Thermo, TEOM 1405DF	6'

(1) Not operational since 2017, (2) Usually only in summer (August), Not operational since, (3) June 2017, (4) March 2025

Parameter	Start date	Present instrument	Data frequency
Column aerosols			
AOD and Angstrom at 340, 380, 440, 500, 675, 870, 936, 1020 nm	Mar 2003	CIMEL CE318 sun photometer	~ 15'
Fine/Coarse AOD Fine mode fraction	Mar 2003	CIMEL CE318 sun photometer	~ 15'
Optical inversion products	Mar 2003	CIMEL CE318 sun photometer	~ 1h
AOD and Angstrom during night period	July 2012	CIMEL CE318-T sun-sky-lunar photometer	~ 15' during moon phases
AOD and Angstrom at 368, 412, 500 and 862 nm	July 2001	WRC Precision Filter Radiometer (PFR)	1'
AOD at 769.9 nm	July 1976	MARK-I (at the IAC)	AOD at 769.9 nm
Elastic backscatter and depolarization measurements at 532 nm and 808 nm	Dec 2015	CIMEL CE376 micro-lidar	1'
Vertical Backscatter-extinction at 532 nm, clouds alt. and thickness (with depolarization)	Feb 2020	Micro Pulse Lidar MPL-4B	1'
Radiation			
Global Rad. 285–3 000 nm	Jan 1977	Pyranometers CM-21 & CM-11 Kipp & Zonen, EKO MS-801 and MS-80S	1'
Direct Rad. 200–4 000nm	Aug 2005	Pyrheliometers CH-1 Kipp & Zonen, EKO MS-56 and MS-57	1'
Direct Rad.	Jun 2014	Absolute Cavity Pyrheliometer PMO6	Calibration campaigns (1')
Spectral direct Radiation 300–1 100 nm	Dec 2016	Spectroradiometer EKO MS-711	1'
Spectral global and diffuse Radiation 300–1 100 nm	Feb 2020	Spectroradiometer EKO RSB	1'
Spectral global Radiation 900–2 600 nm	Dec 2022	Spectroradiometer EKO MS-713	1'
Diffuse Rad. 285–3 000 nm	Aug 2005	Pyranometers CM-21 Kipp & Zonen, EKO MS-801 and MS-80S	1'
Downward Longwave Rad. 4.5–42 μ m	Mar 2009	Pyrgeometers CG-4 Kipp & Zonen and EKO MS-21	1'
UVB Radiation 315–400 nm	Aug 2005	Yankee YES UVB-1 Pyranometer (in parallel)	1'
UVA Radiation 280–400 nm	Mar 2009	Radiometers UVS-A-T Kipp & Zonen and EKO MS-10S	1'

Parameter	Start date	Present instrument	Data frequency
Radiation (continued)			
Photosynthetically Active Radiation (PAR) 400–700 nm	Aug 2005	Pyranometers Par Lite Kipp & Zonen and Photon Sensor EKO ML-020P	1'
Net Radiation	Nov 2016	Net Radiometer EKO MR-60	1'
Luminance/Radiance	Nov 2020	EKO MS-321LR Sky Scanner	10'
Global and Diffuse Rad.	Jun 2021	SPN1 Sunshine Pyranometer	1'
DOAS (managed by the Spanish National Institute for Aerospace Technology, INTA)			
Column NO ₂	May 1993	UV-VIS DOAS EVA and MAXDOAS RASAS II (INTA's homemade; www.inta.es)	Every ~20' during twilight
Column O ₃	Jan 2000	UV-VIS MAXDOAS RASAS II (INTA's homemade)	Every ~20' during twilight
Column BrO	Jan 2002	UV-VIS MAXDOAS ARTIST-II (INTA's homemade)	Every ~20' during twilight
Tropospheric O ₃	May 2010	UV-VIS MAXDOAS RASAS II (INTA's homemade)	Every ~20' during twilight
Tropospheric NO ₂	May 2010	UV-VIS MAXDOAS RASAS II (INTA's homemade)	Every ~20' during twilight
Tropospheric IO	May 2010	UV-VIS MAXDOAS RASAS II (INTA's homemade)	Every ~20' during twilight
Tropospheric HCHO	May 2015	UV-VIS MAXDOAS ARTIST II (INTA's homemade)	Every ~20' during twilight
Water vapour			
Precipitable Water Vapour (PWV)	Jul 2008 (ultra-rapid orbits) Jan 2009 (precise orbits)	GPS/GLONASS LEICA GRX1200GGPRO satellite ground-based receiver	15' (ultra-rapid orbits) and 1h (precise orbits)
PWV Total Column and Profiles for layers from 2.4 km up to 12 km altitude	Dec 1963	Väisälä RS-41	Daily at 00 and 12 UTC
PWV	Mar 2003	CIMEL CE318 sun photometer	~ 15'
PWV	Jan 1999	Fourier Transform Infrared Spectroscopy	3 days/week when cloud-free conditions
Integrated Water Vapour (IWV)	May 2020	Microwave Radiometer LHATPRO G5	1''
Vertical Absolute Humidity Profile (HPC)	May 2020	Microwave Radiometer LHATPRO G5	1'
Vertical Relative Humidity Profile (HRC)	May 2020	Microwave Radiometer LHATPRO G5	1'
Liquid Water Path (LWP)	May 2020	Microwave Radiometer LHATPRO G5	1''
Liquid Water Profile (LPR)	May 2020	Microwave Radiometer LHATPRO G5	1''
Cloud Base Height (CBH)	May 2020	Microwave Radiometer LHATPRO G5	1''

Parameter	Start date	Present instrument	Data frequency
Meteorology			
Temperature	Jan 1916	THIES CLIMA 1.1005.54.700 3 VAISALA HMP45C (in parallel) VAISALA PTU300 THIES CLIMA 1.0620.00.000 (thermo-hygrograph) CAMPBELL SCIENTIFIC CS215 (Tower top)	1' 1' 1' Continuous 1'
Relative humidity	Jan 1916	THIES CLIMA 1.1005.54.700 3 VAISALA HMP45C (in parallel) VAISALA PTU300 THIES CLIMA 1.0620.00.000 (thermo-hygrograph) CAMPBELL SCIENTIFIC CS215 (Tower top)	1' 1' 1' Continuous 1'
Wind direction and speed	Jan 1916	Sonic anemometer Thies 2D 4.3820.31.401 Sonic anemometer FT Technologies FT742-D-DM Sonic anemometer FT Technologies FT742-D-DM (Tower Top)	1' 1' 1'
Pressure	Jan 1916	SETRA 470 VAISALA PTU 300 BELFORT 5/800AM/1 (Barograph) SETRA 470 (Tower top)	1' 1' Continuous 1'
Rainfall	Jan 1916	THIES CLIMA Tipping Bucket THIES CLIMA Tipping Bucket Hellman rain gauge Hellman pluviograph	1' 1' Daily Continuous
Sunshine duration	Aug 1916	KIPP & ZONEN CSD3 Campbell Stokes Sunshine recorder	10' Continuous
Present weather and visibility	Jul 1941	BIRAL 10HVJS	10'
Vertical profiles of T, RH, P, wind direction and speed, from sea level to ~30 km altitude	Dec 1963	RS41+GPS radiosondes launched at Güimar automatic radiosonde station (WMO GRUAN station #60018) (managed by the Meteorological Centre of Santa Cruz de Tenerife)	Daily at 00 and 12 UTC
Soil surface temperature	Jan 1953	2 THIES CLIMA Pt100 (in parallel)	10'
Soil temperature (20 cm)	Jan 2003	2 THIES CLIMA Pt100 (in parallel)	10'
Soil temperature (40 cm)	Jan 2003	2 THIES CLIMA Pt100 (in parallel)	10'
Atmospheric electric field	Apr 2004	Electric Field Mill PREVISTORM-INGESCO	10"
Lightning discharges	Apr 2004	Boltek LD-350 Lightning Detector	1'
Cloud cover	Sep 2008	Sieltec Canarias S.L. SONA total sky camera Sieltec Canarias S.L. SONA total sky camera (Model 201D, daytime) Sieltec Canarias S.L. SONA total sky camera (Model 502N, nighttime)	5' 5' 5'

Fog-rainfall	Nov 2009	THIES CLIMA Tipping Bucket with 20 cm ² mesh Hellman rain gauge with 20 cm ² mesh	1' Daily
Sea-cloud cover	Nov 2010	AXIS Camera: West View (Orotava Valley) AXIS Camera: South View (Meteo Garden) AXIS Camera: North View AXIS Camera: East View (Güimar Valley)	5' 5' 5' 5'
Drop size distribution and velocity of falling hydrometeors	May 2011	OTT Messtechnik OTT Parsivel	1'
Aerobiology			
Pollens and spores	Jun 2006	Hirst, 7-day recorder VPPS 2000 spore trap (Lanzoni S.r.l.). Analysis performed with a Light microscope, 600 X at the Laboratori d'Anàlisi Palinològiques, Universitat Autònoma de Barcelona	Continuous (1 h resolution; usually daily) from April to October

On the ground floor of the technical tower, there are two storage spaces, one of them is for pressured cylinders (tested and certified at the Canary Islands Regional Council for Industry) and the other one is for cylinder filling using oil-free air compressors. This floor also includes the central system for supplying high purity gases (H₂, N₂, Ar/CH₄) and synthetic air to the different laboratories. On the second floor, there is a dark-room with the necessary calibration set-ups for the IZO radiation instruments. On the top of the technical tower there is a 160 m² flat horizon-free terrace for the installation of outdoor scientific instruments that need sun or moon radiation. It also has the East and West sample-inlets which supply the ambient air to in situ trace gas analysers set up in different laboratories.

The “Joseph M. Prospero Aerosol Research Laboratory” is a 40 m² building used as an on-site aerosol measurement laboratory.

It has four sample-inlets connected to aerosol analysers. For more details, see section 8. Outside Izaña Observatory there are the following facilities: 1) a 160 m² flat horizon-free platform with communications and UPS used for measurement field campaigns; 2) the meteorological garden, containing two fully-automatic meteorological stations (one of them is the SYNOP station and the second one is for meteorological research), manual meteorological gauges, a total sky camera, a GPS/GLONAS receiver, a lightning detector, and an electric field mill sensor; and 3) the Sky watch cabin hosting four cameras for cloud observations with corresponding servers. The following sections give further details of some of the facilities located at IZO.

Table 3.3. Izaña Observatory technical tower facilities

Floor	Facilities	Description
Ground floor	Mechanical Workshop	33 m ² room with the necessary tools to carry out first-step mechanical repairs.
	Electronics Workshop	25 m ² room equipped with oscilloscopes, power supplies, multimeters, soldering systems, etc. to carry out first-step electronic repairs.
	Heating system	Central heating and hot water 90 kW system.
	Air Conditioning System	Central air conditioning system for labs.
	Engine Room: Backup Generators	General electrical panel and two automatic start-up backup generators (400 kVA and 100 kVA, respectively).
	UPS room	Observatory's main UPS (40 kVA redundant) used for assuring the power of the equipment inside the building and an additional UPS (10 kVA) for the outside equipment.
	Compressor room	Room with clean oil-free air compressors used for calibration cylinders filling. It also contains the general pumps for the East and West sample inlets.
	Warehouse / Central Gas Supply System	30 m ² warehouse authorized for pressurized cylinders. Central system for high purity gas (H ₂ , N ₂ , Ar/CH ₄) and synthetic air supply.
	Lift	6-floors. No lift access to roof terrace.
First floor	Archive room	Archive of bands and historical records.
	Technical equipment warehouse	Spare parts for the Observatory's technical equipment.
	Meeting room	8-person meeting room
Second floor	Optical Calibration Facility	30 m ² dark room hosting vertical and horizontal absolute irradiance, absolute radiance, angular response, and spectral response calibration set ups.
	T2.1 Laboratory	10 m ² lab with access to West sample inlet.
	T2.2 Laboratory	9 m ² lab with access to East sample inlet.
	T2.3 Laboratory	13 m ² lab hosting Picarro L2120-I δ D and δ^{18} O analyser with access to East sample inlet
Third floor	Greenhouse Gases Laboratories	70 m ² shared in two labs hosting CO ₂ , CH ₄ , N ₂ O, SF ₆ and CO analysers with access to the East and West sample inlets.
Fourth floor	All purpose laboratories	Three labs with access to the East and West sample inlets.
Fifth floor	Reactive Gases Laboratory	10 m ² lab hosting NO-NO ₂ and SO ₂ analysers with access to West sample inlet.
	Communications room	Server room and WIFI connection with Santa Cruz de Tenerife headquarters.
	Brewer Laboratory	20 m ² lab for Brewer campaigns.
Sixth floor	Surface Ozone Laboratory	10 m ² laboratory hosting surface O ₃ analysers with access to West sample inlet.
	Solar Photometry Laboratory	10 m ² maintenance workshop for solar photometers.
	Spectroradiometer Laboratory	25 m ² laboratory hosting two MAXDOAS and two spectroradiometers connected with optical fibre.
Roof	Instrument Terrace	160 m ² flat horizon-free terrace hosting outdoor instruments, East and West sample-inlets, wind, pressure, temperature and humidity sensors.

3.1.1 Optical calibration facility

The optical calibration facility at IZO has been developed within the framework of the Specific Agreement of Collaboration between the University of Valladolid and IARC to establish methodologies and quality assurance systems for programmes of photometry, radiometry, atmospheric ozone and aerosols within WIGOS. The main objective of the optical calibration facility is to perform Quality Assurance & Quality Control (QA/QC) assessment of the solar radiation instruments that support the ozone, aerosols, radiation, and water vapour programmes of the IARC. The seven set-ups available are the following:

1) Set-up for the absolute radiance calibration by calibrated integrating sphere (Figure 3.4A). The system is traceable to the AEROSOL RObotic NETwork (AERONET) standard at the Goddard Space Flight Center (GSFC) (Washington, USA). This set-up is mainly used by Cimel sun-photometers, but other instruments can also be calibrated. At the end of 2017, a new integrating sphere was installed at IZO for AERONET-Europe absolute radiance calibrations as well as optical tests required for QC/QA of reference instruments. The new integrating sphere has a 50.8 cm diameter and 20.3 cm aperture (Figure 3.4B). This system is also traceable to the AERONET standard at GSFC.

2) Set-up for the slit function determination (Figure 3.4 C). The characterization of the slit function is performed illuminating the entrance slit of a spectrophotometer with the monochromatic light of a VM-TIM He-Cd laser. The nominal wavelength of the laser is 325 nm, its power is 6 mW, and its beam diameter is 1.8 mm.

3) Set-up for the alignment of the Brewer spectrophotometer optics (Figure 3.4D). It is suitable to perform adjustments of the optics without sending the instrument to the manufacturer.

4) Set-up for the angular response calibration (Figure 3.4E). It is used to quantify the deviations of the radiometer's angular response from an ideal cosine response. The relative angular response function is measured by rotating the mechanical arm where the seasoned DXW-type 1000 W lamp is located. The rotation over $\pm 90^\circ$ is controlled by a stepper motor with a precision of 0.01° while the instrument is illuminated by the uniform and parallel light beam of the lamp.

5) Set-up for the spectral response calibration. It is used to quantify the spectral response of a radiometer (Figure 3.4F). The light is scattered by an Optronic double monochromator OL 750 within the range from 200 to 1100 nm with a precision of 0.1 nm. An OL 740-20 light source positioned in front of the entrance slit acts as radiation source and two lamps, UV (200–400 nm) and Tungsten (250–2500 nm) are available.

6) Set-up for the absolute irradiance calibration by calibrated standard lamps in a horizontally oriented position (Figure 3.4G).

7) Set-up for the absolute irradiance calibration by calibrated standard lamps in a vertical oriented position suitable for relatively large spectrophotometers (Figure 3.4H). The basis of the absolute irradiance scale consists of a set of DXW-type 1000 W lamps traceable to the primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB).

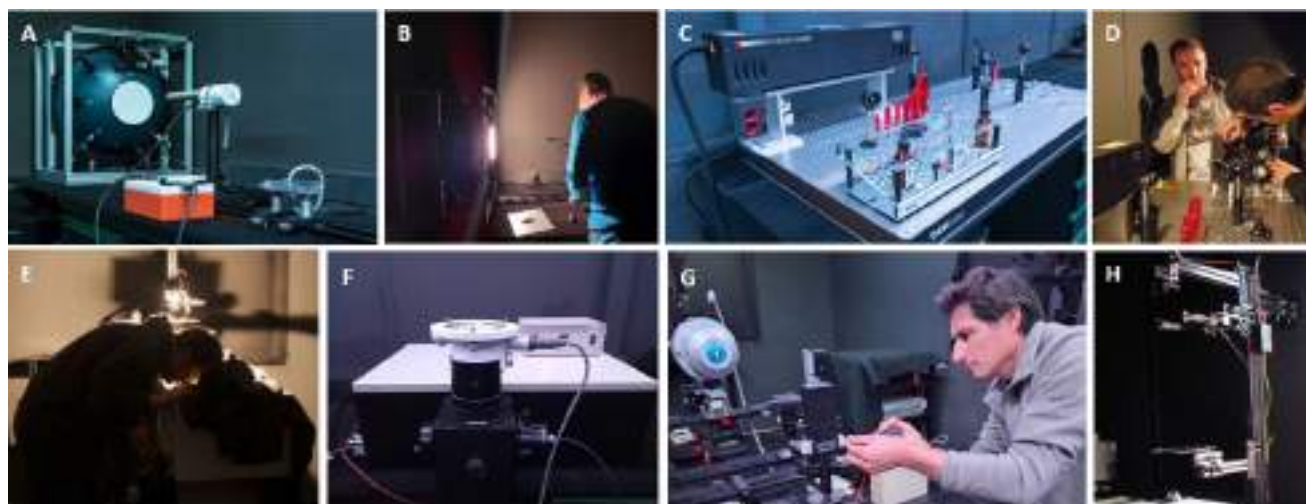


Figure 3.4. Images of the IZO Optical calibration facility. A, B) Absolute radiance calibration of a Cimel CE318 with integrating sphere, C, D) Set up for slit function determination and alignment of a Brewer spectrophotometer optics, E) Angular response function determination of a Brewer, F) Spectral response calibration of a Yankee UVB radiometer, G) Horizontal absolute irradiance calibration of a EKO MS-711 spectroradiometer and (H) Set up for the absolute calibration in a vertical oriented position of a Brewer.

In 2023–2024, the optical calibration laboratory has been used during 74 days. Calibrations were carried out on several instruments: Cimel photometers, a Brewer spectroradiometer, an EM27/SUN spectrometer and EKO MS-711 and EKO RSB spectroradiometers. In particular, 52 Cimel photometers were calibrated from various institutions and networks, including IARC, the University of La Laguna (ULL), the NASA Goddard Space Flight Center, and the China Aerosol Remote Sensing Network (CARSNET).

3.1.2 In situ system used to produce working standards containing natural air

The GAW network requires very high accuracy in the atmospheric GHG mole fraction measurements, and a direct link to the WMO primary standards maintained by the GAW Central Calibration Laboratories (CCLs) for GHG, most of which are located at the National Oceanic and Atmospheric Administration-Earth System Research Laboratory-Global Monitoring Laboratory (NOAA-ESRL-GML). To meet these requirements, IARC uses Laboratory Standards prepared (using natural air) and calibrated by NOAA-ESRL-GML. Indeed, the Laboratory Standards used at IARC are WMO tertiary standards. However, due to the fact that the consumption of standard and reference gases by the IARC GHG measurement systems is relatively high, an additional level of standard gases (working standards) prepared with natural air is used.

These working standards are prepared at IZO using an in-situ system (Figure 3.5) and then calibrated against the Laboratory Standards using the IARC GHG measurement systems. The system used to fill the high-pressure cylinders (up to 120-130 bars) with dried natural air, takes clean ambient air from the East sample-inlet located on top of the IZO tower (30 m above ground), and pumps (using an oil-free compressor) it inside the cylinders after drying it (using magnesium perchlorate), achieving a H_2O mole fraction lower than 3 ppm.

Additionally, it is possible to modify slightly the CO_2 mole fraction of the natural air pumped inside the cylinders. To this end, air from a cylinder containing natural air with zero CO_2 mole fraction (prepared using the same system but adding a CO_2 absorber trap) or a tiny amount of gas from a spiking CO_2 cylinder (5% of CO_2 in $\text{N}_2/\text{O}_2/\text{Ar}$) is added to the cylinder being filled. This system is similar to that used by NOAA-ESRL-GML to prepare WMO secondary and tertiary standards, and it is managed and operated at IZO through a subcontractor (Air Liquide Canarias). The prepared working standards are mainly used in the GHG measurement programme, but some of them are used for other purposes, including for natural air supply for a H_2O isotopologue CRDS analyser located at Teide peak and for a CO NDIR analyser located at SCO.

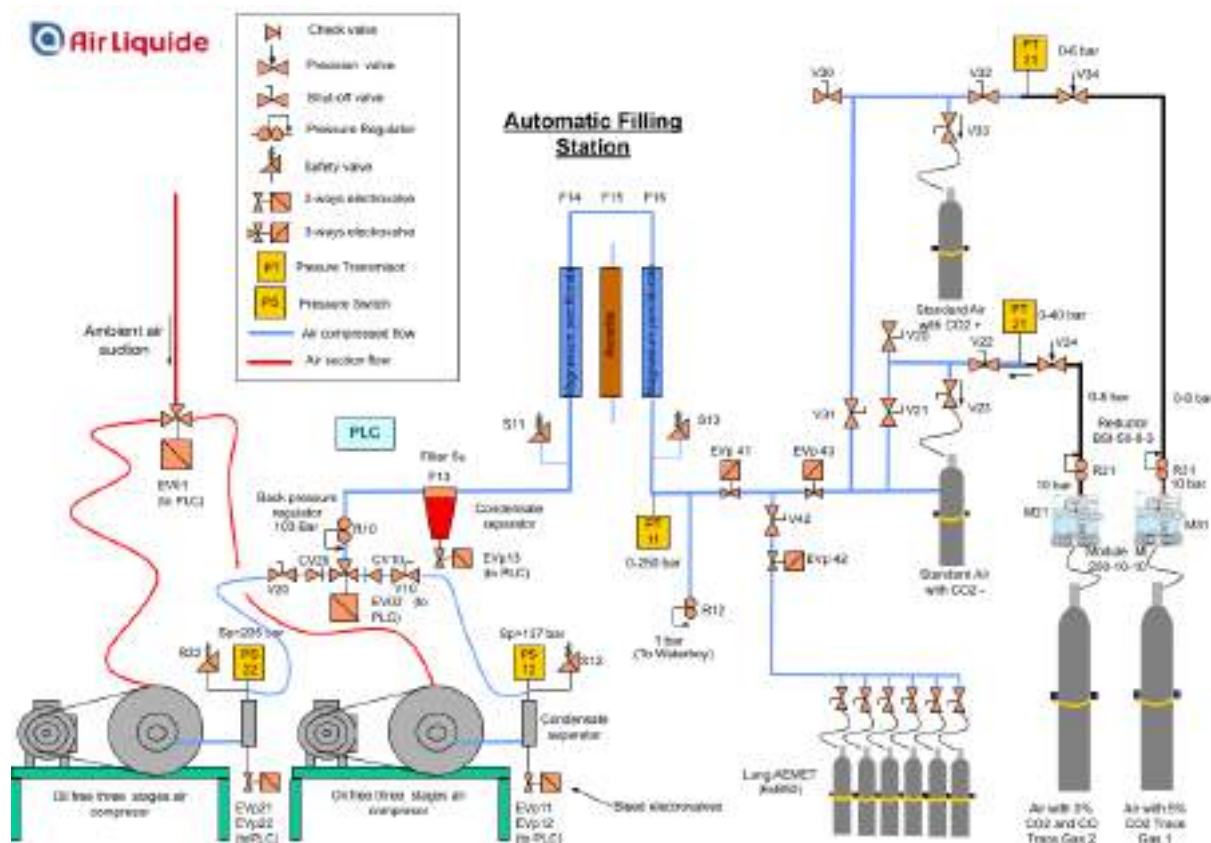


Figure 3.5. In situ system used to produce working standards containing natural air at Izaña Observatory

3.1.3 Central gas supply system

There is a gas central facility located on the IZO tower ground floor for supplying support gases to the different instruments. This central facility supplies high purity: N_2 (used as carrier gas for the GC-FIDs, and for the IZO H_2O isotopologue Cavity Ring-Down Spectroscopy (CRDS) analyser), synthetic air (used as oxidizer in the FIDs, as carrier gas in the GC-RGD, as carrier gas in the IZO H_2O isotopologue CRDS analyser, and as diluting air used in the calibrations of the reactive gas instruments), 99.9995% O_2 (used for O_3 generation in the CrNOx-II analyzer), 95% Ar /5% CH_4 (used as carrier gas for the CD-ECD), and H_2 (used as combustible in the FIDs). The H_2O isotopologue CRDS analyser located at Teide peak has its own dedicated high purity N_2 supply.

Additionally, other gases (provided by Air Liquide) are used at IZO: high purity CO_2 for the calibration of an aerosol nephelometer, high purity N_2O for FTIR instrumental line shape monitoring, liquid N_2 to cryocool the FTIR detectors, and calibrated concentrated gas standards in N_2 (1 ppm NO , 10 ppm NO , 1 ppm SO_2 and 2 ppm CO) for the calibration of the instruments of the reactive gases programme.

3.1.4 Aerosol Filters Laboratory

The Aerosol Filters Laboratory at IZO is equipped with an auto-calibration microbalance (Mettler Toledo XS105DU) with a resolution of 0.01 mg, a set of standard weights, and an oven that reaches 300 °C. Filters are weighed following the requirements of the UNE-EN-12341-2015 standards. This filter weighing procedure is used for determination of concentrations of PM_{10} , $PM_{2.5}$ and PM_1 by means of standardized methods, within a methacrylate chamber, which also contains the balance used for weighing the filters (Figure 3.6).



Figure 3.6. IZO Aerosol Filters Laboratory: temperature- and relative humidity-controlled chamber

3.1.5 Modifications and improvements to the IZO facilities carried out in 2023–2024

In February 2023, The Izaña Cosmic Ray Observatory (ICaRO) was installed at IZO (Figure 3.7) in the framework of a research collaboration between AEMET and the University of Alcalá (UAH), for more details see section 22.



Figure 3.7. a) ICaRO's location at IZO, in the Comet Hangar, and b) ICaRO Installation with the University of Alcalá and IARC Team



Figure 3.8. Images of IZO Instrument terrace and technical tower

3.2 Santa Cruz Observatory

The Santa Cruz de Tenerife Observatory (SCO) is located on the roof of the IARC headquarters at 52 m a.s.l. in the capital of the island (Santa Cruz de Tenerife), close to the city harbour (Figures 3.9 and 3.10). Details of the SCO measurement programme are given in Table 3.4.



Figure 3.9. Images of Santa Cruz Observatory (SCO)

This observatory has two main objectives: 1) to provide information on background urban pollution to support atmospheric research and to study contribution of the long-range pollution transport driven by trade winds or Saharan dust outbreaks on local air quality and 2) to perform complementary measurements to those at IZO. The IARC headquarters include the following facilities:

- A laboratory for reactive gases measurements (surface O_3 , NO - NO_2 , CO and SO_2).
- A laboratory hosting Micro Pulse Lidar (MPL) and ceilometer VL-51.
- A laboratory for the preparation of ozonesondes.
- A 25 m² flat horizon-free terrace for radiation instruments and air intake.



Figure 3.10. Image of the Santa Cruz de Tenerife Observatory (SCO) instrument terrace

3.2.1 The Ozonesonde Laboratory

Science Pump Corporation (SPC) Electrochemical Concentration Cell (ECC) ozone sensors (model ECC-6A) are used in the IARC Ozonesonde Programme. Ozonesonde conditioning and pre-flight preparation is performed at the Ozonesonde Laboratory at SCO.

A SPC TSC-1 Ozonizer/Test Unit was used for ozonesonde preparation since 1992. The ozonizer was changed for a new instrument (EN-SCI KTU3) in the beginning of 2022. This unit has been designed for conditioning of ECC ozonesondes with ozone, and for checking the performance of the sondes prior to balloon release. The new KTU3 allows to measure the ECC cell current, down to 0.001 μA , and uses synthetic air (ozone free air) and a UV lamp to produce high concentrations of ozone. The sensing solution used in the ECC sonde is prepared inside a hood in which ambient air is passed through an active charcoal filter to purify the air.

The volumetric flow of the gas sampling pump of each ECC sonde is individually measured at the Ozonesonde Lab before flight. The pump flow rate of the sonde is measured with a bubble meter at the gas outlet of the sensing cell and is corrected for temperature and humidity. On the day of release, the ECC-6A ozonesonde is checked for proper operation, filled with the sensing solution and the background current measured. The ECC sonde is transported to the Botanic Observatory ozonesonde launching station (30 km distance) where pre-launch tests are performed.

Table 3.4. Santa Cruz Observatory (SCO) measurement programme

Parameter	Start date	Present instrument	Data frequency
In situ reactive gases			
O ₃	Nov 2004	UV Photometry TECO 49-C (replaced in 2025) Thermo Scientific 49i (installed in 2025)	1' 1'
CO	Mar 2006–Jun 2024	Non-dispersive IR abs. Thermo 48C-TL	1'
SO ₂	Mar 2006	UV fluorescence Thermo 43C-TL	1'
NO-NO ₂ -NO _x	Mar 2006–Oct 2019	Chemiluminescence Thermo 42C-TL	1'
O ₃ , NO ₂ , CO, PM _{2.5} , PM ₁₀	Mar 2017–Sept 2021	Väisala Air Quality Sensor AQT420	1'
Ozone and UV (managed by the AEMET's Special Networks Service at the nearby Met Center)			
Column O ₃	Oct 2000	Brewer Mark-II#033	> ~20/day
Spectral UV	Oct 2000	Brewer Mark-II#033	~30'
SO ₂	Oct 2000	Brewer Mark-II#033	~30'
Column aerosols			
AOD and Angstrom at 340, 380, 440, 500, 675, 870, 936, 1020 nm	Jul 2004	CIMEL CE318 sun photometer	~ 15'
Fine/Coarse AOD	Jul 2004	CIMEL CE318 sun photometer	~ 15'
Vertical Backscatter-extinction @523 nm, clouds alt. and thickness	Nov 2005-May 2018	Micro Pulse Lidar MPL-3, SES Inc., USA (co-managed with INTA (www.inta.es))	1'
Vertical Backscatter-extinction @532 nm, clouds alt. and thickness (with depolarization)	May 2018	Micro Pulse Lidar MPL-4B, provided by NASA Goddard Space Flight Center MPLNET	1'
Vertical backscatter-extinction, AOD profiles @910 nm and clouds altitude	Jan 2011-May 2015	Väisala CL-51 Ceilometer	16"
	Jun 2015	Väisala CL-51 Ceilometer	36"
First Aerosol Layer and Mixing Layer Height	Aug 2016	Väisala CL-51 Ceilometer	60'
Radiation			
Global Radiation	Feb 2006	Pyranometer CM-11 Kipp & Zonen	1'
Direct Radiation	Feb 2006	Pyrheliometer EPPLEY	1'
Diffuse Radiation	Feb 2006	Pyranometer CM-11 Kipp & Zonen	1'
Global and Diffuse Radiation	Jun 2021	SPN1 Sunshine Pyranometer	1'

Parameter	Start date	Present instrument	Data frequency
Water vapour			
PWV Total Column and Profiles for 13 layers from sea level up to ~12 km of altitude	Dec 1963	Väisala RS41 launched at Güimar automatic radiosonde station (WMO GRUAN station #60018) (managed by the Meteorological Centre of Santa Cruz de Tenerife)	Daily at 00 and 12 UTC
Precipitable Water Vapour (PWV)	Mar 2003	CIMEL CE318 sun photometer	~ 15'
PWV	July 2008	GPS/GLONASS LEICA GR50 satellite ground-based receiver	15' (ultra-rapid orbits)
PWV (total column) over SCO when cloudless skies. Cloud base heights when cloudy skies over SCO	Jun 2014	1 SIELTEC Sky Temperature Sensor (infrared thermometer prototype)	Every 30" during the complete day
Water vapour isotopologues (δD and $\delta^{18}O$)	May 2019	Picarro L2120-I δD and $\delta^{18}O$ Analyser	Continuous (2")
Meteorology*			
Vertical profiles of T, RH, P, wind direction and speed, from sea level to ~30 km altitude	Dec 1963	RS41+GPS radiosondes launched at Güimar automatic radiosonde station (WMO GRUAN station #60018) (managed by the Meteorological Centre of Santa Cruz de Tenerife)	Daily at 00 and 12 UTC
Temperature	Jan 2002	VAISALA HMP45C	1'
Relative humidity	Jan 2002	VAISALA HMP45C	1'
Wind Direction and speed	Jan 2002	RM YOUNG wind sentry 03002	1'
Pressure	Jan 2002	VAISALA PTB100A	1'
Rainfall	Jan 2002	THIES CLIMA Tipping Bucket	1'
Aerobiology			
Pollens and spores	Oct 2004	Hirst, 7-day recorder VPPS 2000 spore trap (Lanzoni S.r.l.). Analysis performed with a Light microscope, 600 X at the Laboratori d'Anàlisis Palinològiques, Universitat Autònoma de Barcelona	Continuous (1 h resolution; usually daily)

* Meteorological data from Santa Cruz de Tenerife Meteorological Center headquarters, 1 km distant, are also available since 1922.

3.3 Botanic Observatory

The Botanic Observatory (BTO) is located 13 km north of IZO at 114 m a.s.l. in the Botanical Garden of Puerto de la Cruz (Figure 3.11). BTO is hosted by the Canary Institute of Agricultural Research (ICIA) and includes the following facilities:

- Ozone Sounding Monitoring Laboratory: equipped with a Digicora MW41 receiver with Vaisala data acquisition and processing software.
- Launch container: equipped with a Helium supply system used for ozonesonde balloons filling.

In addition to the ozonesonde measurements, there is a fully equipped automatic weather station (temperature, relative humidity, pressure, precipitation, wind speed and direction) and a global irradiance pyranometer. For details of the BTO measurement programme, see Table 3.5.



Figure 3.11. Image of Botanic Observatory (BTO)

Table 3.5. Botanic Observatory (BTO) measurement programme

Parameter	Start date	Present instrument	Data frequency
Reactive gases and ozonesondes			
Vertical profiles of O ₃ , pressure, temperature, humidity, wind direction and speed, from sea level to ~33 km altitude	Nov 1992	ECC-A6+RS41/GPS radiosondes	1/week (Wednesdays)
Radiation			
Global Radiation	May 2011	Pyranometer CM-11 Kipp & Zonen	1'
Column water vapour			
Precipitable Water Vapour	July 2008	GPS/GLONASS TRIMBLE NETR9 satellite ground-based receiver	15' (ultra-rapid orbits)
Meteorology			
Temperature	Oct 2010	VAISALA F1730001	1'
Relative humidity	Oct 2010	VAISALA F1730001	1'
Wind direction and speed	Oct 2010	VAISALA WMT702	1'
Pressure	Oct 2010	VAISALA PMT16A	1'
Rainfall	Oct 2010	VAISALA F21301	1'

3.4 Teide Peak Observatory

The Teide Peak Observatory (TPO) is located at 3 555 m a.s.l. at the [Teide Cable Car](#) terminal in the Teide National Park (Figure 3.12). TPO was established as a satellite station of IZO primarily for radiation and aerosol observations at very high altitude. TPO station, together with Jungfraujoch (3 454 m a.s.l.) in Switzerland, are the highest permanent radiation observatories in Europe.

This measurement site provides radiation and aerosol information under extremely pristine conditions and in conjunction with measurements at SCO and IZO allows us to study the variation of global radiation, UV-B and Aerosol Optical Depth (AOD) from sea level to 3 555 m a.s.l. In addition to radiation and aerosol measurements, there is a meteorological station and a water vapour isotopologues analyser. Full details of the measurement programme are given in Table 3.6.



Figure 3.12. Measurements at Teide Peak Observatory (TPO)

Table 3.6. Teide Peak Observatory (TPO) measurement programme

Parameter	Start date	Present instrument	Data frequency
Column aerosols			
AOD and Angstrom at 340, 380, 440, 500, 675, 870, 936 and 1020 nm	Jun 1997	CIMEL CE318 sun photometer (Co-managed with the University of Valladolid Atmospheric Optics Group)	~ 15' (during Apr-Oct)
Fine/Coarse AOD Fine mode fraction	Jun 1997	CIMEL CE318 sun photometer (Co-managed with the University of Valladolid Atmospheric Optics Group)	~ 15' (during Apr-Oct)
Radiation			
Global Radiation	Jul 2012	Pyranometer CM-11 Kipp & Zonen	1'
UVB Radiation	Jul 2012	Pyranometer Yankee YES UVB-1	1'
Global and diffuse radiation	Sep 2019	SPN1 Sunshine Pyranometer	1'
Water vapour			
Water vapour isotopologues (δD and $\delta^{18}O$)	June 2013	Picarro L2120-I δD and $\delta^{18}O$ analyser	2"
Precipitable Water Vapour	Feb 2020	GPS/GLONASS TRIMBLE NETR9 satellite ground-based receiver	15' (ultra-rapid orbits)
Meteorology			
Wind direction and speed	Oct 2011	THIES CLIMA Sonic 2D	1'
Temperature	Aug 2012	VAISALA HMP45C	1'
Relative humidity	Aug 2012	VAISALA HMP45C	1'
Pressure	Aug 2012	VAISALA PTB100A	1'

3.5 Computing facilities and communications

The computing facilities and communications form an integral component of all measurement programmes and activities in IARC. In the IARC headquarters there is a temperature-controlled room hosting server computers devoted to different automatic and continuous tasks (Network-Attached Storage (NAS), numerical modelling, spectra inversion, etc.) for the research groups.

A EUMETCast (European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Broadcast System for Environmental Data) reception station is available at SCO. It consists of a multi-service dissemination system based on standard Digital Video Broadcast (DVB) technology. Most of the satellite information is received via this system (see section 13 for more details).

Data communications were notably improved at the IARC in 2020 by its incorporation into the Advanced Communications Network for Spanish Research (IRIS NOVA network).

RedIRIS-NOVA is the high-capacity optical network of RedIRIS, which connects the regional networks of all the autonomous regions and the main research centers in Spain with the rest of international academic networks, especially the Portuguese academic and research networks and the European research network [GÉANT](#). Fibre optics makes it possible to easily deploy 10Gbps or 40Gbps circuits, and soon 100Gbps, at a much lower cost than the network model based on capacity rental. RedIRIS-NOVA connects more than 50 Points of Presence with each other, making up a mesh network on which the RedIRIS IP Trunk Network and the regional networks are deployed. This network for research allows collaboration between researchers and the deployment of next-generation services.

IARC is the only AEMET unit that has IRIS NOVA Network communications due to its status as a research center.

IARC currently has two data networks, the AEMET network, with access from the central headquarters in Santa Cruz, and linked to the Izaña Observatory by a microwave link (Figure 3.13), and the IRIS NOVA Network with a double entry. The IARC offices in Santa Cruz are linked to the IRIS NOVA network through a fibre optic connection to the IGN node located in the same building, and to the Izaña Observatory through a fibre optic connection, approximately 1 km long, with the IRIS NOVA node at the Teide Observatory of the Instituto de Astrofísica de Canarias (IAC) (Institute of Astrophysics of the Canary Islands).

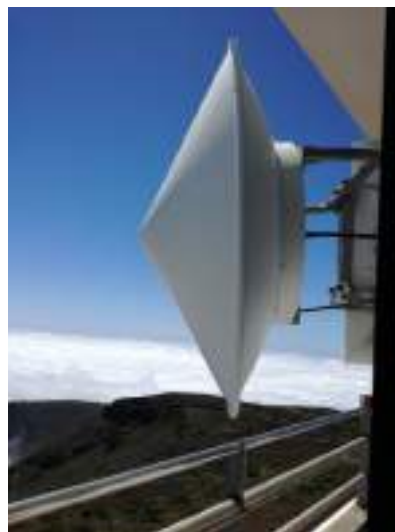


Figure 3.13. Microwave link antenna between Santa Cruz (SCO) and the Izaña Observatory (IZO) of the AEMET data network

3.6 Staff

Activities universal to all measurement programmes such as operation and maintenance of IARC facilities, equipment, instrumentation, communications and computing facilities are made by the following staff:

Ramón Ramos (AEMET; Head of Scientific instrumentation and infrastructures)

Enrique Reyes (AEMET; IT development specialist)

Antonio Cruz (AEMET; IT specialist)

Rocío López (AEMET; IT specialist)

Concepción Bayo (AEMET; Meteorological Observer)

Virgilio Carreño (AEMET; Meteorological Observer)

Cándida Hernández (AEMET; Meteorological Observer)

Belén Querol (AEMET; Meteorological Observer)

Irene Tovar (AEMET; Meteorological Observer)

4 Greenhouse gases and carbon cycle

4.1 Main scientific goals

The Greenhouse Gases and Carbon Cycle programme conducted by IARC supports two independent in situ greenhouse gases (GHG) measurement networks: the WMO GAW and ICOS. The ICOS station was awarded the official ICOS label on 23 May 2023, and its instruments have been providing GHG data to the ICOS network since November 2022 (see section 18 for more details). The main goal of the WMO GAW station is to carry out highly accurate continuous in situ measurements of long-lived GHGs in the atmosphere at IZO. Additional goals are: 1) to study with precision the long-term evolution of the GHGs in the atmosphere, as well as their daily, seasonal and inter-annual variability; 2) To incorporate continuously technical instrumental improvements and new data evaluation and calibration methodologies in order to reduce uncertainty and improve the accuracy of the GHG measurements; 3) to carry out research to study the processes that control the variability and long-term changes of the GHGs in the atmosphere; and 4) to contribute to international research and its documentation via recommendations and guidelines.

4.2 Measurement programme

Table 4.1 gives details of the record of in situ analysers (owned by AEMET) at IZO used for measuring atmospheric GHG for the WMO GAW network, as well as information on the measurement schemes. Further information can be found in the most recent WMO GAW scientific audit reports: Zellweger et al. (2020 and 2024) and in Gomez-Pelaez et al. (2019). Yearly WMO GHG bulletins are also available, which include the IZO data, for example see WMO (2024, 2025).



Figure 4.1. Front and rear view of the Los Gatos Research (LGR) CO/N₂O analyser at Izaña Observatory

Additionally, weekly discrete flask samples have been collected at IZO since 1991 for the NOAA-ESRL-GML Carbon Cycle Greenhouse Gases Group (CCGG) [Cooperative Air Sampling Network](#).



Figure 4.2. IZO Gas Chromatograph measurement system for N₂O and SF₆

The air inside the flasks has been analysed for the following gas species mole fractions: 1) CO₂, CH₄, CO, and H₂ since 1991; N₂O and SF₆ since 1997 (NOAA-ESRL-GML-CCGG); 2) Isotopic ratios ¹³C/¹²C and ¹⁸O/¹⁶O in carbon dioxide since 1991 at the Institute of Arctic and Alpine Research ([INSTAAR](#)) Stable Isotope Lab; 3) Methyl chloride, benzene, toluene, ethane, ethene, propane, propene, i-butane, n-butane, i-pentane, n-pentane, n-hexane and isoprene were measured from 2006 to 2018 at INSTAAR.

Two-week integrated samples of atmospheric CO₂ have also been collected for Heidelberg University ([Institute of Environmental Physics](#), Carbon Cycle Group) since 1984 to measure the radiocarbon (¹⁴C) isotopic ratio in carbon dioxide. These data are part of a cooperative CO₂ background air sampling network for high-precision ¹⁴C analysis in the Heidelberg Radiocarbon laboratory, and are utilized to study global and hemispheric trends of Δ¹⁴C-CO₂ which provide constraints for ¹⁴C-free fossil CO₂ emission changes on both global and regional scales (Levin et al., 2022). The data have also been utilized in various carbon cycle modelling activities (e.g. Graven et al., 2017).

Table 4.1. Atmospheric greenhouse gases measured in situ at IZO, together with the measurement methods and analysers used.

Gases	Start date	Measurement method	Model	Ambient air measurement period	Reference gas/es calibration frequency	Status
CO ₂	1984	NDIR	Siemens Ultramat 3	10 s	Biweekly using 4 S	Retired
CO ₂	2007	NDIR	Licor 7000	1 s	Biweekly using 4 S	Retired
CO ₂	2008	NDIR	Licor 6252	1 s	Biweekly using 4 S	Retired
CH ₄	1984	GC-FID	Dani 3800	30 min	Biweekly using 2 S	Retired
CH ₄	2007	GC-FID	Varian 3800	15 min	Biweekly using 2 S	Retired
N ₂ O, SF ₆	2007	GC-ECD	Varian 3800	15 min	Biweekly using 5 S	Retired
CO	2008	GC-RGD	Trace Analytical RGA-3	20 min	Biweekly using 5 S	Retired
CO ₂ , CH ₄ , CO	2015	CRDS	Picarro G2401	2 s	Monthly using 4 S	Active
N ₂ O, CO	2018	OA-ICOS	LGR N2OCM-913	4 s	Monthly using 4 S	Active
N ₂ O, SF ₆	2021	GC-ECD	Agilent 8890	15 min	Monthly using 4 S	Active

Nondispersive Infrared sensor (NDIR), Laboratory Standard (S), Gas Chromatography (GC), Flame Ionization Detector (FID), Electron Capture Detector (ECD), Reduction Gas Analyser (RGD), Cavity Ring-Down Spectroscopy (CRDS), Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS)

4.3 Summary of remarkable activities during the period 2023–2024

This programme has continued performing continuous high-quality GHG measurements and annually submitting the data to the GAW World Data Centre for Greenhouse Gases (WDCGG), where data are publicly available, as well as included in the data summaries (e.g. WDCGG, 2024, 2025).

Figure 4.3 shows the time series of daily average atmospheric CO₂ mole fraction, measured at IZO since 1984 using various spectroscopic techniques. The CH₄, N₂O, SF₆ and CO time series at IZO are shown in Figure 4.4. All data are used for analysis and investigation of the carbon cycle and understanding of the role of anthropogenic and natural factors that control GHG variability.

The curve fitting methods applied to the IZO time series are those used by NOAA GML (Thoning et al., 1989). Only nighttime data are used for daily averages due to cleaner air during this period caused by the nighttime katabatic wind pattern at Izaña. The visible annual oscillation of the CO₂ data reflects the seasonal cycle of continental vegetation in the northern hemisphere. CO₂ concentrations peak in spring, after the winter accumulation period when photosynthetic activity is low, and then decrease during the boreal summer

as photosynthesis intensifies. Due to its public interest, the IARC published a news item about the CO₂ maximum each year, in 2023 and 2024.

The trend line is derived by removing this seasonal cycle. While the seasonal cycle is relatively stable and of natural origin, the trend line shows a clear increase attributable to anthropogenic emissions. The figure reveals a persistent annual increase in CO₂ since the 1980s, with an average rate of +2 ppm per year. This growth rate has tended to accelerate, reaching an average of +2.4 ppm per year over the past decade, but the acceleration is not constant.

Between 2022 and 2023, the annual CO₂ average at Izaña rose by 2.3 ppm, while in 2024 it increased by 3.4 ppm. These year-to-year variations in the CO₂ growth rate are strongly influenced by the El Niño–Southern Oscillation climate phenomenon. During its warm phase, El Niño, atmospheric CO₂ concentrations tend to increase more rapidly, while the cold phase, La Niña, is typically associated with more moderate growth rates. In May 2023, a transition occurred from a prolonged La Niña episode, lasting nearly three years and associated with relatively moderate CO₂ growth, towards an El Niño phase. This shift may explain the accelerated growth observed after 2023 at IZO.

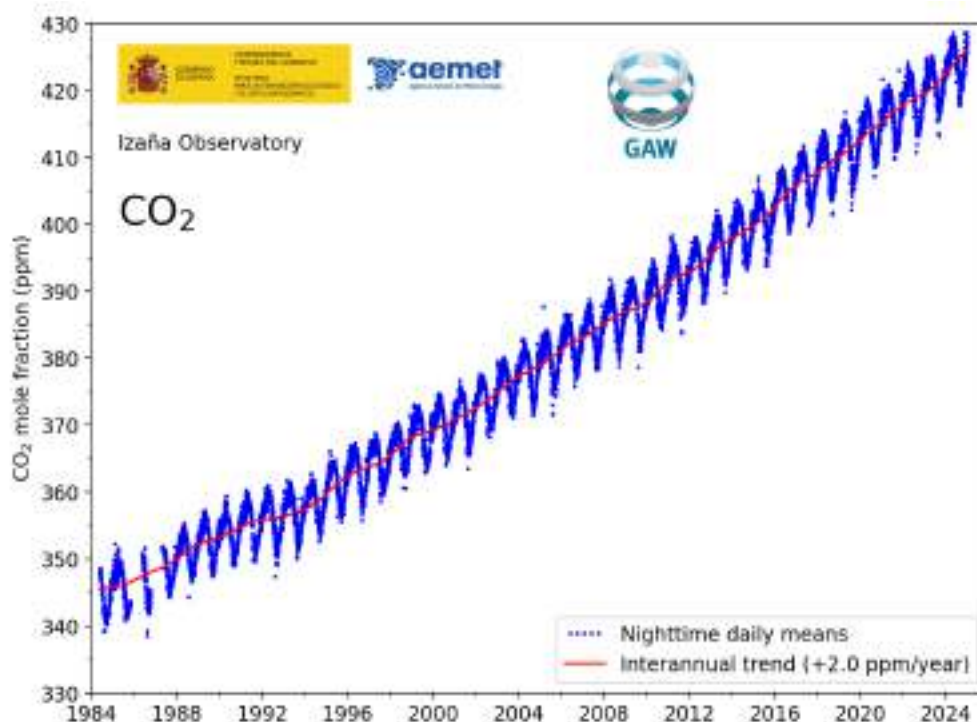


Figure 4.3. Izaña Observatory CO₂ time series (1984–2024)

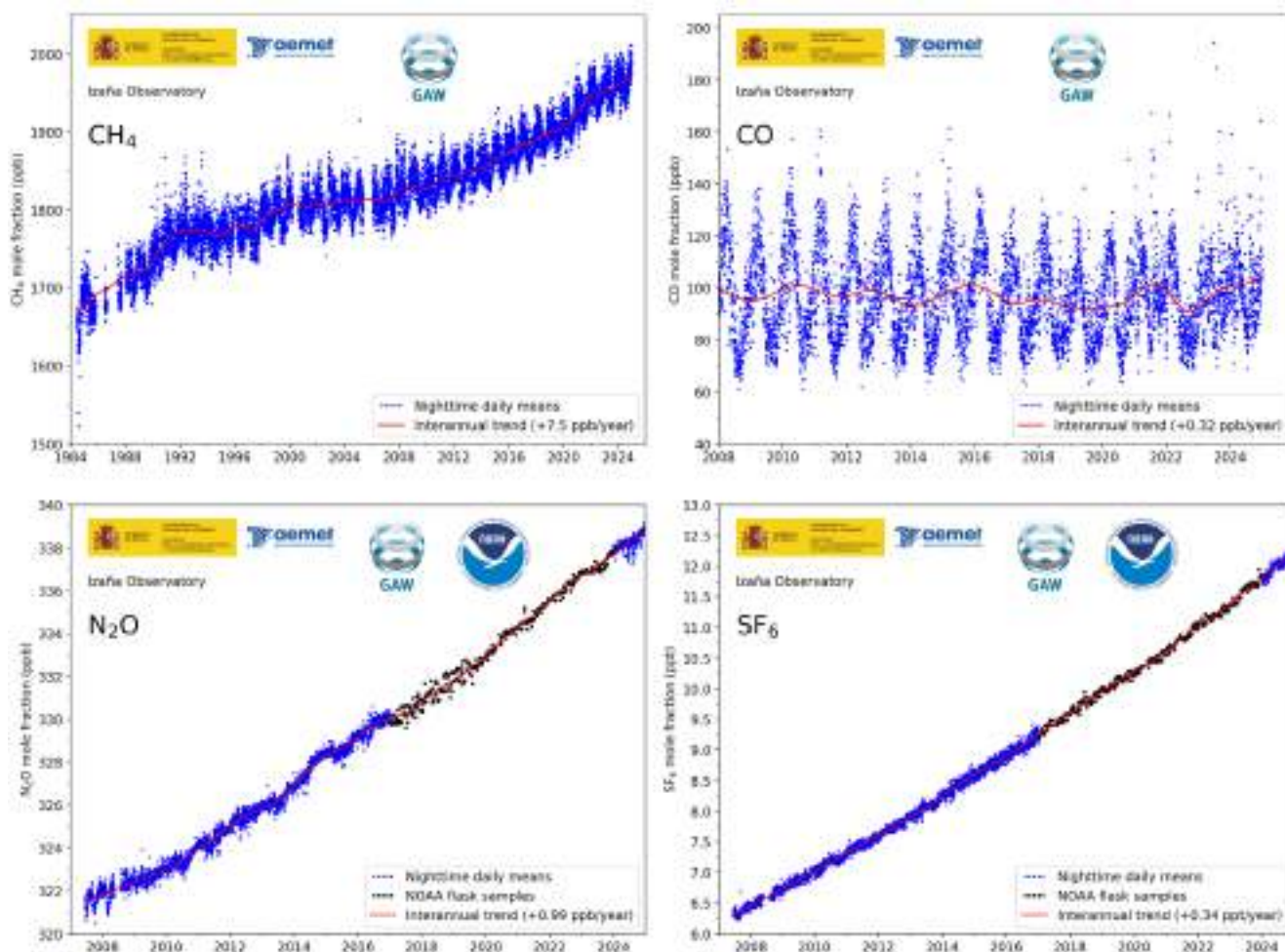


Figure 4.4. CH₄, CO, N₂O and SF₆ IZO time series. N₂O and SF₆ measurements by IZO analysers from 2017 to 2023 are temporarily unavailable due to technical problems and system updates. Data shown in these figures during this time interval come from the NOAA Cooperative Air Sampling Network and are shown as black points.

In line with global observations, an increase in atmospheric CH₄ has been observed at Izaña since 2007, after a period of stability between 1999 and 2006. The causes of this recent trend are still being investigated. Its coincidence with a decline in the proportion of ¹³C in atmospheric CH₄ indicates that it originates from microbial emissions, but the relative contribution of anthropogenic and natural sources is unclear (WMO, 2024).

IARC has also continued contributing to the Observation Package (ObsPack) Data Products led by NOAA GML CCGG (e.g. Schuldt et al., 2024a, 2024b). ICOS ERIC has developed similar products, the European Obspack compilations of atmospheric carbon dioxide, methane and nitrous oxide data from ICOS and non-ICOS European stations (ICOS RI et al., 2024a, 2024b, 2024c). IARC has contributed as well to this data compilation by providing its long-term CO₂, CH₄ and N₂O data series.

4.3.1 System and performance audit by WCC-Empa

The 8th system and performance audit by the [World Calibration Centre \(WCC-Empa\) for Surface Ozone, Carbon Monoxide, Methane, Carbon Dioxide and Nitrous Oxide](#) at the IZO was conducted from 5–9 June 2023 in accordance with the WMO GAW quality assurance standards.

CO₂, CH₄, N₂O and CO analyzers and also surface ozone analyzers (see section 5) at IZO were repeatedly tested, measuring randomized levels of gas concentrations from WCC-Empa travelling standard tanks. The audit included parallel measurements of CO₂, CH₄ and CO with a WCC-Empa travelling Picarro G2401, running from 6 June through to 3 July 2023. Both the GAW and ICOS Picarro G2401 instruments were compared to the WCC-Empa travelling Picarro. As part of the system audit, data within the scope of WCC-Empa available at WDCGG was reviewed.

The 8th system and performance audit concluded that most of the measurements evaluated were of high data quality and met the WMO GAW network compatibility or extended compatibility goals (WMO, 2020) in the relevant amount fraction range. The parallel measurements indicated a small leak in the inlet system which was repaired. Figure 4.6 summarizes the ranking of the Izaña station. Adequacy ranges from 0 (inadequate) through to 5 (adequate). All primary instruments proved full adequacy. Detailed information can be found in Zellweger et al. (2024).

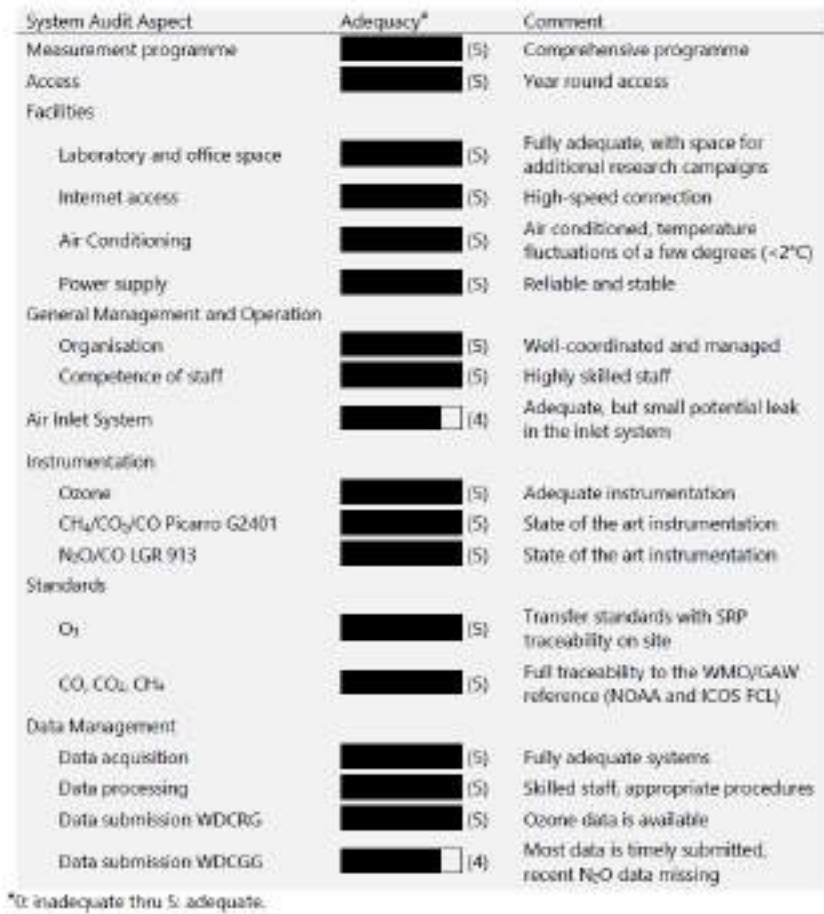


Figure 4.5. Summary ranking of the Izaña GAW station. Reprinted from Zellweger et al. (2024).

4.3.2 Impact of the August 2023 wildfire in Tenerife

In August 2023, a massive wildfire devastated a large forested area in close proximity to IZO. The event released substantial amounts of gases from biomass combustion, disrupting the typical atmospheric background conditions at Izaña. Higher than usual CO₂ and CH₄ values were measured. CO concentrations were the most impacted, reaching peaks above 10 000 ppb, about 100 times higher than typical values. In addition to GHG, many other measurement programmes by IARC were affected. For more details see section 24.

4.3.3 FETCH₄ project

In 2024, IZO began collaborating on the Fate, Emissions, and Transport of CH₄ (FETCH₄) project, an international collaboration of scientists focused on improving knowledge of the global methane cycle in the past, present and future. Part of the project involves measuring ¹⁴C in CO and CH₄ at a global network of clean-air sites (currently ten stations including Izaña). For this purpose, a system has been installed at IZO for sampling atmospheric air in stainless steel bottles (Figure 4.6), which are then sent to the Department of Earth and Environmental Sciences, University of Rochester (USA) for analysis.



Figure 4.6. FETCH₄ project sampling system at IZO.

Sampling began in April 2024 and is planned to continue until April 2028. During the first year of sampling, from April 2024 to April 2025, samples were taken biweekly to measure ¹⁴CO, which serves as a proxy for the OH radical, the primary sink of CH₄. During the following year, until April 2026, samples will be taken to measure ¹⁴CH₄, which is a good indicator of the fossil fraction of CH₄ emissions.

4.4 References

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5 Reactive gases and ozonesondes

5.1 Main scientific goals

The main scientific objectives of this programme are:

- Long-term high-quality observations and analysis of tropospheric O₃ in both the free troposphere (FT) and the Marine Boundary Layer (MBL).
- Long-term high-quality observations of reactive gases (CO, NO_x, SO₂) in the FT and in the MBL to support other measurement programmes at IARC.
- Air quality studies in urban and background conditions.
- Analysis of long-range transport of pollution (e.g. transport of anthropogenic and wildfire pollution from North America).
- Study of the impact of mineral dust and water vapour on tropospheric O₃.
- Characterization of the vertical profile of ozone in subtropical latitudes.
- Analysis of Stratosphere-Troposphere Exchange processes.

5.2 Measurement programme

The measurement programme of reactive gases (O₃, CO, NO_x and SO₂) is developed within the framework of the WMO GAW network and includes long-term observations at IZO (Figure 5.1), SCO and BTO (Tables 3.2, 3.4 and 3.5) and ozonesonde vertical profiles (now at BTO). In addition, IARC (through AEMET and INTA) has a long-term collaboration with the Argentinian Meteorological Service (SMN) and in the framework of this collaboration, ozone vertical profiles are measured at WMO GAW Global station Ushuaia (Argentina). Surface O₃ measurements started in IZO in 1987, CO in 2004, and SO₂ and NO_x measurements were implemented in 2006. At SCO, surface O₃ measurements started in 2001, and CO, SO₂ and NO_x programmes were also implemented in 2006 (see González, 2012, for more details).

5.2.1 New instrumentation

In recent years a greater investment has been made in the renewal of most of the equipment and the improvement of the already established measurement programme. The acquisition of instrumentation is motivated by the following reasons:

- The instrumentation that is in operation 24/7, after more than 15 years of operation, becomes obsolete, and the necessary spare parts to ensure its maintenance are no longer available on the market.
- GAW standards evolve over time, for example there can be changes in the precision with which a parameter must be obtained, changes in the detection limit, or improvements in the equipment verification/calibration protocols to ensure the quality of the measurements.

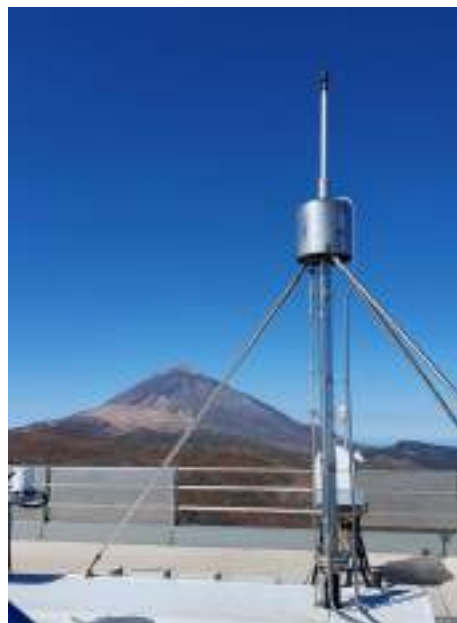


Figure 5.1. Sample inlet for reactive gas measurements located on top of the Izaña Observatory technical tower

Two ozone analyzers and an ozone primary standard were acquired in 2022 upon recommendation of the WCC-Empa 2019 audit, which noted that the C-Series instruments (TEI 49C) were reaching the end of their lifetime and these instruments should be replaced within the next two years. Both the new analyzers and the primary standard are from the new Thermo Fisher Scientific 49i series and were installed in December 2022 and audited in 2023.

In order to ensure continuity to the measurement programme at IZO, to improve the quality of measurements and increase precision, two new SO₂ analyzers, a zero air generator and a multigas calibrator were acquired, as part of the Reactive Gases programme in 2022. The new SO₂ analyzers are from the Thermo Fisher Scientific new 43i series, while the zero air generator and the multigas calibrator are from the TELEDYNE T series. The new equipment was installed in May 2023. CO is measured with high accuracy at IZO by both the Greenhouse Gases and Carbon Cycle Programme and as an ICOS atmospheric station (see sections 4 and 18), therefore CO is not currently measured at IZO within the Reactive Gases programme. CO measurements were performed at SCO from Oct 2013 – June 2024.

5.2.2 Surface ozone

The surface ozone measurement programme started, as previously mentioned, in IZO in 1987. The almost uninterrupted 38-year time series of surface O₃ at IZO is shown in Figure 5.2.

At present, surface ozone at IZO is measured with two ozone analyzers (main and auxiliary). The auxiliary analyzer is needed to fill any gaps that occur, for example while calibrating the main analyzer or in the daily zero/span check.

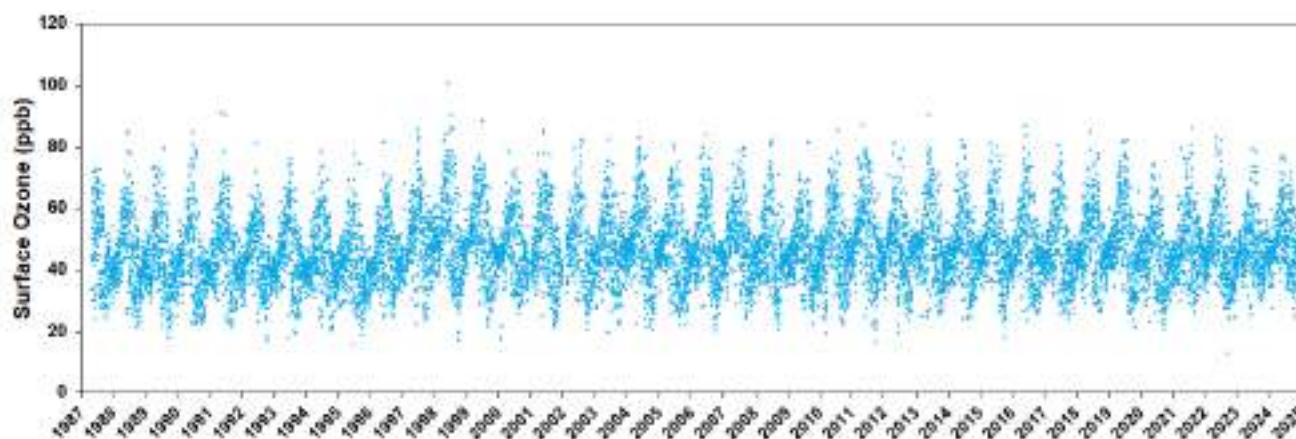


Figure 5.2. Long-term daily (night period) surface O₃ at IZO (1987–2024)

There are also two additional (reserve) analyzers measuring simultaneously which are utilized in the case of the two operational analyzers having a problem. All analyzers determine the ozone mixing ratio by UV absorption.

The main and auxiliary analyzers (and one of the reserve analyzers) are from the new series of Thermo Scientific 49i analyzers. The other reserve analyzer belongs to the old series of Thermo Scientific 49C analyzers, it is currently maintained to compare measurements. All analyzers are compared every three months with the IARC primary ozone standard (Thermo Scientific 49i), which has previously been calibrated against a reference equipment (SRP#15) from the [WCC-Empa](#) to check if there is any drift in the instruments (Figure 5.3). The error should be <1% to ensure that the analyzer has not changed and therefore maintains the WCC-Empa calibration.



Figure 5.3. Ozone analysers (two TEI 49i and TEI 49C in the rack) at Izaña Observatory: comparison of the analysers with primary ozone standard (TEI 49i-PS)

In addition, all analyzers and their installation are audited every 2–3 years by WCC-Empa to check if the calibration has been maintained over time. This redundancy of equipment, together with the rigorous verification and calibration protocols, are necessary to maintain the quality

and continuity of ozone measurements required by the WMO GAW network.

The surface O₃ programme at IZO has been audited by the WCC-Empa in 1996, 1998, 2000, 2004, 2009, 2013, 2019 and 2023. All Empa's audit reports are available [here](#). During the most recent audit (June 2023) the three IZO analysers (TEI 49i #1153030026, TEI 49i #12218618528, TEI 49i #12218618529) and the primary ozone standard (TEI 49i-PS CM 22277105) were compared against the WCC-Empa travelling standard (TS) with traceability to a Standard Reference Photometer (SRP), (see Zellweger et al., 2024 for more details). Good agreement between the WCC-Empa travelling instrument and the IZO calibrator was found, which confirms the validity of the last calibration made at Empa in 2019. The main and auxiliary ozone analysers were all in agreement within 1 ppb at the relevant mole fraction range from 0–100 ppb ozone, which confirms that the quality control and maintenances made periodically in IZO are appropriate.

However, the reserve analyser TEI 49i #12218618528, showed significantly more noise compared to the other analysers. The analyser was not performing well and was recommended to be returned to the manufacturer for inspection and repair. Until the reason is identified and repaired, the former ozone analyser from the 49C series TEI 49C#72491-371 remains in use as reserve to ensure consistent datasets.

5.2.3 Nitrogen oxides: CraNOx II analyzer

NO_x and SO₂ instruments at IZO usually operate below the detection limit (50 ppt) during the night-time period when we can ensure background conditions. However, these measurements are quite useful for studies of local or regional pollution during daytime, when concentrations are modulated by valley-mountain breeze, and help to understand the impact of regional pollution and of long-range transport of pollution on the background atmosphere. For example, high concentrations of SO₂ were measured in IZO at the end of 2021, during episodes of transport of the

volcanic plume associated with the eruption on the island of La Palma.

The CraNOx analyser is a high-performance device based on a chemiluminescence detection principle (O₃-CLD, Ozone Chemiluminescence Detection), which detects NO directly and NO₂ after converting it into NO with a photolytic converter (PLC, Photolytic Converter). This NO measurement technique is recommended by WMO GAW at its NO_x measurement stations (WMO, 2011 and 2017) given its reliability, linearity and proven reproducibility in a wide range of conditions. The technique consists of enriching the air sample, whose concentration of NO is to be studied, with O₃, which produces a set of reactions resulting in the generation of NO₂ and release of radiation proportional to the initial concentration of NO. This radiation is measured using a photomultiplier tube (PMT) with a signal proportional to NO in the initial sample.



Figure 5.4. EcoPhysics CraNOx II analyser at the Izaña Observatory

In order to obtain the concentration of NO₂ in the sample, all the NO₂ must first be converted into NO, and then subsequently, the same direct NO measurement process is repeated with the O₃-CLD detector. There are several methods to produce NO₂ from NO, e.g. using a photolytic converter or a heated molybdenum converter. At WMO GAW stations, photolytic conversion is recommended (WMO, 2011) since it is a more selective method, avoiding the overestimation of NO₂, by preventing other nitrogen compounds in the air from being transformed into NO during the process. The air sample is irradiated in a photolytic cell and a fraction of the NO₂ is converted into NO, depending on an efficiency factor related to the intensity and type of lamp, e.g. mercury or xenon arc lamp or UV-LEDs.

The CraNOx II installed at IZO complies with the WMO GAW recommendations in terms of measurement technique, precision and detection limit for the measurement of NO and NO₂ under background conditions (WMO, 2011 and 2017). It is a compact instrument consisting of a double O₃-CLD detector for the simultaneous measurement of NO and NO₂, with a pre-chamber, to minimize interference due to the reaction of

ozone with other compounds present in the air, and uses a photolytic converter with a metal halide lamp (200W). For the ozone required in the O₃-CLD chemiluminescence detector, the analyser has an internal ozone generator. This ozone is generated by applying an electrical discharge to a constant flow of oxygen (O₂), taken from a bottle, breaking the O₂ molecules down into more unstable atoms, which recombine to form ozone. Thanks to this design, the analyser allows the measurement of NO and NO₂ mole fractions < 25 ppt, with great stability and precision (Fig 5.5).

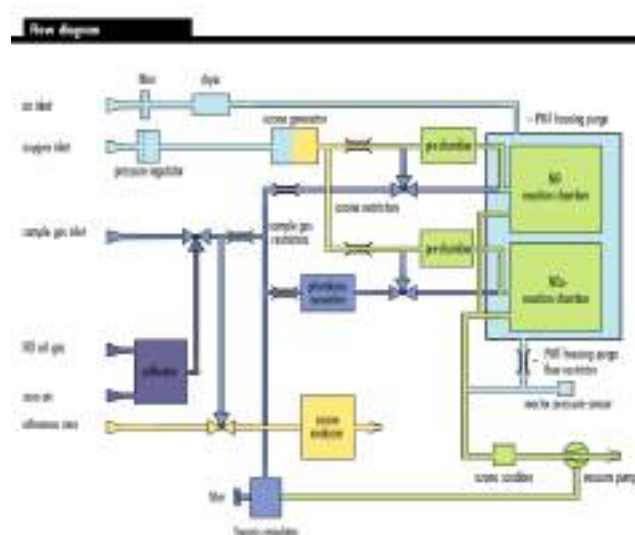


Figure 5.5. Flow diagram of the EcoPhysics CraNOx II (<https://www.ecophysics.com/environmental/supreme-line/cranox-ii/>)

The CraNOx II also incorporates an internal calibration module that allows the automatic verification/calibration of the analyser: NO-zero (synthetic air with zero NO mole fraction), NO-span (measurement of a known dilute amount of NO) and efficiency of the PLC converter. The high degree of instrument automation always allows control of both the quality of the measurement and of the equipment itself. The CraNOx II is completed with an internal O₃ analyzer, by UV photometric absorption, which measures O₃ mole fraction of the air sample simultaneously with the NO and NO₂ measurements, which will allow the detailed study of how the chemical reactions that connect these three compounds occur under background conditions.

5.2.4 Sulfur dioxide: Thermo Fisher analyzer 43i

The Thermo Fisher Scientific Model 43i utilizes pulsed fluorescence technology to measure SO₂. It operates on the principle that SO₂ molecules absorb ultraviolet (UV) light and become excited at one wavelength, then decay to a lower energy state emitting UV light at a different wavelength (Thermo Fisher Scientific, 2015).

Once the sample enters the fluorescence chamber, pulsating UV light excites the SO₂ molecules. The condensing lens focuses the pulsating UV light into the mirror assembly. The

mirror assembly contains four selective mirrors that reflect only the wavelengths which excite SO₂ molecules. As the excited SO₂ molecules decay to lower energy states they emit UV light that is proportional to the SO₂ concentration. The bandpass filter allows only the wavelengths emitted by the excited SO₂ molecules to reach the photomultiplier tube (PMT). The PMT detects the UV light emission from the decaying SO₂ molecules. The photodetector, located at the back of the fluorescence chamber, continuously monitors the pulsating UV light source and is connected to a circuit that compensates for fluctuations in the UV light.

As stated earlier, SO₂ instruments at IZO usually operate below the detection limit (50 ppt) during the night-time period when we can ensure background conditions. However, during specific events, SO₂ concentrations can increase, for example, high concentrations of SO₂ were measured in IZO during episodes of transport of the 2021 La Palma volcanic eruption (see Milford et al. 2023 for details) and increased SO₂ concentrations were also registered during the Tenerife wildfires in August 2023 (see section 24 for more details).

5.2.5 Ozone soundings

The geographical location of the island of Tenerife, at the subtropical limit of the North Atlantic, makes the vertical ozone profiles measured in this region exceptionally valuable, not only because the island is frequently located at the northern limit of the Hadley Cell, under the descending branch in which a subsidence regime prevails in the free troposphere, but also due to the scarcity of stations in this region. This makes Tenerife a privileged place for studying the evolution of tropospheric-stratospheric ozone and for analysing the influence of the subtropical jet stream (STJ) on the stratosphere-troposphere exchange.

With the support of the WMO GAW Programme, the IARC Ozone Sounding Programme began in November 1992. The first ozonesonde was launched on 4 November 1992 from Santa Cruz. After that first ozone sounding, a weekly launch routine was established, every Wednesday, which has continued uninterrupted to this day. The frequency of ozone soundings is significantly increased during intensive campaigns. In 2011 the launch site was changed to the BTO (Figure 5.6). The launch equipment and stations used during these 33 years are listed in Table 5.1.

The ozone soundings programme uses ECC sondes along with a helium balloon (TOTEX TA 1200) to obtain the ozone profiles from the ground to the burst level (generally between 30 and 35 km) with a resolution of about 10 metres. A constant mixing ratio above burst level is assumed for the determination of the residual ozone if an altitude equivalent to 17 hPa has been reached (Väisälä Software).

Ozonesondes are checked before launch with a Ground Test with Ozonizer/Test Unit EN-SCI KTU3 (see section 3.2.1).

The ECC-ozone sensor used is an electrochemical cell consisting of two half cells, made of Teflon, which serve as cathode and anode chambers, respectively. Both half cells contain platinum mesh electrodes. They are immersed in a KI-solution, always with the same sensing solution type (SST1.0: 1.0% KI & full pH-buffer). The two chambers are linked together by an ion bridge in order to provide an ion pathway. Each ozone molecule reacts with the KI releasing 2 electrons and the current generated between the two cells is measured to provide the ozone content in the sampled air.

The preparation and conditioning of the ozonesondes follows the protocol established in “Assessment of Standard Operating Procedures for Ozonesondes (ASOPOS)” (Smit, 2013) and ASOPOS 2.0 (WMO, 2021).



Figure 5.6. Preparation and launch of the ozonesonde from BTO

Table 5.1. Ozonesonde programme equipment used during different time periods and launch stations since November 1992

Instrument manufacturer and model	Frequency	Period/Launching station
OZONESONDES: Nov 1992 – Sep 1997: Science Pump Corp. Model ECC-5A Sep 1997 – present: Science Pump Corp. Model ECC-6A GROUND EQUIPMENT: Nov 1992 – Oct 2010: VAISALA DigiCora MW11 Rawinsonde Oct 2010 – Feb 2018: VAISALA DigiCora MW31 Mar 2018 – present: VAISALA DigiCora MW41 RADIOSONDES: Nov 1992 – Oct 1997: VAISALA RS80-15NE (Omega wind data) Oct 1997 – Sep 2006: VAISALA RS80-15GE (GPS Wind data) Sep 2006–Dec 2018: VAISALA RS92-SGP (GPS Wind data) Dec 2018–present: VAISALA RS41-SGP (GPS Wind data)	1/week (Wed)	Nov 1992 – Oct 2010: From Santa Cruz Station (28.46°N, 16.26°W; 36 m a.s.l.) Oct 2010 – Feb 2011: From Santa Cruz/ BTO (In alternate launches) Feb 2011 – present: From BTO Station (28.41°N, 16.53°W; 114 m a.s.l.)

5.3 Summary of remarkable results during the period 2023–2024

5.3.1 Software for the evaluation of reactive gases data (O₃, NO_x, SO₂, CO)

The software for reactive gases data evaluation was developed during 2015 and 2016, and is improved each year. This software makes it possible to carry out the evaluation and processing of the data of the reactive gases programme (surface O₃, NO_x, SO₂ and CO). The software works in a web environment that facilitates consultations with the database and data processing.

The raw data of the TEI analysers are acquired by a CR1000 Campbell datalogger, which interrogates each instrument every minute. The data are automatically stored in a database; zeros, span and calibration coefficients of the analysers are also recorded. NO, NO₂ and NO_x data from the CraNOx-II are also stored in the same database. The software uses all this information to process data automatically and it allows us to choose the desired component to evaluate and visualize its record along with that of another component and/or together with the meteorological information (temperature, relative humidity, pressure and wind). The software has an option to download the processed data in the [EBAS format](#).

5.3.2 World Data Center for Reactive Gases (WDCRG)

The GAW World Data Center for Reactive Gases ([WDCRG](#)) is the data repository and archive for reactive gases and is managed by the Norwegian Institute for Air Research (NILU). The WDCRG was established on 1 January 2016 and took over the responsibility for RG data archiving from the Japan Meteorological Agency, which continues to host the WDCGG. Some of the reactive gases hosted at WDCRG are SO₂, oxidized nitrogen species, surface O₃ and VOCs. We developed the necessary software to edit surface O₃ data in the EBAS NASA-Ames format required by the WDCRG. Hourly surface O₃ data from 2014 to 2024 have been submitted directly to WDCRG (<http://ebas.nilu.no>) and O₃ data from 1987 to 2013 have been transferred from the WDCGG to WDCRG in the EBAS format. Monthly average values of surface O₃ data for 1987 to 2024 at IZO are shown in Figure 5.7.

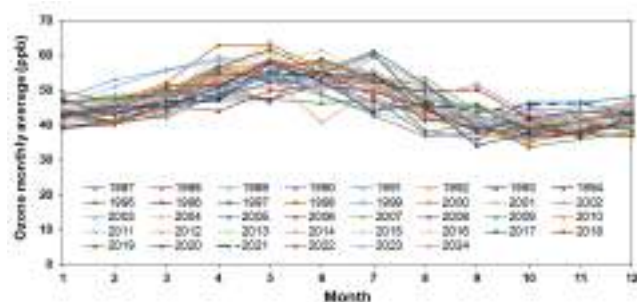


Figure 5.7. Surface ozone mean seasonal cycle from 1987 to 2024 at IZO

5.3.3 Network for the Detection of Atmospheric Composition Change

In 2004, IARC joined NDACC and began routinely archiving the ozonesonde data into the NDACC database; in addition, all the ozonesonde records since 1995 were uploaded to the NDACC at this time. Ozonesonde data archived in the NDACC database must meet certain quality criteria. Currently 91% of the ozone soundings performed in the period 1995–2024 are available in the NDACC database (Figure 5.8). Ozonesonde data from the early period (November 1992–1994) need to be reprocessed and reanalysed carefully.

All NDACC data are available at <https://www-air.larc.nasa.gov/missions/ndacc/data.html> or through search tools available on the [NDACC](#) website. At present, NDACC is working on the homogenization of the ozone soundings of all NDACC-stations' data and implementation of a new data format.

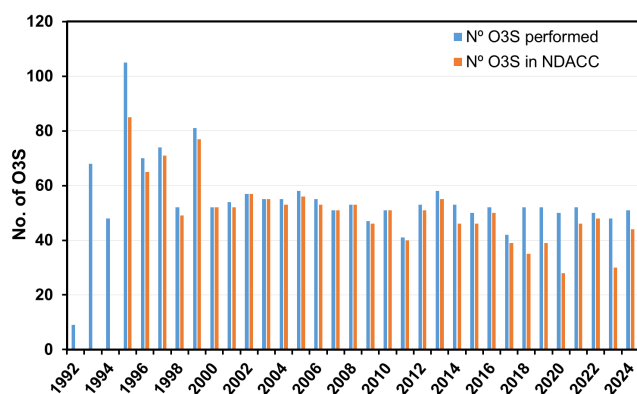


Figure 5.8. Number of ozone soundings (O3S) since the beginning of the programme and the number of ozonesonde datasets recorded in the NDACC database that meet the quality assurance criteria (1992–2024)

5.3.4 Ozonesonde data homogenization activity

An Ozonesonde Data Quality Assessment (O3S-DQA) activity was initiated in 2011 to homogenize temporal and spatial ozonesonde data records under the framework of the SI2N (SPARC [Stratosphere-troposphere Processes And their Role in Climate], IO3C [International Ozone

Commission], and NDACC) initiative on “Past Changes in the Vertical Distribution of Ozone”. The aim of O3S-DQA activity is to correct for biases related to instrumental (such as sonde type or sensing solution strength) or processing changes to reduce the uncertainty (from 10%–20% down to 5%–10%), and to provide an uncertainty estimate for every single ozone partial pressure measurement in the profile.

In this context, some O₃-sounding stations (Figure 5.9), one of them being the IZO station, were selected to be involved in the homogenization process, following Smit et al. (2012) and WMO (2021). The reprocessing carried out for IZO station is being supervised by Dr H. Smit (FZJ, Germany), leader of the O3S-DQA panel, and Dr R. Van Malderen (KMI, Belgium).

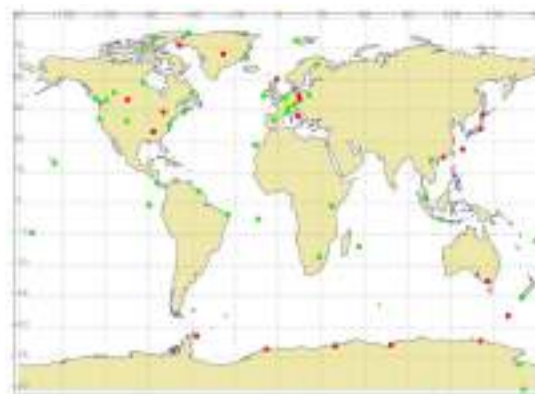


Figure 5.9. Global map of around 60 active ozonesonde sites. Green dots mark the stations with homogenized data available at the HEGIFTOM ftp-server.

At present, the O3S-DQA activity continues to support the Tropospheric Ozone Assessment Report, phase II (TOAR-II) Focus Working Group “HEGIFTOM” (Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements), see section 5.3.5 for more details. The homogenized O3S-data (HO3S) are available at the HEGIFTOM ftp-server ([KMI - Datasets](#)).

In our case, although there have not been any changes in ECC ozonesonde manufacturer (Vaisala ECC-SPC) or changes in sensing solution type (STT 1.0% KI & full pH-buffer) since the beginning of the Ozonesonde Programme (November 1992), some non-uniformity in ozonesonde and data processing could have occurred during the programme implementation period: changes in the ozonesonde type (ECC5A, November 1992 to September 1997 and ECC6A, September 1997 to present), in the pump temperature measurement, in the background current, in the correction (temperature and humidity) of the pump flow or in the method of determining the ozone residual. All this can lead to some inhomogeneities in the time series and may influence the trends derived from such data dramatically (Figure 5.10).

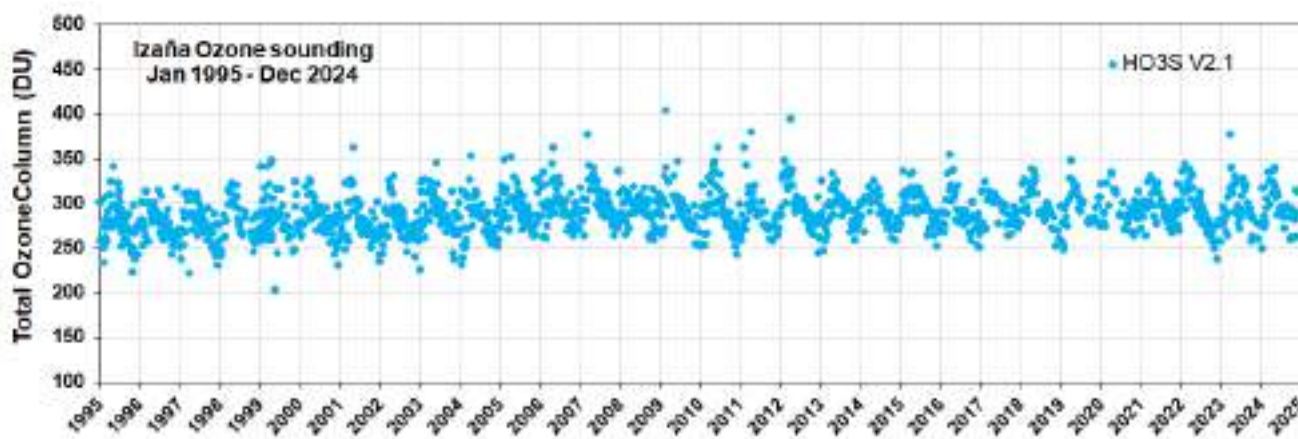


Figure 5.10. Long-term total ozone column with Izaña homogenized ozone sounding data (1995–2024). A satellite ozone climatology is used to determine the residual ozone from 10 hPa.

5.3.5 TOAR II project

The Tropospheric Ozone Assessment Report (**TOAR-II**) is an official activity of the International Global Atmospheric Chemistry Project (IGAC). The goal of TOAR-II (2020–2026) is to build on the success of TOAR-I (2014–2019) and produce an updated assessment of tropospheric ozone’s global distribution and trends from the surface to the tropopause. This effort includes an analysis of the impacts of ozone on human health, crop and ecosystem productivity, and climate.

Forming part of these activities is the **TOAR-II Community Special Issue** in the Copernicus journals (Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, Biogeosciences, and Geoscientific Model Development). As of June 2025, there are 57 Community Special Issue papers (30 published, 27 in review). These are distributed across the various TOAR-II working groups.

IARC participates in TOAR-II within the HEGIFTOM working group with surface ozone measurements, ozonesonde profiles and FTIR ozone profiles (for further details refer to section 7). The HEGIFTOM working group brings together different networks of ground-based instruments measuring free tropospheric ozone, not only to strengthen, speed up, and expand existing activities of harmonization of instruments, but also to compare QA/QC) procedures and reports, and harmonization efforts between the different networks.

IARC has participated in the TOAR-II Community Special Issue in the following studies: Björklund et al. (2024) and Van Malderen et al. (2025).

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5.5 Staff

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6 Total ozone column and ultraviolet radiation

6.1 Main scientific goals

The main scientific objective of this programme is to obtain the total ozone column (TOC) and ultraviolet (UV) spectral radiation data with the highest precision and long-term stability that the current technology and scientific knowledge allows to achieve. To reach this objective the group uses two interconnected areas: instrumentation and modelling. The basis of the research is the measurements, supported by strict QA/QC protocols, laboratory calibrations and theoretical modelling. Finally, web-oriented [databases](#) and scientific publications are utilized for dissemination of the observational data.

6.2 Measurement programme

Measurements of total ozone and spectral ultraviolet radiation began in May 1991 at IZO with the installation of Brewer spectrometer #033. Ozone profile measurements were added in September 1992 with two daily (sunrise and sunset) vertical ozone profiles obtained with the Umkehr technique. In July 1997, a double Brewer #157 was installed at IZO and it ran in parallel with Brewer #033 for six months. In 2003, a second double Brewer #183 was installed, and it was designated the travelling reference of the Regional Brewer Calibration Center for Europe (RBCC-E).



Figure 6.1. RBCC-E Brewer spectrophotometer triad located at IZO

In 2005, a third double Brewer #185 was installed, and it completes the reference triad of the RBCC-E (Figure 6.1). The measurement programme was complemented with the installation of a Pandora spectroradiometer in October 2011 and the BiTec-Sensor (BTS) array spectrometer in 2023. Also in 2021, AEMET acquired three new Brewer spectrophotometers (#256, #257, #258) to form a replacement reference triad for the Regional Brewer Calibration Center for Europe (RBCC-E). After mechanical adjustments, the new instruments became operational in September 2022 and coexist with the original triad (#157, #183, #185). The technical specifications of both Brewer, Pandora and BTS instruments are summarized in Table 6.1.

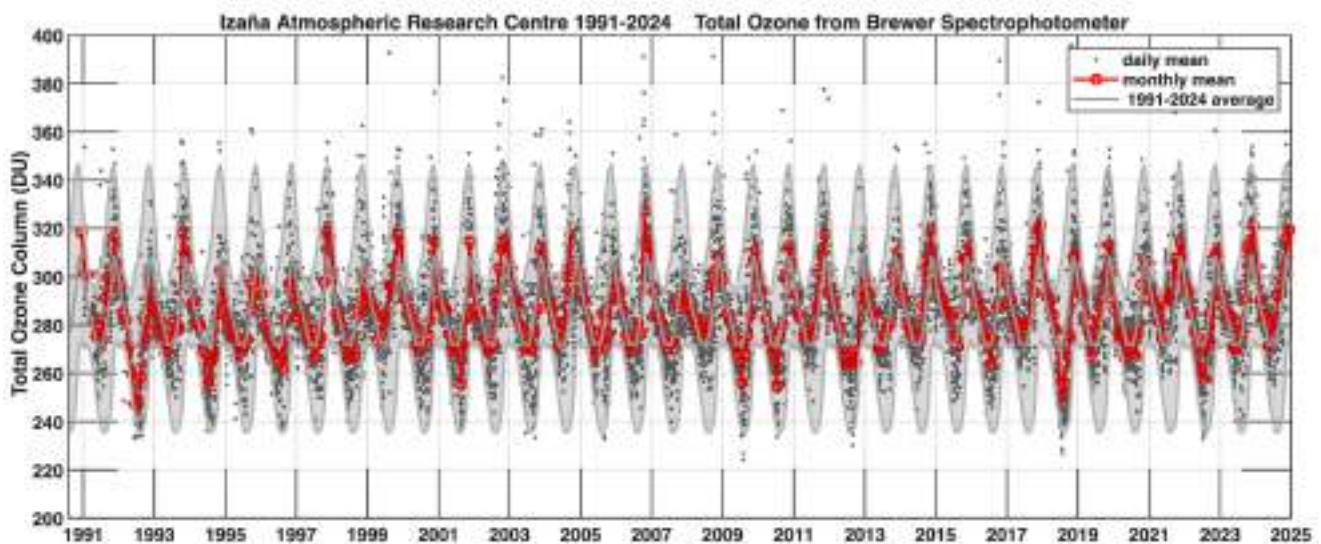


Figure 6.2. Total Ozone time series at Izaña Observatory (1991–2024), daily mean (grey dots) and monthly mean (in red), the long-term daily mean from the period 1991–2024 is also shown (grey line) with the shaded area corresponding to the standard deviation in the long-term mean

Table 6.1. Spectrometer specifications

Brewer	
Slit Wavelengths	O ₃ (nm): 303.2 (Hg slit), 306.3, 310.1, 313.5, 316.8, 320.1
Mercury-calibration (O ₃ mode)	302.15 nm
Resolution	0.6 nm in UV; approx 1nm in visible
Stability	±0.01 nm (over full temperature range)
Precision	0.006 ± 0.002 nm
Measurement range (UVB)	286.5 nm to 363.0 nm (in UV)
Exit-slit mask cycling	0.12 sec/slit, 1.6 sec for full cycle
O ₃ measurement accuracy	±1% (for direct-sun total ozone)
Ambient operating temperature range	0 °C a +40 °C (no heater) -20 °C a +40 °C (with heater option) -50 °C a +40 °C (with complete cold weather kit)
Physical dimensions (external weatherproof container)	Size: 71 by 50 by 28 cm Weight: 34 kg
Power requirements Brewer and Tracker	3A @ 80 to 140 VAC (with heater option) 1.5A @ 160 to 264 VAC 47 to 440 Hz
Pandora	
Instrument spectral range	265–500 nm
Spectral window for NO ₂ fit	370–500 nm
Spectral resolution	0.4 nm
Total integration time	20 s
Number of scans per cycle	50–2500
Spectral sampling	3 pixels per Full Width at Half Maximum (FWHM)
BTS	
Instrument spectral range	290–430 nm
Spectral resolution	0.8 nm
Total integration time	0.1–6000 ms
Pixel Resolution	0.13 nm/pixel
Spectral sampling	6 pixels per Full Width at Half Maximum (FWHM)

The spectral UV measurements are routinely quality controlled using IZO calibration facilities. The stability and performance of the UV calibration is monitored by 200W lamp tests twice a month. Every six months the Brewers are calibrated in a laboratory darkroom, against 1000W DXW lamps traceable to the World Radiation Center (WRC) standards. The [SHICrvm](#) software tool is used to analyse quality aspects of measured UV-spectra before data transfer to the databases. In addition, LibRadtran model to measurements comparisons are regularly done. Every year the Brewer #185 is compared with the Quality Assurance of Spectral Ultraviolet Measurements (QASUME) International portable reference spectroradiometer from Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center ([PMOD/WRC](#)).

Concerning total ozone, the Brewer triad has an exhaustive quality control in order to assure its performance, with routine calibrations performed on a monthly basis. With this procedure, we have achieved a long-term agreement between the instruments of the triad with a precision better than 0.25% in total ozone column. A similar agreement is achieved with the new triad (Berjon et al., 2024).

The Total Ozone programme is a part of the NDACC programme. The total ozone time series for 1991–2024 is shown in Figure 6.2 and is available at the NDACC [website](#) and at the World Ozone and Ultraviolet Data Center ([WOUDC](#)). Figure 6.3 shows the UV index calculated on the basis of UV observations from Brewer spectrophotometer #157, available also at the WOUDC.

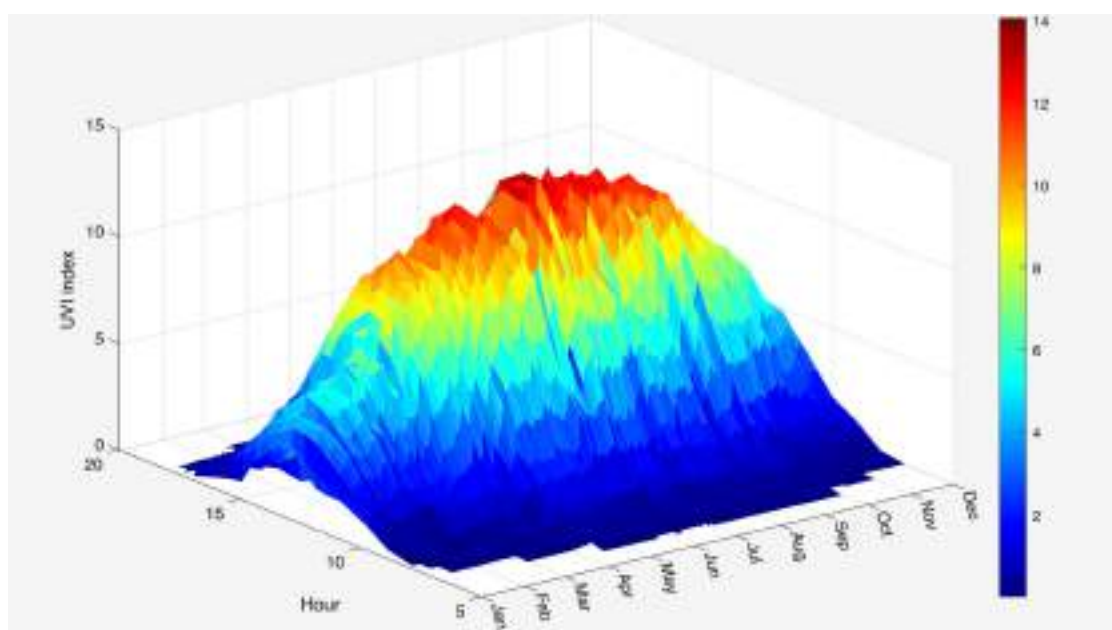


Figure 6.3. UV index during 2023, calculated on the basis of measurements from Brewer #157, at Izaña Observatory

6.3 Summary of remarkable results during the period 2023–2024

The participation in scientific projects of this measurement programme is intertwined with the activities of the Regional Brewer Calibration Center for Europe (RBCC-E) (see section 17 for more details).

6.3.1 EUBREWNET

EUBREWNET is a federated network of Brewer spectrophotometers created in 2013 to measure atmospheric ozone. It originally started as a European Cooperation in Science and Technology (COST) Action (ES1207) to form a European Brewer Network (Rimmer et al., 2018). The COST Action was active from April 2013 to July 2017. The original European COST action involved 18 countries, but EUBREWNET has since grown into a global network comprising ~ 80 instruments at 57 stations worldwide (Figure 6.4). The network is coordinated and managed by AEMET through IARC.

The network specializes in centralized, real-time processing of ozone data. Data processing levels range from raw data (Level 0), real-time data useful for assimilation in systems like Copernicus (Level 1.5), to calibrated data for climatological studies (Level 2). This allows for unique, high-quality, rapid ozone observations that support satellite data validation and atmospheric research. EUBREWNET is recognized as a Fiducial reference network for validation activities for Copernicus and other international initiatives.

EUBREWNET emerged from the European COST action to provide homogeneous, consistent, and high-quality data to monitor the ozone layer, crucial for protecting terrestrial life from solar ultraviolet radiation. The network aligns with

global programmes such as WMO, the United Nations Environment Programme (UNEP), and the EU Copernicus Atmosphere Monitoring Service (CAMS).

Reports from the 11th and 12th Ozone Research Managers meetings of the Vienna Convention highlight EUBREWNET as essential for ozone monitoring. The 11th meeting report particularly stresses the network's provision of homogeneous, high-quality, near-real-time data vital for satellite validation and programmes like the Copernicus Atmosphere Monitoring Service (CAMS) and Copernicus Climate Studies. The central role of AEMET in data processing and centralization is also underlined, positioning EUBREWNET as an internationally trusted reference network.

EUBREWNET is centrally managed through a governance committee involving the WMO and a scientific management committee. Technical support and operational coordination are provided by AEMET. Management tasks include maintaining the central database, harmonizing protocols, supporting users, developing new functions, and providing technical support.

Since the end of 2018, support to EUBREWNET has been provided by AEMET. Since February 2019, AEMET through TRAGSATEC, provides two staff positions to support the EUBREWNET and the RBCC-E activities. This support has recently been extended until 2026, ensuring and reinforcing the continuation of these two services. Input is provided by the EUBREWNET Management Committee, consisting of A. Redondas (IARC, Spain), K. Lakkala (Finnish Meteorological Institute, Finland), A.F. Bais (Aristotle University of Thessaloniki, Greece) and J. Gröbner (PMOD/WRC, Switzerland).



Figure 6.4. Location of Brewer stations currently participating in EUBREWNET. The network started as a European network but now includes 81 spectrometers at 57 stations located world-wide.

EUBREWNET relies on the work of two European calibration Centers, the RBCC-E and the WRC. The RBCC-E plays a key role in EUBREWNET, coordinating the standardization of operation, characterization and calibration of the network instruments as well as providing the Brewer database. Now recognized by the WMO and the International Ozone Commission (IO3C), it represents an extremely valuable network of ground station data points without which the space-borne instruments would not be able to function with any degree of accuracy. In the current times when we are trying to identify ozone recovery rates of 1% per decade, it is highly important that data are both accurate and consistent across all stations.

The purpose of EUBREWNET is to harmonize observations, data processing, calibrations and operating procedures so that a measurement at one station is entirely consistent with measurements at all the others. Additionally, the Brewer spectrophotometers are also used to measure spectral UV irradiance, the sulfur dioxide column and aerosol optical depth. Some Brewer spectrophotometers are also able to measure the nitrogen dioxide column. This harmonized Brewer network (Figure 6.4) constitutes the largest harmonized ground-based UV network in the world,

available for assimilation into satellite retrievals and models to greatly improve accuracy of the satellite data and ozone and UV radiation forecasting. Another important point is the link to climate change where tropospheric ozone and aerosols are still regarded as having the largest effect on uncertainties in climate models. The Brewer instruments are suitable for the measurement of total column ozone which includes both tropospheric and stratospheric ozone whereas satellites struggle with the lower altitudes.

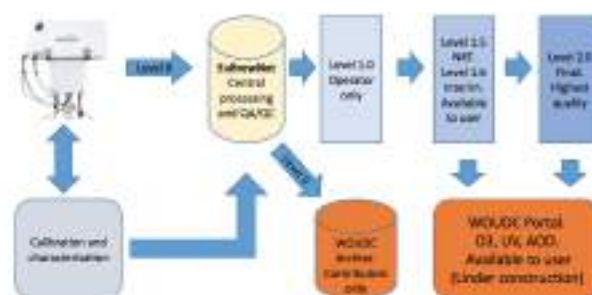


Figure 6.5. EUBREWNET database architecture

The actual implementation of the network can be summarized as follows:

- Automated data transfers to central database (Figure 6.5) started in September 2014. Data submission now became automatic with little operator involvement so improving overall submission rates.
- Calibration data are stored in a central database. This allows for central processing of all stations' data so ensuring consistency and use of up-to-date calibration and processing.
- Near Real Time (NRT) data. Central data processing in addition to data processing at the stations: including part of QC by comparison with near instruments and state-of-the-art algorithms. NRT data are essential for NRT validation of satellite data and model assimilations.
- Central re-processing. Historical data or changes in constants recommended by WMO GAW.
- Central QA/QC systems (QA/QC validated in one place): stations with a problem can be easily identified.

6.3.2 Development of ozone product in EUBREWNET

The determination of the [total ozone column uncertainty](#) has been fully implemented in EUBREWNET for both the standard (V1) and the improved (V2) Brewer algorithms. Access functions to download the data are available for product levels 1 and 1.5, as described in the [EUBREWNET wiki](#). Furthermore, monthly data files are being produced in various formats, including the NASA-AMES and GEOMS formats, these allow the automatic monthly ozone data submission to the WOUDC and ESA Validation Data Center ([EVDC](#)).

The Zenith Sky (ZS) measurements are now also fully processed by EUBREWNET's data server, and ozone ZS level 1, 1.5, and 2 products are available [here](#).

New tools for the ozone calibration of Brewer spectrophotometers are also now available at EUBREWNET's data server. These include a new function to determine the Extra-terrestrial Constant (ETC) as well as functions to determine the so-called ETC filter corrections by different methods. For more details, see the [Calibration Functions](#) section in the EUBREWNET wiki.

6.3.3 Development of UV products in EUBREWNET

Raw UV data are available at EUBREWNET since 2014. Following the ozone and AOD products scheme, we have now implemented four new levels for UV products (Figure 6.6):

- **Level 1** starts from the raw data and implements the dark-count and deadtime corrections to the counts. For Mk II and IV Brewers, the stray-light correction is also added. Finally, the raw counts are converted to irradiances using the UVR files previously uploaded to EUBREWNET.

- **Level 1.5** builds up from level 1 and adds spike and temperature corrections. The spike correction follows the method described in Meinander et al. (2003). The data required for the temperature correction can be obtained following the experimental procedure described in Lakkala et al. (2008). Brewer operators can also define an exclusion list to remove unwanted data.
- **Level 1.6** adds the cosine correction as implemented in the [BUVIC code](#) developed by Basile Maret and Julian Gröbner at PMOD/WRC (Gröbner and Maret, 2020).
- **Level 2.0** returns corrected irradiances calculated by the [SHICrvm code](#) developed by Harry Slaper at the National Institute of Public Health and the Environment ([RIVM](#)). SHICrvm's QA/QC is also available.

These UV product levels, and the access functions available to retrieve the information, are described in more detail in the [EUBREWNET wiki](#).

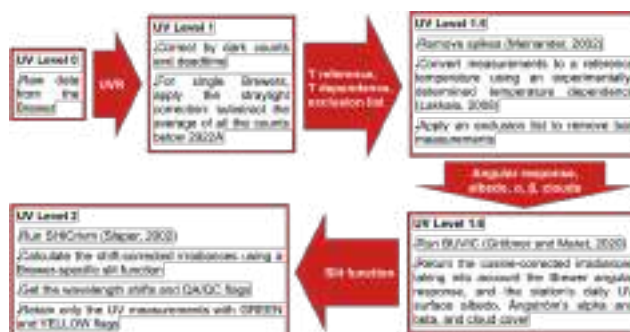


Figure 6.6. Summary of the new levels of UV products implemented in EUBREWNET

This updated UV processing was tested at the 18th intercomparison campaign where two Brewers operated by the RBCC-E (#185 and #256) and the El Arenosillo station home instrument (Brewer #150) provided with a cosine free diffuser, were compared. The figures below show results of the comparison between these three instruments and the QASUME travelling reference from the PMOD/WRC. Note we have used the same triangular slit for all instruments. A more complete comparison can be found in Hülsen and Zeilinger (2023).

Data from the last three days of the campaign, after maintenance on the Brewers had been completed, are shown in Figures 6.7–6.9. For the EUBREWNET Level-2 product, we present the UV Index and the Brewer/QASUME irradiance ratios at selected wavelengths (Figure 6.7). Only Brewer #150 data are corrected for temperature, while all three Brewers include the cosine correction. Good agreement between QASUME and the Brewers is evident, with irradiance ratios close to unity (Figure 6.8). For Brewers #185 and #256, the cosine correction plays a major role, markedly improving the comparison. Brewer #150's diffuser exhibits a better angular response, as indicated in (Figure 6.9), where we plot the L1.6/L1.5 irradiance ratios, which represent the cosine correction.

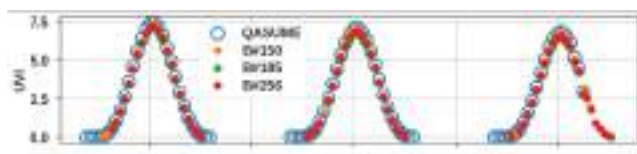


Figure 6.7. UV index as measured by the RBCC-E Brewer B#185 and B#256UV, the station instrument B#150 and the UV reference instrument QASUME during the 18th RBCC-E campaign

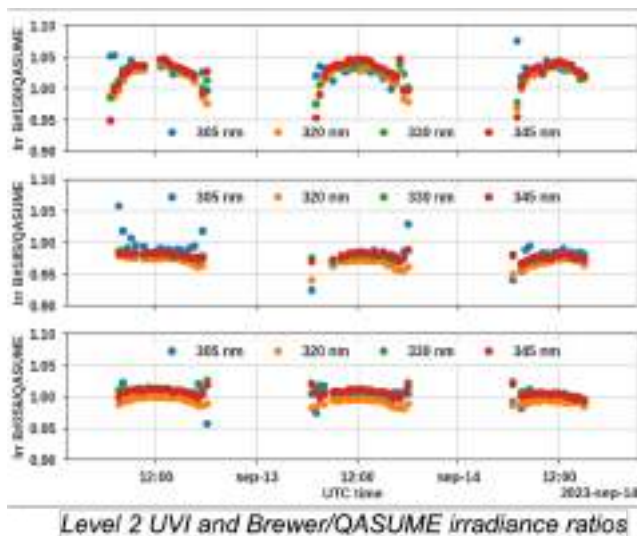


Figure 6.8. Spectral UV ratios for the the Level 2.0 EUBREWNET product for the Brewers with QASUME, with ratios near to 1 showing the improvement of the UV product

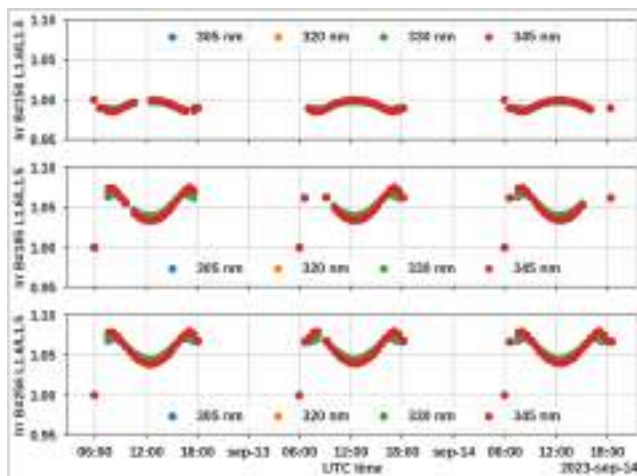


Figure 6.9. Ratio of EUBREWNET levels L1.5/L1.6 during the 18th RBCC-E campaign showing the magnitude of the cosine correction. Note that Brewer#150 has an improved diffuser with much less cosine error than the other instruments.

6.3.4 AOD updates in EUBREWNET

We have continued to process and evaluate AOD in the 306–320 nm wavelength range. This near-real-time product is derived from the same data used in the ozone Direct Sun (DS) measurements, as described in the [EUBREWNET wiki](#). The AOD-specific “JG” Brewer measurements are now fully parsed, processed and calibrated by EUBREWNET’s data processing. For Brewer spectrophotometers with the required [AOD calibration parameters](#), these measurements allow for the determination of the AOD in an extended wavelength range, reaching up to ~360 nm for Mk III instruments. See the EUBREWNET wiki for further details on accessing and downloading the data. These measurements were tested during the CINDI-3 campaign (see section 6.3.5 for details).

6.3.5 EUBREWNET at the CINDI-3 campaign

The Third Cabauw Intercomparison of UV-Vis DOAS Instruments ([CINDI-3](#)) was a one-month field campaign held from 21 May–24 June 2024 at the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands. Its goal was to intercompare and intercalibrate ~30+ UV-Vis MAX-DOAS systems and related sensors, measuring primarily NO₂ and O₃, but also aerosols and reactive gases such as HCHO, CHOCHO and HONO, under real atmospheric conditions, providing high-quality ground truth for satellite validation (e.g. TROPOMI) and community best practices. The effort brought >100 researchers from 18 different countries and included complementary mobile/airborne observations.

IARC participated in the campaign by providing the Total Ozone reference using Brewer#185. As detailed earlier, this instrument is part of the total ozone reference maintained at IZO, which shares the reference with Environment and Climate Change Canada (ECCC). Additionally, a second spectrophotometer (B#256) participated in the campaign, providing AOD measurements in the UV range and serving as an experimental instrument for the DOAS (Differential Optical Absorption Spectroscopy) comparison.

A new station was created in EUBREWNET (Figure 6.10) to host the observations of the campaign. EUBREWNET provided real-time total ozone, SO₂ and AOD observations from the beginning of the campaign. EUBREWNET also hosted the real-time observations of the nearest KNMI Brewer#189 operated at DeBilt by the KNMI.

The operational total ozone provided by EUBREWNET, use the ozone cross section of Bass & Paur. An updated version of the ozone product was provided which used the Ozone cross sections used at the CINDI campaign. This dataset also includes the uncertainty information recently developed. This is the “official” dataset used on the CINDI campaign and for the comparison with the other instruments.



Figure 6.10. Total ozone from Brewers during CINDI-3 (24/5/2024–20/6/2024), which also included the Brewer#189, placed in the near station of DeBilt. With the calibration (provided thanks to Ankie Piters) we were able to produce V2 brewer observations which use the ozone cross section of the CINDI campaign.

This total ozone dataset is used to compare with other instruments which also provided total ozone in the campaign: Pandora instruments (P81, P83 and P118) (Figure 6.11) and DOAS instruments which use the FRMDOAS (a central processing system for DOAS instruments).



Figure 6.11. Pandora instruments P81 and P83 during CINDI-3 (21/5/2024–24/6/2024)

For the comparison to Pandora, two datasets are used: the operational dataset, labelled V1 for both Brewer and Pandora, and the updated dataset, labelled V2. For Brewer, V1 uses the Bass & Paur ozone cross-sections, whereas V2 uses the Serdyuchenko cross-sections, consistent with the participating DOAS instruments. For Pandora, both versions use the SDK cross-section; V1 (operational) assumes a climatological ozone effective temperature, whereas V2 also fits the ozone effective temperature (see details for V1 (out2, Proc 1.8) and V2 (ous1, Proc 1.9) in Cede et al., 2025).

Figure 6.12 shows total-ozone ratios relative to Brewer_V2 for the participating Brewers and the Pandora data in both datasets. The Pandora V2 product requires dedicated calibration and is currently available only for instruments P81 and P83. The Brewer V2 values are about 2% higher than the operational product. Brewer-to-Brewer agreement is 0.2% for Brewer #258 and 0.8% on average for the De Bilt instrument (~85 km from the Cabauw station), with

similar results for the V1 dataset. The comparison with the operational Pandora (V1) is also very good, with differences around 1%, whereas the comparison with V2 increases to about 3%. This difference, and the slightly better agreement with Brewer V1 (noting the different ozone cross-sections used), is under investigation.

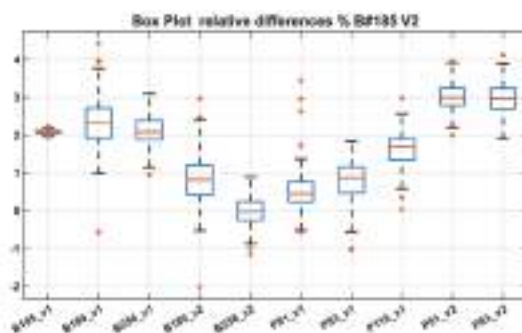


Figure 6.12. Ratio to Brewer reference (B185 V2) with Brewer and Pandora instruments during CINDI-3. V1 is the operational algorithm for Brewer (B258_v1 and B189_v1) and Pandora (P81_v1, P83_v1 and P118_v1) whereas V2 is the updated algorithms for Brewer (B258_v, B189_v2) and also the updated processing for Pandora (experimental 1–9) which is available for P81_v2 and P83_v2.

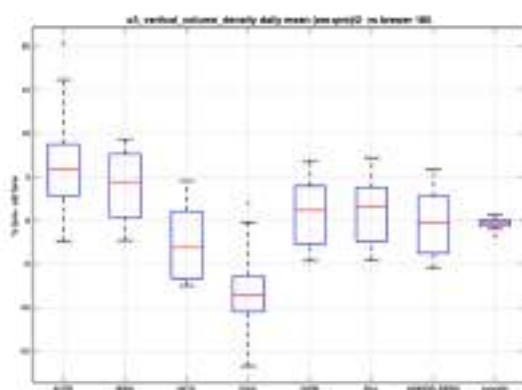


Figure 6.13. Ratio to Brewer reference with DOAS instruments during CINDI-3, the plot shows the daily mean total ozone, calculated as the mean of morning and afternoon FRMDOAS measurements. In addition to DOAS instruments, comparison with the second Brewer (B258) is also shown.

The secondary installed Brewer was used to test the ability of the Brewer spectrometers to provide DOAS observations to the FRMDOAS. Several tests were performed during the campaign with special developed routines to follow the schedule of the intercomparison. Unfortunately, with no success, the Brewer spectrometer is a scanning instrument which is extremely slow compared with the DOAS and MAXDOAS instruments, this made it impossible to follow the schedule of the campaign. This instrument also provides AOD in the UV range (290 nm–360 nm), the observations are available in the campaign database.



Figure 6.14. CINDI-3 group photo (Photo: A. Apituley). (<https://frm4doas.aeronomie.be/index.php/cindi-3>)

6.3.6 Pandonia Global Network

The Pandora Spectrometer System is a ground-based, sun/sky/lunar passive remote sensing instrument for the retrieval of trace gases in the UV/Vis spectral wavelengths. It was developed in 2005 by NASA and the Sciglob company, and since that time the Pandora spectrometer system has evolved. The Pandonia Network, funded by ESA through the LuftBlick company, has unified the operating and calibration procedures for the Pandora instruments since 2011.

NASA and ESA are currently collaborating to expand the global network of standardized, calibrated Pandora instruments focused on atmospheric composition. Through this collaboration the Pandonia Network became the **Pandonia Global Network** (PGN), which emphasizes: homogeneous calibration of instrumentation, low instrument manufacturing and operation costs, remote operative assistance, and central data processing and formatting for near-real-time delivery of final data products.

A major joint objective is to support the validation and verification of more than a dozen Low Earth Orbit (LEO) and Geostationary Orbit (GEO) satellites, most notably Sentinel 5P, TEMPO, GEMS and Sentinel 4. PGN participants are primarily comprised of governmental and academic researchers and technicians. The launch of the PGN in early 2018 represented a programmatic shift by NASA and ESA away from primarily operating and

supporting the research and field campaign operations, to establishing long-term fixed locations that are focused on providing long-term quality observations of total column and vertically resolved concentrations of a range of trace gases. The major trace gases observed by the Pandora systems across the range of 280–530 nm include: O₃, NO₂, HCHO, SO₂ and BrO.

IZO is one of the most important Pandora instrument testing sites together with the Innsbruck Atmospheric Observatory (University of Innsbruck, Austria). Two Pandora instruments were in operation at IZO during 2023–2024, the Pandora 101 (1S model, UV, 270–530 nm) owned by IARC and the Pandora 121 (2S model, UV 270–530 nm + VIS 400–900 nm) owned by LuftBlick.

In addition, funds were received through ESA to purchase and test a third Pandora instrument at IZO (P209). This instrument includes a new set of filters and a new technology of high-speed low noise Complementary Metal-oxide-Semiconductor (CMOS) spectrometers (Avantes EVO). P209 was installed in IZO in July 2022.



Figure 6.15. Daniel Santana and the Pandora 121 mounted at IZO

As part of a collaboration with the LuftBlick company and the EUMETSAT institution, an experimental fourth instrument (Pandora 234, alias “PaNIR”) was installed temporarily at Izaña from March 2023 to January 2025. This 2-spectrometer (NIR + VIS) prototype comprises:

- Spectrometer 1 (NIR): covering 1500–1750 nm at a resolution of ~2.5 nm and 512 pixels, used to measure CO₂, CH₄, and H₂O.
- Spectrometer 2 (VIS): covering 400–930 nm at ~1.1 nm resolution over 2048 pixels, intended for NO₂ and O₂ reference.

The goal of this ongoing PaNIR project is to develop and demonstrate a grating-technology-based ground-based measurement system for retrieving greenhouse gases such as CO₂ and CH₄ with high accuracy, for the purpose of satellite validation.

The project leverages Pandora-heritage data correction methods but adapts them for a near-infrared meteor-grade

spectrometer using a cooled InGaAs detector, managing new challenges posed by its detector and electronics. Specifically, the project aims to robustly process raw spectra through advanced DOAS-like spectral fitting algorithms that account for non-linear cross-section behaviour and temperature dependencies, properly convert measurements of slant columns to vertical columns using accurate air mass factor estimations and calibration techniques, and ultimately derive column-averaged dry-air mole fractions (X-gas) that are directly comparable with satellite and ground-truth instruments like FTIRs. The overarching aim is to establish a cost-effective alternative to FTIR systems, offering complementary GHG observations with potential benefits for satellite validation in terms of acquisition, operation costs, and the capability to observe spatial and temporal inhomogeneities in greenhouse gas distributions.



Figure 6.16. Pandora 234 “PaNIR” temporarily installed at IZO from March 2023 to January 2025

IZO is an invaluable PGN testing location, not only for testing the performance of the hardware, but also for data intercomparison (e.g. total ozone column) and algorithm development due to its remote location, the large fleet of auxiliary datasets and highly experienced staff.

The current activities at IZO related to PGN are focused on maintaining the operation of the instruments, testing new hardware improvements on demand, and serving as a testbed for algorithm refinement and development.

During the 2023–2024 period, we participated as authors or co-authors in Berjón et al. (2024a, b), Cordero et al. (2023), Lambert et al. (2024), López-Solano (2023, 2024a, b), Redondas et al. (2023, 2024a, b), Voglmeier et al. (2024) and Zhao et al. (2023).

A list of publications involving EUBREWNET is available [here](#).

A list of publications involving the Pandonia Global Network is available [here](#).

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6.5 Staff

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7 Fourier Transform Infrared Spectroscopy (FTIR)

7.1 Main scientific goals

Earth observations are fundamental for understanding the drivers of climate change and thus for supporting decisions on adaptation and mitigation strategies. Atmospheric remote sounding from space and ground are essential components of the observational strategy. In this context, the Fourier transform infrared spectroscopy (FTIR) programme at the IARC was established with the main goals of long-term monitoring of atmospheric gas composition (ozone related species and greenhouse gases) and for the validation of satellite remote sensing measurements and climate models. Much effort within the FTIR programme has been put in developing new strategies for observing tropospheric water vapour isotopologues from ground and space-based remote sensors, since these observations play a fundamental role in understanding atmospheric water cycle and its links to the global energy and radiation budgets.

The FTIR programme at the IARC is the result of the close and long-lasting collaboration of more than two decades between the IARC and the [IMK-ASF-KIT](#) (Institute of Meteorology and Climate Research-Atmospheric Trace Gases and Remote Sensing, Karlsruhe Institute of Technology, Germany). The IMK-ASF has operated high-resolution ground-based FTIR systems for almost three decades and they are leading contributors in developing FTIR inversion algorithms and quality control of FTIR solar measurements. As a result of this collaboration, the FTIR observations at IZO have contributed to the prestigious international networks NDACC and TCCON since 1999 and 2007, respectively.

7.2 Measurement programme

A ground-based high-resolution FTIR experiment (HR FTIR in the following) for atmospheric composition monitoring has two main components: a precise solar tracker that captures the direct solar light beam and a high-resolution Michelson interferometer (IFS) (Figure 7.1). IARC's FTIR activities started in 1999 with a Bruker IFS 120M spectrometer, which was replaced by a Bruker IFS 120/5HR spectrometer in 2005 (see technical specifications in Table 7.1).

In the framework of TCCON and NDACC, a new IFS 125HR spectrometer was purchased by AEMET and installed in August 2022 at IZO in order to replace the current instrument (lower panel of Figure 7.1). Both instruments will operate side-by-side for at least one year to ensure the consistency of the FTIR time series at IARC.



Figure 7.1. Upper panel: the ground-based FTIR experiment implemented in 2005 at the IARC. Lower panel: the new ground-based FTIR experiment implemented in 2022. For both experiments, the scientific laboratory is shown on the left panel, and the Michelson interferometer is shown on the right panel.

In order to derive trace gas concentrations from the recorded FTIR solar absorption spectra, synthetic spectra are calculated by the line-by-line radiative transfer model PRFWD (Schneider and Hase, 2009). Then, the synthetic spectra are fitted to the measured ones by the software package PROFFIT (PROFile FIT, Hase et al., 2004)

PROFFIT allows to retrieve volume mixing ratio (VMR) profiles and to scale partial or total VMR profiles of several species simultaneously. There have been a lot of efforts for assuring and even further improving the high quality of the FTIR data products: e.g., monitoring the instrumental line shape (Hase et al., 1999), monitoring and improving the accuracy of the applied solar trackers (Gisi et al., 2011), as well as developing sophisticated retrieval algorithms (Hase et al., 2004). The good quality of these long-term ground-based FTIR datasets has been extensively documented by theoretical and empirical validation studies (e.g. Schneider et al., 2008; Schneider et al., 2010; García et al., 2012; Sepúlveda et al., 2012).

In 2021 a portable and low-resolution FTIR spectrometer (LR FTIR in the following), the Bruker EM27/SUN, was acquired by IARC. This instrument operates within the Collaborative Carbon Column Observing Network (COCCON) (Frey et al., 2019, Alberti et al., 2022) and is mainly dedicated to the participation in field campaigns (see section 7.3.2).

Table 7-1. Technical Specifications for Bruker IFS 120/5HR (in brackets, if different for 120M).

Manufacturer, Model	Bruker, IFS 120/5HR [IFS 120M]
Spectral range (cm ⁻¹)	700 - 4250 (NDACC) and 3500 - 9000 (TCCON) Optional: 20 - 43000
Apodized spectral resolution (cm ⁻¹)	0.0025 [120M: 0.0035]
Resolution power ($\lambda/\Delta\lambda$)	$2 \cdot 10^5$ at 1000 cm ⁻¹
Typical Scan velocity (cm/s)	2.5 (scan time about 100 s @ 250 cm of Optical Path Difference)
Field of view (°)	0.2
Detectors	MCT and InSb (NDACC); InGaAs (TCCON)
Size (cm)/Weight (kp)/Mobility	320 x 160 x 100 [120M: 200 x 80 x 30] 550 + 70 (Pump) [120M: 100 + 30 (Electronics)] Installed inside container, limited mobility
Quality assurance system	Routine N ₂ O and HCl cell calibrations to determinate the Instrumental Line Shape

7.3 Summary of remarkable results during the period 2023–2024

The FTIR activities from 2023 to 2024 have been focused on ground and space-based remote sensing FTIR spectrometry.

7.3.1 Ground-based high-resolution FTIR spectrometry

The ground-based HR FTIR observations have a large potential to support analysis of the composition of the troposphere, the stratosphere and their exchange processes. This is fundamental to monitor and study, for example, the sources and sinks of greenhouse gases or the evolution of the ozone layer. Routinely, the IARC HR FTIR have contributed to NDACC with C₂H₆, ClONO₂, CO, CH₄, COF₂, HCl, HCN, HF, H₂CO, HNO₃, N₂O, NO₂, NO, O₃ and OCS observations (total column amounts and VMR vertical profiles) since 1999. Within TCCON, total column-averaged abundances of CO₂, N₂O, CH₄, HF, CO, H₂O and HDO have been measured since 2007 (Figure 7.2).

With these refined time series, we have participated in numerous studies at a global scale. For example, the IARC HR FTIR station has been one of the 16 NDACC FTIR stations used to demonstrate a harmonized FTIR chlorodifluoromethane (HCFC-22, R-22 or CHClF₂) retrieval strategy and generate a new global NDACC-IRWG HCFC-22 dataset (Zhou et al., 2024). Monitoring the atmospheric HCFC-22 concentrations and its long-term trend is important as it is an ozone-depleting substance with a greenhouse effect. Based on the new FTIR HCFC-22 measurements, a maximum HCFC-22 column annual growth rate was observed in 2009 with a mean of 7.65 ± 1.39 ppt/year, and the HCFC-22 annual growth rate decreased to 3.57 ± 1.39 ppt/year (2016–2020) and 2.15 ± 2.09 ppt/year (2021–2023) (Figure 7.3). The annual growth rates derived from the FTIR measurements are compared to the ones derived from NOAA surface flask samplings and ACE-FTS satellite measurements, and the three independent datasets show a good agreement.

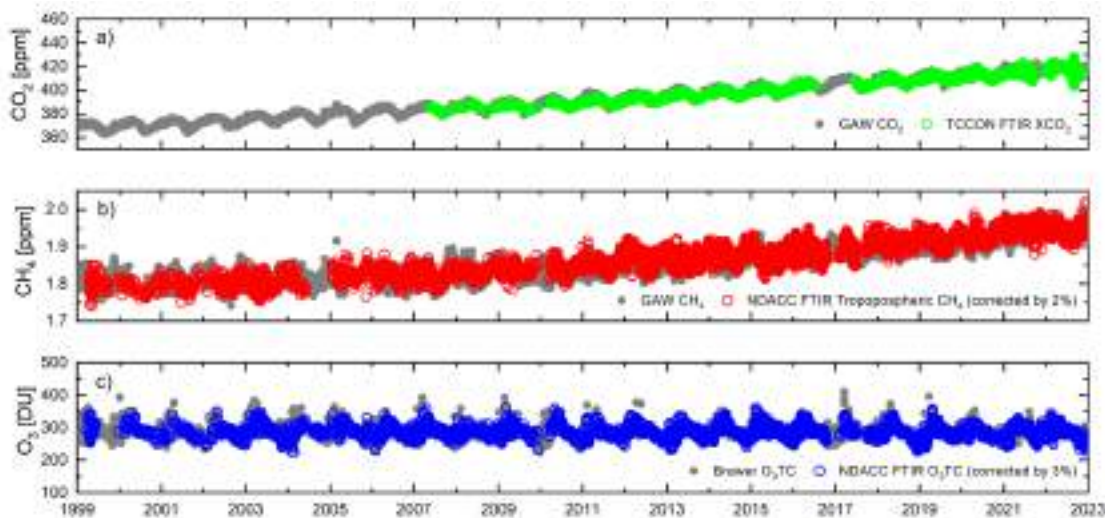


Figure 7.2. Time series of the total column-averaged abundances of a) carbon dioxide (XCO₂) in the framework of TCCON, b) tropospheric methane (CH₄) and c) ozone total column (O₃TC) amounts in the framework of NDACC as observed by the IARC FTIR. For comparison, the time series of these trace gases as observed by other high-quality measurement techniques available at the IARC are also displayed (WMO GAW in situ records for CO₂ and CH₄, and Brewer O₃TC amounts for O₃).

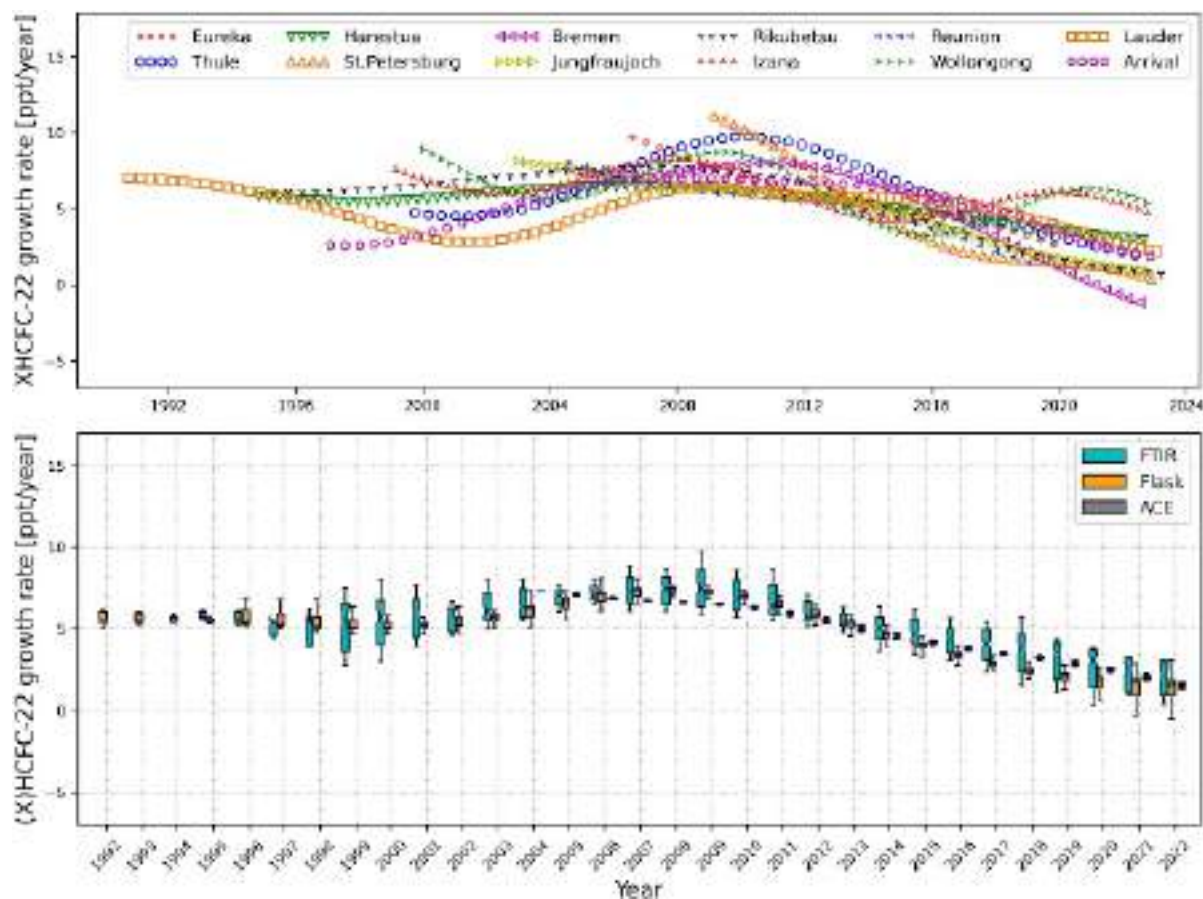


Figure 7.3. The annual growth rates of XHCFC-22 derived from the FTIR measurements at each site (upper panel) and a box plot of the HCFC-22 annual growth rates from FTIR sites, co-located ACE-FTS satellite measurements, and all NOAA surface flask observations in each year (bottom panel). The boxplot only shows the FTIR results after 1995, where at least 3 FTIR sites are available. Reprinted from Zhou et al. (2024).

Other studies have investigated changes in key elements in the atmosphere such as O_3 , which plays a vital role in atmospheric chemistry. Hence, high-quality and long-term O_3 measurements are essential for further improving our understanding of the O_3 response to natural and anthropogenic forcings, as well as to estimate consistent trends at a global scale. In this context, the IARC FTIR programme has developed several works to improve O_3 monitoring by ground-based FTIR spectrometry by examining the performance of different O_3 retrieval strategies (García et al., 2022a, 2022b).

These strategies were tested at different NDACC FTIR sites (Björklund et al., 2023) and adopted as the new harmonized O_3 FTIR strategy by the NDACC IRWG community in 2024. In particular, using the new NDACC O_3 strategy and in the context of the LOTUS (Long-term Ozone Trends and Uncertainties in the Stratosphere) and TOAR-II (Tropospheric Ozone Assessment Report, phase II) initiatives, a detailed intercomparison study of total column ozone and its vertical distribution was performed at the NDACC Lauder FTIR site using the ground-based measurement instruments available from 2000 to 2022, which are FTIR and Dobson spectrometers, a UV2-ultraviolet double monochromator, a microwave

radiometer-MWR, ozonesondes, and a stratospheric lidar (Björklund et al., 2024).

Regarding temporal drifts, as stated by Björklund et al. (2024), no significant drift was observed in the stratosphere between ozonesondes and FTIR for all partial columns, with ozonesonde trends being less negative than in LOTUS (Godin-Beekmann et al., 2022, further referred to as the LOTUS22). The only significant drift in the lower-stratospheric columns is obtained between FTIR and Umkehr, as was already found in LOTUS22. Two significant positive drifts are observed in the middle stratosphere (2 % and 3 % per decade) with lidar and MWR, respectively, while two significant negative drifts are observed in the upper stratosphere (−3 % and −4 % per decade) with Umkehr and lidar, respectively.

While remaining drifts are still present, the analysis of Björklund et al. (2024) explains roughly half of the differences in observed trends in LOTUS22 by the different sampling, vertical sensitivity, or time periods and gaps. In addition, the FTIR data in the present work have been improved since LOTUS22, reducing the differences in the upper-stratospheric and tropospheric trends. This shows the necessity for continuous review and improvement of the measurement and retrieval processes.

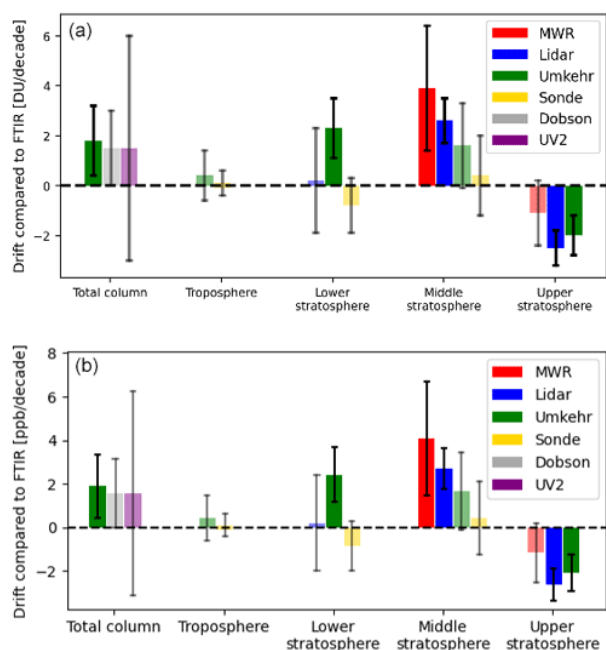


Figure 7.4. For the total column and each of the partial columns, the drift in DU per decade with respect to FTIR is shown for the Umkehr, ozonesonde, lidar, Dobson, and MWR data in panel (a). Additionally, the error margins from the trend analysis are shown. Non-significant trends are shown in pale colours for distinction. In panel (b), we show the same drifts but in molar fraction (ozone over dry air) per decade with units of parts per billion. Reprinted from Björklund et al. (2024).

Continuing the activities related to the 2021 La Palma volcanic eruption emergency response described in the previous IARC Activity Report 2021–2022, the FTIR group contributed to the deployment carried out by IARC in La Palma and to the reinforcement of the monitoring activities at IZO. As a result, numerous studies have emerged, improving the characterization and monitoring of such volcanic events, as well as the development of management strategies during volcanic crises (e.g. Córdoba et al., 2023; García et al., 2023; Milford et al., 2023; Heldelt et al., 2024; Taquet et al., 2025; López-Darias et al., 2025).

In particular, the work by Taquet et al. (2025) provides new insights into the degassing processes of the 2021 La Palma eruption by exploring the potential of combining different atmospheric measurements, including both high- and low-resolution FTIR observations (Figure 7.5). Of particular interest is the combined use of direct-sun ultraviolet and infrared spectroscopic observations, a strategy previously developed for the characterization of the Popocatepetl volcano in Mexico (Taquet et al., 2023).

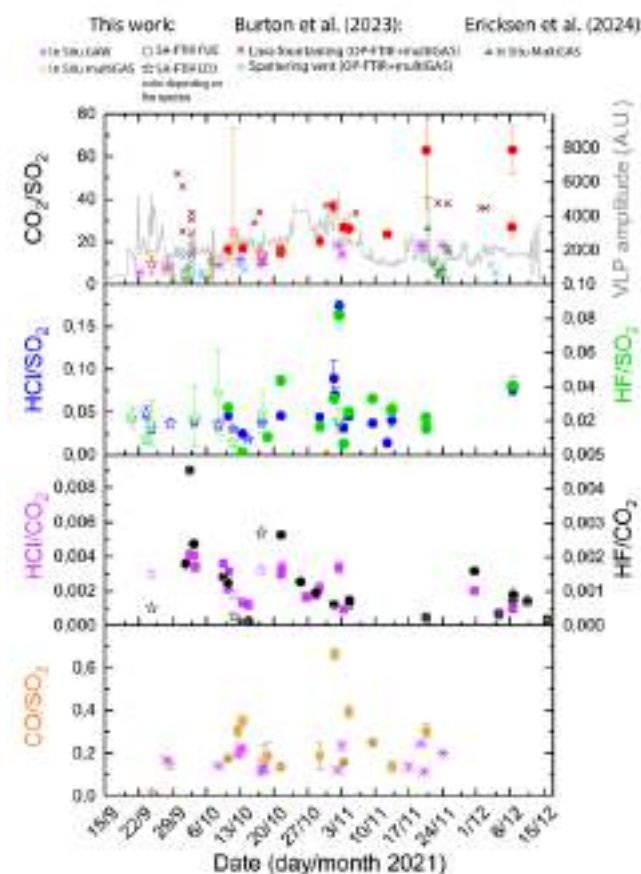


Figure 7.5. Variability of the Tajogaite volcanic plume composition during the eruption. Daily molecular ratios are calculated from the daily species-to-SO₂ or species-to-CO₂ correlation plots of the total columns (SA: solar absorption FTIR and DOAS measurements) and surface (WMO GAW and multiGAS analysis) time series. Reprinted from Taquet et al. (2025).

ATMO ACCESS

In the framework of the ATMO-ACCESS project (see section 16 for further details), the COCCON Travel Standard (TS) performed an intercomparison exercise with the IZO TCCON HR FTIR instrument in July 2023 with the aim of ensuring the TCCON intra-network consistency. As displayed in Figure 7.6, the intercomparison results agree well with other TCCON sites (Herkommer et al., 2024; Sha et al., 2024).

In coincidence with the COCCON TS campaign, we started to test a new solar spectrometer for CO₂ monitoring based on laser heterodyne radiometry in the framework of the national project CarbonSurvey.

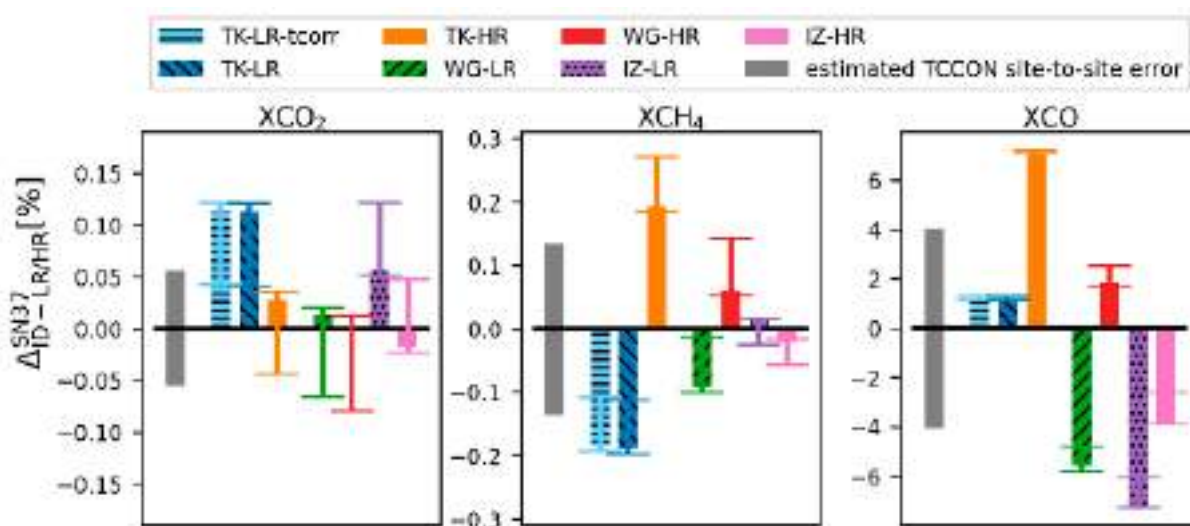


Figure 7.6. The results of the TS campaigns conducted so far, Izaña (IZ), Tsukuba (TK) and Wollongong (WG). The bars give the deviation in percentage of the HR and LR data at the individual sites relative to the reference in Karlsruhe (SN37 EM27/SUN instrument). The tcorr represents the time-corrected LR data for the Tsukuba site. Reprinted from Sha et al. (2024).

CARBONSURVEY

In December 2022, the CarbonSurvey project (“Towards the Next Generation of Sensors for Surveying the Atmospheric Carbon Cycle”) started, funded by the Spanish Ministry of Science and Innovation. The main expected contribution of this project is to develop a new generation of instruments to enable unprecedented CO₂ monitoring capabilities. These new sensors will provide an accurate measurement of the gas concentration not only at ground level, but also at the different layers of the atmosphere for a full characterization of the CO₂ distribution. The IARC CO₂ in situ and total column FTIR observations will serve as the reference for the validation of the new CO₂ sensors developed during this project.



Figure 7.7. Left: LHR system at the campus of the Universidad Carlos III de Madrid. Right: LHR setup coupled to the HR FTIR solar incoming beam at IZO.

This evaluation exercise began in July 2023 at IZO (Figure 7.7), where a new solar spectrometer for CO₂ monitoring based on Laser Heterodyne Radiometry (LHR) was tested (Moreno-Oyervides et al., 2023). This field campaign enabled us to demonstrate the high consistency between the measured LHR spectra and the HR FTIR

spectra, and to develop new CO₂ retrieval strategies from LHR measurements (Moreno-Oyervides et al., 2024). These works will continue within the European GASPOF project, where a dedicated retrieval software for this instrument will be developed.

GASPOF

GASPOF (Pervasive gas spectroscopy using optical fibres, as part of the communication network of the future), funded by the European Union HORIZON-CL4-2024-DIGITAL-EMERGING-01 call (No 10118965, 2024–2028) and formed by a consortium of ten European research and technological organizations, aims to contribute to the development of the optical infrastructure of the future, where the communications network also acts as a large-scale distributed multi-parameter sensor. Focus will be put on two different optical techniques for gas sensing using the fibre optics network: laser-based PTS and LHR. Both techniques will be advanced and integrated with the existing optical fibres network infrastructure. In parallel, the possibility of using coherent OTDR for distributed gas sensing will be investigated, while a reduced-cost approach for acoustic sensing will also be designed for measuring physical parameters of interest (e.g. vibrations) in addition to gas sensing.

The GASPOF system configurations will demonstrate their performance and capabilities in important four application use cases (Figure 7.8). Particularly, the IARC FTIR group will be involved in the Use case #1: Greenhouse gases monitoring, where an experiment to validate LHR greenhouse gas measurements in Barcelona will be carried out, using the URBAG surface network and the COCCON-Spain instruments.

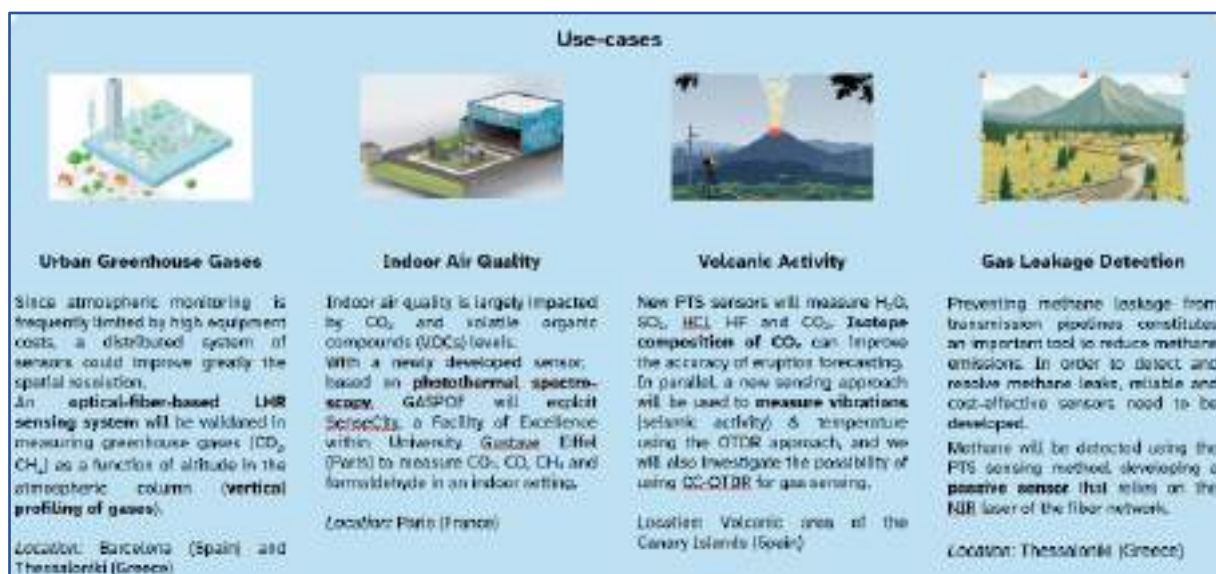


Figure 7.8. Map of the GASPOF test sites in Europe. Urban GHG: UAB-ICTA (Barcelona, Spain); Volcanic activity: CSIC (Tenerife, Spain); Indoor air quality: UGE (Paris, France); and pipeline safety: LANCOM (Thessaloniki, Greece). Additionally, some of the sensors will be tested in the laboratories of TUV (Vienna, Austria) and ADTRAN (Meiningen, Germany) (<https://gaspof.eu/>).

7.3.2 Ground-based low-resolution FTIR spectrometry

The EM27/SUN spectrometer shares the same working principles as HR FTIR and, by covering the near infrared spectral range from 5 000 to 11 000 cm^{-1} with a spectral resolution of 0.5 cm^{-1} , it is able to measure total column-averaged amounts of O_2 , CO_2 , CH_4 , CO and H_2O .

The IARC EM27/SUNs are operated in accordance with COCCON requirements (Frey et al., 2019; Alberti et al., 2022). This guarantees strict common methods for ensuring the quality of measurements (evaluation of the optical alignment and instrumental line shape), proper calibration of all COCCON spectrometers with respect to the TCCON site Karlsruhe and the COCCON reference EM27/SUN spectrometer operated permanently at KIT (in terms of the standard retrieved species), and adherence to the COCCON data analysis scheme ensures the generation of precise and accurate data products.

MEGEI and COCCON-Spain

COCCON EM27/SUN instruments are a useful complement to the existing TCCON HR network in remote areas as its data can be used for the quantification of local sinks/sources and fluxes of greenhouse gases. With this idea, the IARC is leading the Spanish project, Monitoring greenhouse Gas Emissions (MEGEI), to monitor GHG concentrations to evaluate fluxes in different environments by using the COCCON LR spectrometers. MEGEI activities are mainly focused on performing routine measurements at IZO (background conditions) and SCO stations and in addition, on carrying out field campaigns under different atmospheric conditions. As an evolution of MEGEI, the COCCON-Spain project started in 2023 with the aim of addressing the

existing gap in atmospheric greenhouse gas observations in Spain by implementing a network of stations for GHG measurements at a national scale. This initiative, coordinated by AEMET, is part of the project to modernize observation networks and digitize production processes for the development of intelligent meteorological services in the context of climate change (C05.I03.P05). It is integrated into the Recovery, Transformation, and Resilience Plan (PRTR) of the Spanish Government, and is funded with the funds approved by the European Council on 21 July 2020, to address the consequences of the international COVID-19 pandemic (specific PRTR actions P02.C05.I03.P05.S000.042 and P02.C05.I03.P05.S000.043).

The COCCON-Spain network will initially consist of fourteen stations for measuring key GHG, and potential locations are shown in Figure 7.9. These locations have been selected based on their placement in major urban/industrial GHG emission zones (e.g., Madrid and Barcelona) as well as background environments, under different surface reflectance conditions for possible satellite measurement validation (e.g. CEDEA-INTA, the Solar Platform of Almería, CIBA, IZO, or SCO). Additionally, efforts have been made to ensure they cover a geographically homogeneous distribution, representative of the maximum latitudinal gradients in Spain.

Together with permanent stations, COCCON-Spain will continue with the monitoring of GHG concentrations in areas of special interest. In this context, during December 2022 and February 2023, the first measurements of XCO_2 and XCH_4 were conducted at the Juan Carlos I Antarctic base during the AEMET Antarctic campaign by using the IARC COCCON LR instrument. These measurements mark

a milestone in AEMET's observation programme in Antarctica and will contribute to a better understanding of the GHG balance in the Earth-atmosphere climate system.



Figure 7.9. Distribution of potential stations in the COCCON-Spain network (in blue and red): IZO (Izaña Observatory), SCO (Santa Cruz de Tenerife Observatory), ARE (El Arenosillo Experimentation Center), PSA (Solar Platform of Almería), CIB (Lower Atmosphere Research Center), MAD (Madrid), BAR (Barcelona), and COR (A Coruña). In magenta, green, and light blue, are the stations that are part of ICOS-Spain in the atmospheric, ecosystem, and oceanic domains, respectively.

Another remarkable field activity was the participation in the “First Ibero-American Campaign for Brewer Spectrophotometer Calibration and Intercomparison” which took place in Santa Maria, Brazil, in February–March 2024. This campaign was focused on ozone measurements (for more details see section 17.4.7). In addition to take observations there, we took the opportunity to introduce the EM27/SUN instrument and COCCON protocols to the South American ozone community. This was a great opportunity to meet and establish potential collaborations for future COCCON sites.

RESPIRE

COCCON-Spain is also integrated in the [RESPIRE](#) project, led by the Barcelona Supercomputing Center (BSC) and AEMET and also funded by the PRTR. RESPIRE develops systems to accurately quantify atmospheric pollutant and GHG emissions resulting from human activities in Spain. These systems generate key data for research and support decision-making on mitigation measures for air pollution and climate change at both local and national levels. Additionally, the project integrates Artificial Intelligence (AI) techniques to improve emission estimation and enhance the accuracy of prediction models, contributing to the development of future environmental policies. Therefore, the project will support air quality simulation and GHG monitoring efforts in Spain.

MAPP

In June 2020, the Metrology for aerosol optical properties (MAPP) project started, supported by the European Metrology Programme for Innovation and Research (EMPIR). With a consortium of fourteen European organizations (IARC among them), the overall goal of MAPP was to enable the SI-traceable measurement of column-integrated aerosol optical properties for assessing the radiative forcing impact on climate. These properties are retrieved from the passive remote sensing of the atmosphere using solar and lunar radiation measurements that are largely lacking traceability to the SI.

An additional objective was to evaluate the retrieval of aerosol optical properties from emerging technologies such as solar and lunar spectroradiometers. The IARC FTIR programme contributed to this activity by developing the methodology required to retrieve aerosol properties from EM27/SUN instruments used within the research infrastructure COCCON (Álvarez et al., 2023).

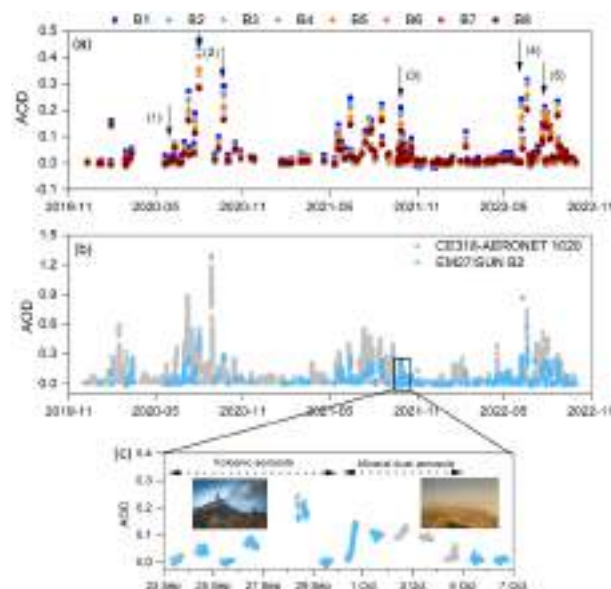


Figure 7.10. Time series, from December 2019 to September 2022, of (a) the daily mean AOD data for the eight EM27/SUN spectral bands and (b) the CE318-AERONET and EM27/SUN AOD values measured at the coincident B2 and 1020 nm band. (c) AOD evolution over a 14 d period in September 2021. The images in panel (c) correspond to the volcano on La Palma (LuzLux/AEMET) and a Saharan dust event at the IZO. The black arrows in panel (a) mark important AOD events: (1) spring/summer 2020, (2) mineral dust outbreaks in July and September 2020, (3) La Palma volcanic eruption between September and December 2021, (4) mineral dust outbreak in June 2022, and (5) forest fire in July 2022. Reprinted from Álvarez et al. (2023).

Figure 7.10 documents the excellent agreement at the near-coincident spectral bands between the co-located AERONET, used as reference, and the new COCCON aerosol database. This work demonstrates the potential of the portable low-resolution COCCON instruments to enhance the multi-parameter capability of the FTIR

technique for atmospheric monitoring. For further details about the MAPP project and the IARC contributions, see section 9 and 19.

7.3.3 Space-based FTIR spectrometry

The IARC's high quality HR FTIR data have been extensively applied for many years for the validation of trace gases measured by different satellite instruments. During the period 2023–2024, particularly, IARC participated in the development of new methodologies for estimating NO₂ and CH₄ emission fluxes from space-based platforms, as well as in the validation of new satellite products like those from the TROPOspheric Monitoring Instrument (TROPOMI), the Greenhouse gases Observing SATellite (GOSAT), or the Orbiting Carbon Observatory-2 (OCO-2) (Tu et al., 2023; Sha et al., 2025; Tsuruta et al., 2025).

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7.5 Staff and collaborators

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8 In situ aerosols

8.1 Main scientific goals

Atmospheric aerosol is composed of a mixture of natural (e.g. sea salt, desert dust or biogenic material) and anthropogenic (e.g. soot, industrial sulphate, nitrate, metals or combustion linked carbonaceous matter) airborne particles whose size range from a few nanometres (nm) to tens of microns (μm). Aerosols contribute to deterioration of air quality with impacts on human health due to cardiovascular, cerebrovascular and respiratory diseases such as asthma and chronic obstructive pulmonary disease; they also influence climate by scattering and absorbing radiation and by influencing cloud formation and rainfall.

The activities of the In situ Aerosols programme (AIS group, *Aerosol In Situ*) are developed in line with scientific priorities of the WMO GAW Programme and ACTRIS. One of the main tasks of this group is to maintain the long-term observations of aerosols at IZO. The group focuses its research on: 1) Long-term multi-decadal variability and trends of aerosols; 2) Aerosols and climate interaction and 3) Aerosols and air quality interaction.

8.2 Measurement programme

The long-term in situ aerosols observation programme of Izaña Observatory includes measurements of aerosol mass and number concentration, chemical composition, size distribution and optical properties by in situ techniques. Instruments are placed in the Aerosols Research Laboratory (ARL) renamed as the Joseph M. Prospero Aerosols Research Laboratory, as a tribute to the pioneer of dust research, in 2016 (Figure 8.1). The laboratory is equipped with a whole air inlet for aerosol sampling for the on-line analysers (CPCs, SMPS, APS, MAAP, aethalometer, nephelometer), two additional PM_{10} and $\text{PM}_{2.5}$ inlets for the aerosol filter samplers and also two additional inlets for TEOM (PM_{10} and $\text{PM}_{2.5}$) and BETA (PM_{10}) analysers respectively. A new inlet has been designed for operation within ACTRIS (Figure 8.1 lower panel) expected to start once the labelling process is finished.

The interior of the Aerosols Research Laboratory is maintained at 22 °C. Driers are not needed during the sampling because of the low relative humidity (RH) of the outdoor ambient air (RH percentiles 25th, 50th and 75th are 15%, 31% and 55%, respectively). Measurements of number concentration, size distribution and optical properties of aerosols are performed with high time resolution (Table 3.2).



Figure 8.1. Joseph M. Prospero Aerosols Research Laboratory at IZO (upper panel: building; lower panel: Óscar Álvarez working with the new ACTRIS inlet in the ARL)

For the automatic instruments in the aerosol laboratory, the QA/QC activities include:

- <daily checks> of the data and status of the instruments
- <weekly checks> of the airflows and leak tests for some instruments (e.g. SMPS)
- <quarterly checks> includes measurements of the instrumental zero (24h filtered air) for all the instruments (CPCs, SMPS, APS, MAAP, aethalometer nephelometer) and calibration checks (e.g. nephelometer)
- <annual intercomparisons> for some instruments
- <regular> calibration of the instruments at the World Calibration Centre for Aerosols Physics (WCCAP).

These activities in the main inlet follow the recommendations of WMO GAW for aerosols (GAW Report n°227, 2016).

During 2022 the final post-processing of the internal database for all aerosol in situ parameters measured at ARL was started. This is the final step for making all the QC/QA aerosol information measured at ARL available to the scientific community and it is expected to be used in scientific papers to be published in 2025.

The aerosols chemical composition programme is based on:

- the collection of aerosol samples on filters. Samples are collected at night to avoid the diurnal upslope winds that may bring material from the boundary layer.
- the determination of the aerosol mass concentrations by the gravimetric method. Filters are weighed, before and after sampling, at 20 °C temperature and 30–35% relative humidity in the Aerosol Filters Laboratory of IARC (see section 3.1.4). The procedure for weighing filters is similar to that described in EN-14907, except that we use a lower relative humidity (30–35%) due to the relative humidity of the ambient air at IZO being much lower than the 50% stated by EN-14907.
- the determination of chemical composition which currently includes elemental composition (those detected by IPC-AES, i.e. Al, Ca, Fe, Mg, K, Na,...), salts (SO_4^{2-} , NO_3^- , NH_4^+ , Cl^-), organic carbon, elemental carbon and trace elements (those detected by IPC-MS, i.e. P, V, Ni, Cd, As, Sb, Sn,...).

The QA/QC procedure for the aerosol chemical composition programme includes:

- airflow checks and calibrations.
- the collection of blank field filters for gravimetry and chemical analysis.
- intercomparison exercises.

The IARC Aerosol In Situ group has participated in the different ACTRIS in situ community meetings about data submission, QA/QC, trainings and labelling held online. Other important meetings attended by IARC staff have been related to ACTRIS Week (October 2023 in person in Crete, Greece and in November 2024 online), and different ACTRIS Centre for Aerosol Remote Sensing (CARS) and ACTRIS Centre for Aerosol In Situ (CAIS) European Center for Aerosol Calibration and Characterization (ECAC) meetings (see section 15 for more details).

The AIS group is also responsible for the measurements of different passive samplers, for mercury and persistent organic pollutants. These programmes are led by the Environment and Climate Change Canada (ECCC) and the Spanish National Research Council (CSIC), respectively.

8.3 Summary of remarkable results during the period 2023–2024

During the 2023–2024 biennium, the scientific activities of the In situ Aerosols group were focused on the labelling process within ACTRIS and research collaboration with other groups.

During this period, international cooperation that began in 2019 continued to provide scientific results. These are the activities related to the projects CREWS (Climate Risk and

Early Warning System) West Africa. Further details are given in section 20 (Sand and Dust Storms Centres).

8.3.1 Installation of new instrumentation at AIS

Two new instruments were installed at AIS in this period as a part of the new ACTRIS inlet. One SMPS TSI 3938-CEN10 installed in January 2024 (Figure 8.2) and one nephelometer Ecotech Aurora 3000 installed in October 2024. The new SMPS (called SMPS-ACTRIS from now on) combines electrical mobility sizing with single-particle counting, providing high-resolution continuous monitoring of ultrafine particles in ambient air. SMPS-ACTRIS provides size distributions ranging from 10 to 800 nanometres in a single scan. Aurora 3000 is an advanced integrating nephelometer designed for continuous, real-time monitoring of aerosol light scattering in ambient air. It utilized three-wavelength measurement and integrated and backscatter detection for understanding aerosol optical properties. These two instruments are included in the ACTRIS CAIS-ECAC guidelines, containing the instruments accepted for ACTRIS operation (see [here](#)).



Figure 8.2. Installation of the new SMPS-ACTRIS at IARC-AIS on January 2024 with the staff from CSIC, TSI and AIS

Two Air Photon IMAPs 100 were installed in AIS on June 2023. These instruments are Inverse Multi-Angle Polarimeters with polarization capability, able to measure polarized scattered light at multiple angles and at multiple wavelengths at multiple size bins ranging from PM_{10} to PM_{10} (Figure 8.3). The integrated use of GRASP data retrieval algorithm allows IMAP to accurately determine: particle mass, size distribution, scattering phase function, polarization phase function, real refractive index of the particles and sphericity factor of the particles.



Figure 8.3. Operation of the two IMAPS at AIS by Concepción Bayo

8.3.2 Focus on new particle formation processes

As a continuation of the campaign “Chasing preindustrial aerosols at Izaña” developed at IARC under the umbrella of the ATMO-ACCESS project during April, May and June 2022 with the Institute for Atmospheric and Earth System Research (INAR) at the University of Helsinki, a new Neutral cluster and Air Ion Spectrometer - Particle Size Magnifier (NAIS-PSM) for number concentration and size distribution of atmospheric ions and neutral particles with a mobility diameter of 0.8–42 nm and number concentration of particles with a mobility diameter of 1.25–2.5 nm, was installed in November 2023 (Figure 8.4). This new collaboration and the results from the previous ATMO-ACCESS project have led to relevant scientific presentations (Agro’ et al., 2023; 2024; Casans et al., 2024; Casquero-Vera et al., 2023; Huang et al., 2023; 2024; and Yang et al., 2024).



Figure 8.4. Operation of the NAIS from the University of Helsinki at IARC-AIS

8.3.3 The development of METAL-WRF regional model for the description of dust mineralogy in the atmosphere

The elemental composition of dust analysed at IARC-AIS contributed to the collaborative study by Solomos et al. (2023), where it was utilized to validate the METAL-WRF module designed for simulating the mineralogical makeup of desert dust aerosols, employing the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). In this work, a new wet deposition mechanism was integrated into the dust module, complementing the pre-existing dry deposition process. The updated model now includes separate prognostic variables for nine minerals—illite, kaolinite, smectite, calcite, quartz, feldspar, hematite, gypsum, and phosphorus—sourced from the GMINER30 database, as well as iron, based on the FERRUM30 dataset.

Findings highlight the significant influence of dust minerals as predominant aerosols across regions such as North Africa, southern Europe, the North Atlantic, and the Middle East, encompassing both dry and wet deposition beyond desert areas. Overall, METAL-WRF demonstrated a strong performance in replicating the relative concentrations of various mineral species in the atmosphere. Notably, the model accurately simulated iron (Fe) concentrations, an element crucial for oceanic biogeochemical processes and solar radiation absorption, showing a 22% overestimation at Izaña Observatory and a 4% overestimation at the Agia Marina Xyliatos station (Cyprus, Greece). Future improvements, including the incorporation of more recent mineralogical surface data, for example from NASA's Earth Surface Mineral Dust Source Investigation (EMIT) mission, are expected to enhance the model's predictive capabilities.

8.3.4 AERO-MAP: A data compilation and modelling approach to understand spatial variability in fine and coarse mode aerosol composition

A joint collaboration with researchers of the University of Cornell was established in the frame of AERO-MAP (Mahowald et al., 2024), a new aerosol compilation designed to evaluate the spatial variability of particulate matter in Earth system and air quality models. This dataset, which is based on climatological averages, incorporates both total particulate mass and, where available, detailed composition data, encompassing around 15 000 monitoring stations and over 10 million records of daily to weekly averaged measurements. Despite this effort, the majority of the Earth's surface, including much of the land areas, remains insufficiently sampled regarding surface particle concentrations and especially their composition, limiting our understanding of the current global distribution of aerosols. Furthermore, it was found that in many climate models, between 10% and 30% of aerosol mass in the PM_{2.5} and PM₁₀ size ranges is omitted across extensive regions,

with ammonium nitrate and agricultural dust identified as the major aerosol components typically missing.

8.3.5 Characterizing the atmospheric Mn cycle and its impact on terrestrial biogeochemistry

Data from IARC also contributed to the research conducted by Lu et al. (2024), which focused on investigating the influence of manganese (Mn) on carbon (C) biogeochemical cycling within ecosystems. The study combined compiled emissions inventories from identified sources with an atmospheric model and ground-based concentration measurements to simulate and quantify the global Mn cycle in the atmosphere. It was estimated that annual emissions of atmospheric Mn in aerosols (PM₁₀) reach approximately 1 400 Gg Mn per year, with about 31% originating from human activities.

In industrialized regions, the deposition of anthropogenic Mn significantly reduced the "pseudo" turnover times of Mn in surface soils (originally ranging from 1 000 to over 10 million years) by one to two orders of magnitude. Additionally, human-related Mn deposition elevated the Mn-to-nitrogen (N) ratio in atmospheric deposition across non-desert regions (values between 5×10^{-5} and 0.02), although it remained one to three orders of magnitude lower than the corresponding soil Mn-to-N ratios. A correlation analysis indicated a negative association between Mn deposition rates and topsoil carbon density in temperate and (sub)tropical forests, aligning with evidence from in situ biogeochemical studies that atmospheric Mn input can enhance carbon respiration processes.

8.3.6 Passive samplers: Mercury and persistent organic pollutants

As mentioned previously, the AIS group is also responsible for the measurements of different passive samplers, for mercury and persistent organic pollutants. These passive sampler programmes are led by the ECCC and CSIC.



Figure 8.5. Image showing on the pole on the left, the passive mercury samplers from Environment and Climate Change Canada at the top and several PM₁₀ and PM_{2.5} sensors below. On the right are shown the persistent organic pollutants passive samplers from CSIC.



Figure 8.6. Image showing on the left on the Aerosols Research Laboratory terrace, one of the passive samplers from Environment and Climate Change Canada

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9 Column aerosols

9.1 Main scientific goals

The main scientific goals of this programme are:

- Long-term high-quality measurements of column aerosol properties in the FT and the MBL.
- Aerosol characterization in the Saharan Air Layer and the MBL.
- Development of new methodologies and instrumentation for column aerosols and water vapour observations, as well as new calibration techniques.
- Mineral dust model validation.
- Satellite borne aerosol data validation.
- Provision of accurate sun and lunar photometer calibrations and intercomparisons.

9.2 Measurement programme

The measurement programme is very extensive, including photometric, lidar and ceilometer observations.

Photometric observations are performed at three of the IARC stations, IZO, SCO and TPO (see Tables 3.2, 3.4 and 3.6). Two of the most important parameters for long-term monitoring of the evolution of atmospheric aerosol are AOD, which accounts for the aerosol loading in the atmospheric column, and the Angström Exponent (AE) which gives information on the size and type of the particles. Both parameters have been measured at IZO since 2004 and SCO since 2005, as AERONET-Cimel stations and at IZO also within the WMO GAW - Precision Filter Radiometer (WMO GAW-PFR) network since July 2001.

AOD observations at IZO can be also dated back to 1982 (Figure 9.1) when they were performed with the Astronomical Potassium-based Resonance Scattering Spectrometer Mark-I (Barreto et al., 2014).

An IARC collaborative station at Roque de los Muchachos (La Palma) was established in 2019 to extend the monitoring of atmospheric aerosol at key sites.

IARC manages not only the AERONET sites of IZO (Figure 9.2), SCO (Figure 9.3), TPO and collaborative stations in Spain, but also collaborates closely and provides technical assistance to AERONET-Africa sites, such as Tamanrasset (Algeria), Cairo (Egypt) and Carthage (Tunis). These observations near dust sources over the Sahara provide key information for the WMO Barcelona Dust Regional Center (see section 20) for dust modelling, verification and validation of satellite-based aerosol products.

IZO is a reference calibration site for radiometric observations and calibrations using the Langley plot technique (since 2011) for AERONET and ACTRIS due to the pristine and relatively stable atmospheric conditions at this site. Together with Mauna Loa (Hawaii), IZO is the site for absolute calibration of the WMO GAW-PFR network of the World Radiation Center (Wehrli, 2000, 2005; Toledano et al., 2018).

Moreover, reference instruments belonging to AERONET, AERONET-Europe and the China Aerosol Remote Sensing NETwork (CARSNET), managed by the China Meteorological Administration (CMA; Key Laboratory of Atmospheric Chemistry, Centre for Atmosphere Watch and Services, Chinese Academy of Meteorological Sciences), are periodically calibrated at IZO (Che et al., 2009; Toledano et al., 2018). The absolute calibration of Cimel instruments is complemented by laboratory radiance calibration using the integrating sphere of the Optical calibration facility at IZO.

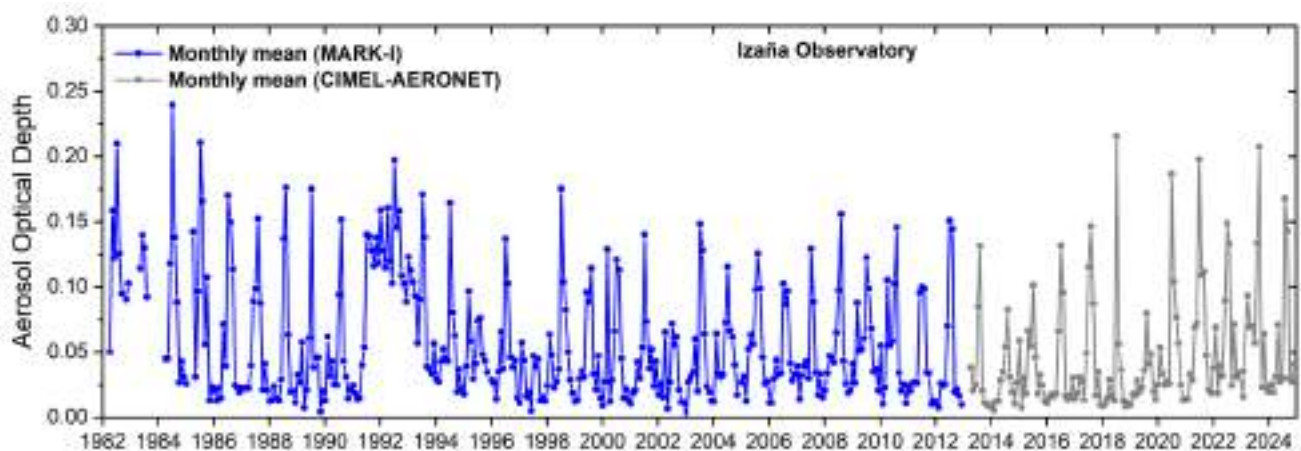


Figure 9.1. Monthly AOD measured at Izaña (in blue) between 1982 and 2012 with the Mark-I spectrometer. AOD measured with Cimel CE318 photometers within AERONET (<https://aeronet.gsfc.nasa.gov/>) are also included, completing the series between 2012 and 2024 (in grey).



Figure 9.2. Cimel reference instruments of the AERONET-Europe Calibration Facility at Izaña Observatory



Figure 9.3. Cimel CE318-TS in operation at Santa Cruz Observatory (SCO). On the right, a ZEN, an IR radiometer, radiation instrumentation and a Hirst volumetric spore trap.

9.2.1 Lidar observations

The IARC and the Spanish Institute for Aerospace Technology (PI: Dr Margarita Yela) co-manage a Micropluse lidar (MPL-3) aerosols programme, belonging to the NASA Micro-Pulse Lidar Network (MPLNET), which started a long-term observation programme in 2005. This instrument is part of the NASA MPLNET worldwide aerosol lidar network and operates in full-time continuous mode (24 hours a day / 365 days a year). This instrument operating at SCO can be considered the unique aerosol lidar in Northern Africa that provides regular and long-term information about the vertical structure of the Saharan Air Layer over the North Atlantic.

This lidar was replaced in May 2018 by a new MPL-4B lidar provided by NASA Goddard Space Flight Center MPLNET. The new MPL-4B lidar provides common features of the previous MPL-3 version in addition to dual polarization backscatter measurements allowing researchers to discriminate between aerosol types and clouds phase. A ferroelectric liquid crystal (FLC) is used in these new systems, in addition to a slightly modified measurement strategy to accommodate the difference in polarizer

properties. The main technical characteristics of the MPL-4B are detailed in Table 9.1.

Table 9.1. Technical characteristics of the Micro-Pulse Lidar (MPL) at Santa Cruz de Tenerife Observatory

Micro-Pulse Lidar version 4 (MPL-4B)	
Transmitter	
Laser	Nd:YAG
Wavelength	532 nm
Pulse repetition rate	2500 Hz
Pulse energy	6–8 μ J
Receiver	
Type	Maksutov Cassegrain
Diameter	18 cm
Focal	240 mm
Field of view	Dual field of view configuration: Narrow FOV: 100 μ rad Wide FOV: 2 mrad
Polarization	Co-polar and cross-polar components
Detector	
Type	Avalanche photodiode (APD)
Mode	Photocounting

Another MPL-4B was acquired by IARC in February 2020 and installed in the Testbed#2 lidar facility at IZO (Figure 9.4) in order to provide simultaneous measurements with two MPLs, one located at sea level, and one located in Izaña (2373 m a.s.l.), along with their co-located AERONET sun photometric measurements. These two pieces of information are useful for the characterization of the Saharan Air Layer, its effects in lower (marine boundary layer) and higher (free troposphere) layers and also its impact on mid and high cloud formation.



Figure 9.4 New lidars facility (Testbed#2) at IZO, hosting both the MPL-4B and the CE376 GPN micro-Lidar

In addition to the two MPL-4B lidars, a Cimel CE376 GPN micro-lidar is also installed at IZO in the same room as the MPL-4B (Figure 9.4). CE376 performs observations at two wavelengths (532 and 808 nm) with two depolarization channels, complementing the existing MPL data with NIR measurements.

As part of the WMO Measurement Lead Centre for Aerosols and Water Vapour Remote Sensing Instruments, IZO carries out some activities related to column aerosol measurements specifically focusing on methodological and instrument development aspects (see section 19 for more details).

9.2.2 Ceilometer observations

The Vaisala CL51 ceilometer was installed in SCO in 2011. It has a single channel centered at 910 nm. Every 36 s, it provides atmospheric backscatter profiles up to 15 km altitude as well as cloud base heights at three different altitude levels. The Vaisala CL51 ceilometer was integrated into the European Meteorological Network (EUMETNET) Automatic Ceilometer and Lidars Network (ALC) within the framework of the EUMETNET Profiling Programme ([E-PROFILE](#)) on 24 April 2018. The height of the mixing layer is also obtained in near real time, as well as profiles averaged over 10 and 60 minutes of atmospheric extinction and AOD at 910 nm, taking the AOD of SCO and/or IZO as a reference.



Figure 9.5. CL51 ceilometer in operation in SCO

9.3 Summary of remarkable results during the period 2023–2024

The most relevant results obtained during the reporting period are summarized hereinafter.

9.3.1 Sharp increase in Saharan dust intrusions over the western Euro-Mediterranean in February–March 2020–2022 and associated atmospheric circulation

Between February and March (FM) of 2020–2022, Europe was impacted by multiple intense dust intrusions originating from northern Africa. These events were notably frequent despite winter typically being the season of minimal dust activity in the Mediterranean, and some episodes reached unprecedented levels of duration and/or intensity, affecting

broad sectors of the western Euro-Mediterranean (WEM) region. Cuevas-Agulló et al. (2024) developed a catalogue of FM dust episodes across the WEM during 2003–2022, using satellite aerosol observations, and examined their large- and synoptic-scale atmospheric drivers, with particular emphasis on the unusually active 2020–2022 period (Figure 9.6).

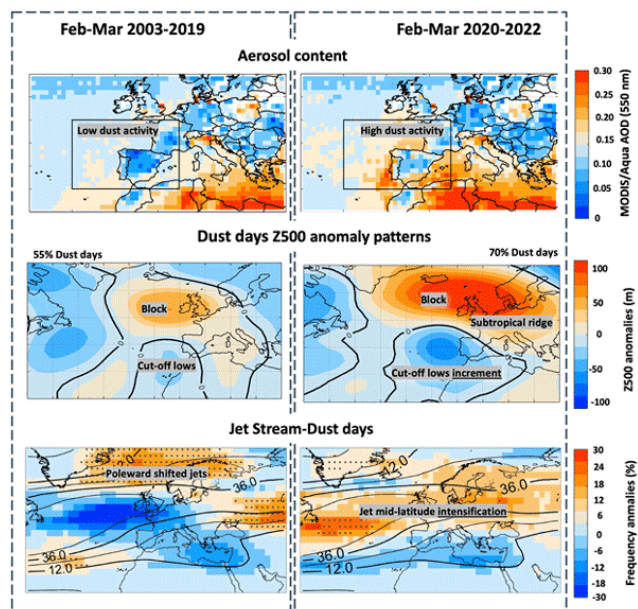


Figure 9.6. Monthly MODIS/Aqua AOD at 550 nm monthly averages (upper panel), Z500 anomalies (in metres) (mid panel) and jet stream frequency anomaly during dust days. Source: Third-party map. This map was taken from Cuevas-Agulló et al. (2024) on 1 April 2026 and may not fully align with United Nations and WMO map guidance.

Their results demonstrated marked variability both within seasons and across years in the occurrence of winter dust events in the region. Dust episodes during FM 2020–2022 stood out for their elevated concentrations and greater maximum altitudes compared to previous years (2003–2019). These events were generally associated with strengthened high-pressure systems over the Euro-Atlantic sector, which disrupt the westerly flow and encourage the formation of cut-off lows at subtropical latitudes. However, the configuration of these systems can vary significantly, encompassing meridional dipole blockings with jets displaced poleward or Mediterranean subtropical ridges coupled with an enhanced mid-latitude jet stream. Although meridional blockings are typically the main favourable pattern for dust outbreaks in the WEM, Mediterranean ridges became relatively common during 2020–2022.

9.3.2 Evaluation of on-site calibration procedures for SKYNET Prede POM sun-sky photometers

The retrieval of columnar intensive aerosol properties from sun-sky photometers requires the calibration of both irradiance and radiance measurements. For irradiance, it is necessary to determine the solar calibration constant (V_0),

which represents the instrument's response to the direct solar flux extrapolated to the top of the atmosphere. Additionally, the solid view angle (SVA), which characterizes the instrument's field of view, is crucial for deriving radiance from diffuse sky irradiance observations.

In this study, the calibration approaches adopted by three sun-photometer networks (SKYNET, AERONET, and WMO GAW), were assessed, focusing particularly on the performance of on-site calibration methods. These methods, while applicable to all sun-sky photometers, were specifically tested on SKYNET's Prede POM01 in the paper published by Campanelli et al. (2024) during four intercomparison campaigns and laboratory calibrations conducted within the Metrology for Aerosol Optical Properties (MAPP) project. These campaigns were held at two mountain sites, Davos and IZO, and at two urban sites, Rome and Valencia.

On-site calibration, ideally performed monthly, helps track instrument condition changes and ensures continuous monitoring, significantly minimizing data loss compared to centralized calibration, which requires shipping instruments off-site. Results show that on-site V0 calibration at low-turbidity locations achieves excellent agreement with reference calibrations, with discrepancies ranging from 0.5 % to 1.5 % depending on wavelength. In contrast, in urban environments, differences increase to between 1.7 % and 2.5 %. Regarding the SVA, deviations ranged from as little as 0.03 % to as much as 3.46 %.



Figure 9.7. Coefficients of variation, calculated as the percent ratio between the standard deviation and the mean values. Reprinted from Campanelli et al. (2024).

9.3.3 Final meeting of the EURAMET/EMPIR project “Metrology for aerosol optical properties” (MAPP)

The European Metrology Programme for Innovation and Research (EMPIR) coordinates research projects including EMPIR-MAPP (Metrology for aerosol optical properties) financed by the European Association of National Metrology Institutes (EURAMET). The EMPIR-MAPP project (2020–2023) was coordinated by PMOD/WRC as a consortium of 14 partners (6 National Metrological Institutes and 8 external partners), in which AEMET was included. The general objective of EMPIR-MAPP was to improve our understanding of the role that aerosols play in the atmosphere by improving the observation of these components and the intercomparability of the different measurement networks that are currently dedicated to monitoring these components.

The final meeting of EMPIR-MAPP project took place in Davos in May 2023 where all the partners made an analysis on the most important outcomes from the 3-year project. The seven deliverables of the project were the following:

- 1) Report on SI-traceable calibrations of reference radiometers (target uncertainty of 0.1%–0.5%) and array spectroradiometers (target uncertainty of 1%) from AERONET Europe, WMO GAW-PFR and SKYNET Europe aerosol monitoring networks measuring direct solar spectral irradiance, in the spectral range 310 nm up to 1 700 nm.
- 2) Methods for SI-traceable calibrations of network radiometers from AERONET Europe.
- 3) Validation report of lunar irradiances and evaluation of the lunar phase models ROLO/RIMO.
- 4) Spectral Aerosol Optical Depth from Traceable Spectral Solar Irradiance Measurements to the SI.
- 5) Estimates of remote sensing retrieval errors by the GRASP algorithm: application to ground-based observations, concept and validation.
- 6) Report on AOD retrievals from emerging technologies such as spectroradiometer measurements.
- 7) Sensitivity of global direct aerosol radiative forcing to uncertainties in aerosol optical properties.

9.3.4 Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements

In September 2022, a 3-week measurement campaign took place at the Izaña Atmospheric Observatory where three spectroradiometer systems conducted spectroradiometric measurements of direct solar irradiance traceable to the International System of Units (SI). This campaign was the purpose of the publication of Gröbner et al. (2023), conducted in the framework of EURAMET/EMPIR.

The instruments in this campaign recorded direct spectral irradiance across different wavelength ranges: 300–550 nm (QASUME), 550–1700 nm (QASUME-IR), 300–2150 nm (BiTec Sensor, BTS), and 316–1030 nm (Precision Solar Spectroradiometer, PSR), achieving relative standard uncertainties of 0.7 % (QASUME/QASUME-IR), 0.9 % (PSR), and 1 % (BTS). Prior to the campaign, QASUME and QASUME-IR calibrations were validated at the Physikalisch-Technische Bundesanstalt (PTB) using two spectral irradiance sources: the high-temperature blackbody BB3200pg, serving as a national primary standard, and the tuneable laser facility TULIP.

Top-of-Atmosphere (ToA) solar irradiance spectra were derived from ground-based measurements through zero-air-mass extrapolation under cloud-free conditions and subsequently compared with the TSIS-1 Hybrid Solar Reference Spectrum (HSRS). The resulting ToA spectra showed agreement within 1 % across wavelengths longer than 400 nm, and for QASUME, even at shorter wavelengths in regions unaffected by significant trace gas absorption, remaining well within combined measurement uncertainties.

The comparison with QASUME data enabled a reduction in the relative standard uncertainty of the TSIS-1 HSRS from 1.3 % to 0.8 % in the 308–400 nm range. Additionally, AOD values retrieved from these irradiance measurements, using the TSIS-1 HSRS as the reference, matched those from Global Atmosphere Watch Precision Filter Radiometer (GAW-PFR) and Aerosol Robotic Network (AERONET) instruments within 0.01 in optical depth for most common spectral channels. These findings demonstrate that spectral AOD can now be reliably retrieved across a wide spectral range (300–1700 nm) using laboratory-calibrated, SI-traceable spectroradiometers, achieving quality comparable to traditional Langley-based methods. A key advancement enabling this improvement is the recent availability of the TSIS-1 HSRS, which provides a high-spectral-resolution top-of-atmosphere solar reference spectrum with minimal uncertainty.

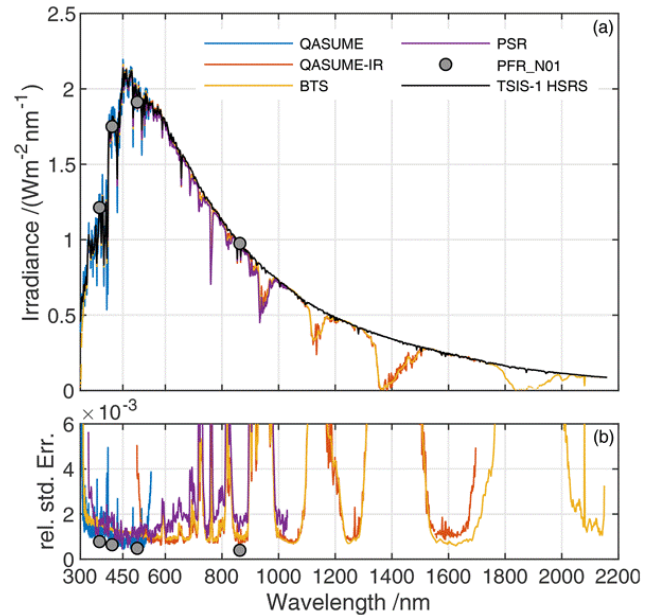


Figure 9.8. Top of atmosphere solar spectra derived from zero-air-mass extrapolations by QASUME (blue), QASUME-IR (red), the BTS (yellow), the PSR (violet), and the TSIS-1 HSRS (black) convolved with a 1 nm FWHM triangular line spread function. The grey circles represent the solar irradiances measured with PFR N01. (b) Relative standard error of the mean of the ToA solar spectra shown in the top panel using the same colour scale. Reprinted from Gröbner et al. (2023).

9.3.5 Assessment of dust size retrievals based on AERONET: A case study of radiative closure from visible-near-infrared to thermal infrared

Super-coarse dust particles (with diameters $>10\ \mu\text{m}$) are observed to be more prevalent in the atmosphere than current model estimates suggest and play a substantial role in dust-related climate effects. Because these large particles contribute less to dust extinction in the visible-to-near-infrared (VIS-NIR) range compared to the thermal infrared (TIR) region, they may be underestimated by remote sensing systems operating solely in the VIS-NIR spectrum, such as the Aerosol Robotic Network (AERONET), which is commonly used for dust model validation.

In this context, Zheng et al. (2024) conducted a radiative closure analysis by comparing AERONET-derived aerosol size distributions with collocated observations at Santa Cruz de Tenerife from the Atmospheric Infrared Sounder (AIRS) in the TIR, incorporating a thorough uncertainty assessment. The persistent warm bias identified in the comparisons indicates that AERONET retrievals may underrepresent super-coarse dust due to the spectral limitations of VIS-NIR measurements. Incorporating an additional super-coarse particle mode into the AERONET size distribution improves the closure with TIR observations without compromising the retrieval performance in the VIS-NIR range.

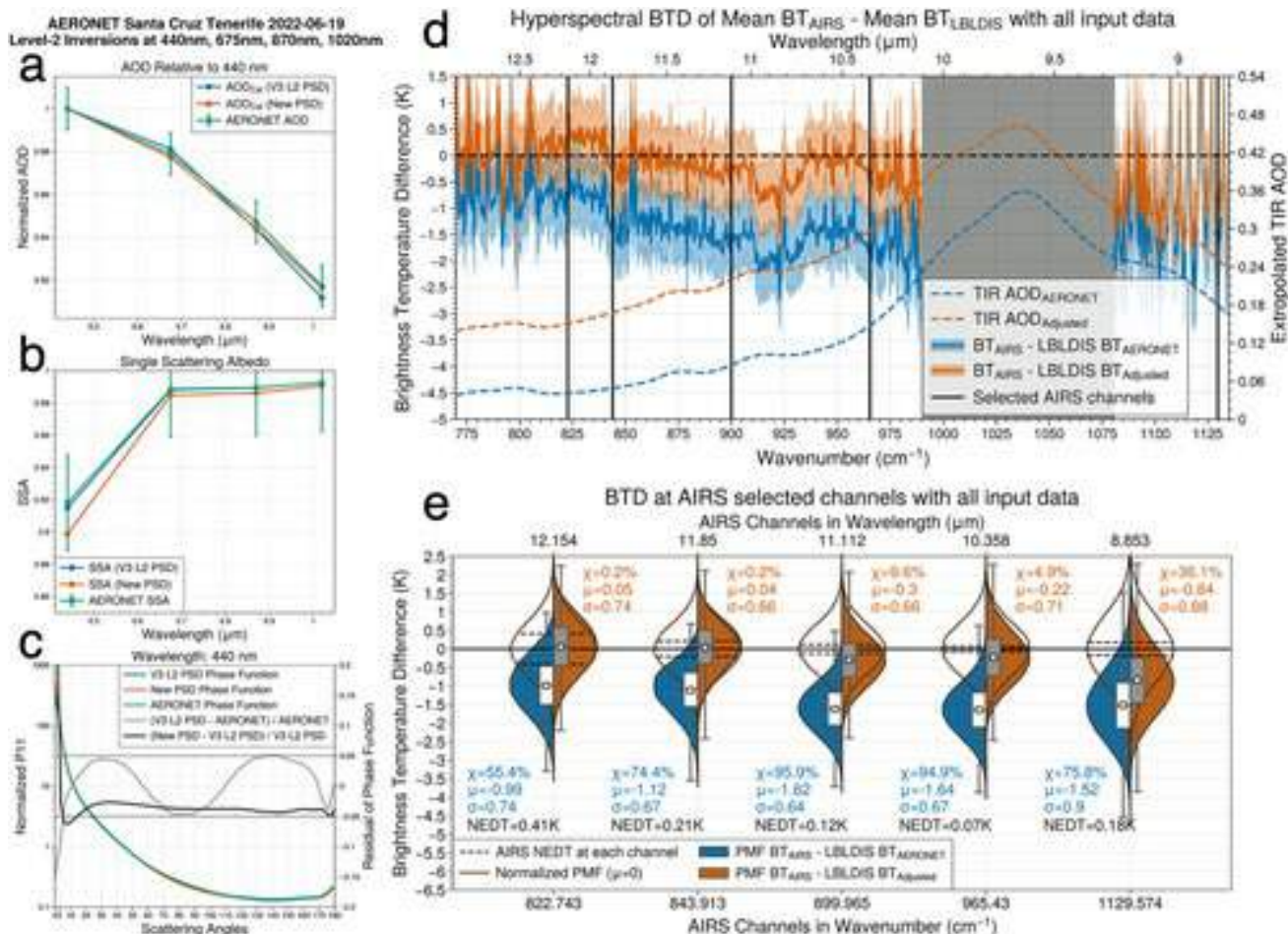


Figure 9.9. Dust spectral AOD normalized to 440 nm (a), SSA (b), phase functions (left y-axis in c) and residuals (gray and black curves for the right y-axis in c) at 440 nm from AERONET V3 L2 Inversions (a–c, green) and IITM calculations based on the AERONET V3 L2 PSD (a–c, blue) and the adjusted dust PSD (a–c, red). (d) The mean spectral BTDs (AIRS BT—LBDIS BT; real curves with respect to the left y-axis) from 770 to 1130 cm^{-1} simulated using extrapolated TIR AODs (dash curves with respect to the right y-axis) based on AERONET PSD (blue) and the adjusted PSD (red), and other reference inputs indicated in section 3.1. The gray mask represents the ozone absorption spectral regime. (e) The violin and box plots of the distribution of BTDs at the five selected AIRS channels based on AERONET PSD (blue violins, white box) and the adjusted PSD (red violins, gray box). The box boundaries and whiskers represent the 25th and 75th percentiles, and the minimum and maximum of BTDs, respectively. The χ , μ and σ represent the bias, mean and standard deviation. The brown curves represent the normalized PMF with $\mu = 0$ and the same σ as BTD distributions. The black dashed lines represent the range of AIRS NEDTs at the five channels that are listed as black texts. Reprinted from Zheng et al. (2024).

9.3.6 HARMONIA COST-Action

In October 2022, the EU COST Action “International network for harmonization of atmospheric aerosol retrievals from ground-based photometers” (HARMONIA) started. Its objective is to establish a network involving institutions, instrument developers, scientific and commercial end users, in order to improve and homogenize aerosol retrievals using mainly solar and sky but also lunar and star photometers from different networks. It aims to bridge user needs and the science and technology expertise residing in academia and industry, through:

- Increasing the interactions and knowledge exchanges between several atmospheric aerosol network measurement scientists and users.

- Standardizing and improving existing aerosol products and tools, towards a “harmony” in aerosol photometry.
- Stimulating the communication between operational agencies and academia, with the aim of increasing the applicability of aerosol products.
- Encouraging and organizing the dialogue between researchers and instrument manufacturers, towards innovation actions on current and future photometric-aerosol instrumentation.

The PI of the aerosol group (Dr África Barreto) is a member of the HARMONIA Management Committee. During 2023–2024, IARC participated in various HARMONIA meetings for example in the Working Group (WG) 3 workshop in Athens (September 2023) (Figure 9.10) and in the WG1 workshop and associated training school in Berlin (April 2024) (Figure 9.11).



Figure 9.10. Participants of HARMONIA WG3 workshop in Athens (Greece), 19 September 2023



Figure 9.11. Participants of HARMONIA WG1 workshop in Berlin (Germany), April 2024

9.3.7 A neural network to retrieve cloud cover from all-sky cameras: A case of study over Antarctica

Novel research was developed by González-Fernández et al. (2024), who introduced CNN-CC, a model based on a convolutional neural network (CNN) designed to predict daytime cloud cover (CC) from images captured by all-sky cameras. A dataset comprising 49 016 daytime sky images, collected at different Spanish sites (Valladolid, La Palma, and Izaña) using two types of all-sky cameras, was manually annotated by trained researchers into cloud cover categories (oktas).

The model demonstrated high accuracy, matching the reference values within 1 oktas for 99% of clear-sky and overcast cases, and above 93% for partially cloudy conditions. The mean bias error (MBE) and standard deviation (SD) between the predicted and observed CC values were calculated, showing low discrepancies. Further analysis across different aerosol optical depth and Ångström exponent intervals indicated that CNN-CC's performance is not influenced by aerosol load or particle size. After validation, CNN-CC was applied to a set of images taken every 5 minutes from January 2018 to March 2022 at the Marambio station in Antarctica, a site not included in the training phase. Here, the model slightly underestimated field observations, yielding an MBE of 0.3 oktas. A detailed analysis of the retrieved data showed that overcast

conditions dominated, representing 46.5% of observations annually and increasing to 64.5% in January. The annual average cloud cover was 5.5 oktas, with a standard deviation of about 3.1 oktas. An hourly breakdown of the data revealed no significant diurnal cycle, except during a few isolated months.

9.3.8 Calibration of world reference photometers

Following the volcanic eruption at Mauna Loa Observatory (Hawaii) in late 2022, which disrupted operations, IARC temporarily assumed the role of global calibration centre for several reference instruments and networks. These emergency actions were supported under the ATMO-ACCESS “Fast Track” access scheme (see section 16). Between January 2023 and April 2024, six NASA master photometers were calibrated to cover the disruption of MLO operations. One NASA reference photometer is still located at Izaña and serves as a link between the two absolute calibration centers of the network.

9.3.9 Contributions to the study of 2021 La Palma volcanic eruption processes

The aerosol group contributed to activities carried out by IARC during the 2021 La Palma volcanic eruption both in the emergency deployment in La Palma and in Tenerife at IZO. The column aerosol group participated as co-authors in the following research studies related to the volcanic eruption process:

- Córdoba-Jabonero et al. (2023): “Fresh volcanic aerosols injected in the atmosphere during the volcano eruptive activity at the Cumbre Vieja area (La Palma, Canary Islands): Temporal evolution and vertical impact”.
- García et al. (2023): “Spectral Aerosol Radiative Forcing and Efficiency of the La Palma Volcanic Plume over the Izaña Observatory”.
- Milford et al. (2023): “Impact of the 2021 La Palma volcanic eruption on air quality: Insights from a multidisciplinary approach”.
- Salgueiro et al. (2023): “Characterization of Tajogaite volcanic plumes detected over the Iberian Peninsula from a set of satellite and ground-based remote sensing instrumentation”.
- Hedelt et al. (2024): “Analysis of the long-range transport of the volcanic plume from the 2021 Tajogaite/Cumbre Vieja eruption to Europe using TROPOMI and ground-based measurements”.

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10 Radiation

The radiation programme, and specifically the implementation of its core component, the Baseline Surface Radiation Network (BSRN) programme, has been performed in close collaboration with the [University of Valladolid Atmospheric Optics Group](#).

10.1 Main scientific goals

The main scientific goals of this programme are:

- To conduct high quality measurement of radiation parameters.
- To investigate the variations of the solar radiation balance and other solar energy parameters at the four radiation measurement stations managed by the IARC.
- To investigate aerosols radiative forcing with a particular focus on the role played by dust taking advantage of the privileged situation of the Canary Islands to analyse dust outbreaks over the North Atlantic and the unique local radiation network with stations at different altitudes (from sea level to 3 555 m a.s.l.).
- To recover, digitize and analyse historical radiation data in order to reconstruct long-term radiation series that allow us to make precise studies concerning sky darkening and brightening, and relate radiation and cloud cover and solar flux.
- To conduct the spectral characterization of the solar radiation with respect to impacts of different types of clouds, aerosols, especially mineral dust, and precipitable water vapour.

10.2 Measurement programme

Direct radiation records from an Abbot silver-disk pyrheliometer are available since 1916, although this information has not yet been analysed. Global solar radiation records from a bimetallic pyranograph are available both in bands and as daily integrated values in printed lists, since 1977. This information has been digitized, recalibrated and processed. The results show an excellent agreement between the bimetallic pyranograph and the BSRN CM21 pyranometer, which allowed the successful reconstruction of a long-term global radiation data series (since 1977), after a careful analysis of historical data (Figure 10.1).

Global and direct radiation measurements started in 1992 as part of a solar radiation project of the Canary Islands Government. In 2005, IZO joined the Spanish radiation network managed by the AEMET National Radiation Center (CNR). Since 2009, IZO has been a BSRN station providing the basic set of radiation parameters (Drieme et al., 2018; García et al., 2019; 2022; 2024). In addition, other parameters, including shortwave and long wave upward radiation, UV-A and UV-B radiation are also measured within the BSRN Programme (Figure 10.1–10.4). Later, some basic radiation measurements were implemented at the other three IARC measurement stations (TPO, BTO and SCO, Figure 10.2). A summary of the radiation measurement programme managed by the IARC is given in Table 10.1.

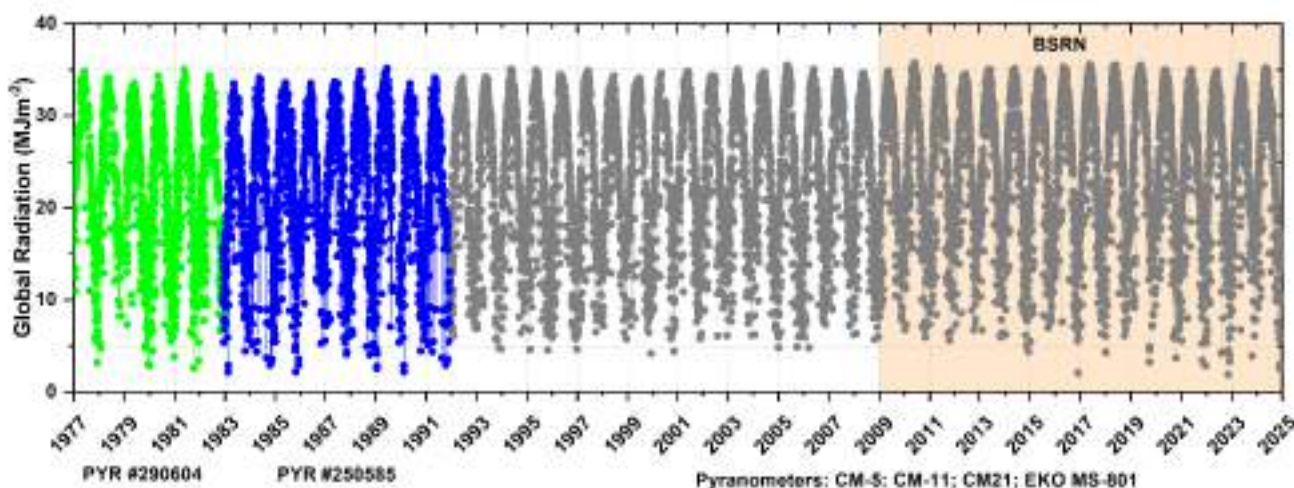


Figure 10.1. Daily GSR_H data time series between 1977 and 2024 at IZO. The green and blue dots correspond to the measurements performed with PYR #290609 and #250585, respectively, between 1977 and 1991, and the grey dots represent the measurements performed with different pyranometers (CM-5, CM-11, CM-21 and EKO MS-801) between 1992 and 2024 (García et al., 2014; 2017; 2019).

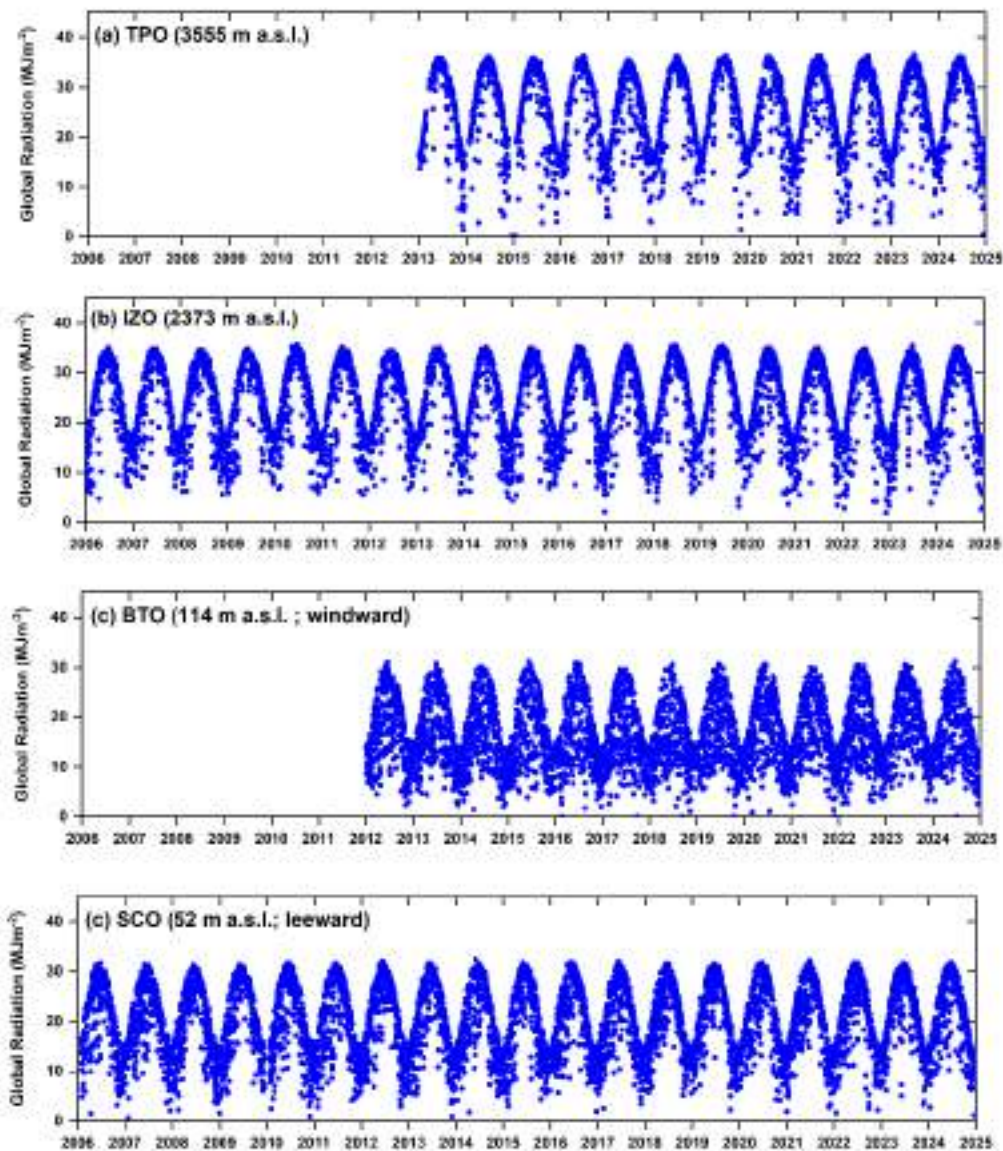


Figure 10.2. Daily global radiation (MJ m^{-2}) data time series at (a) TPO at 3555 m a.s.l., (b) IZO at 2373 m a.s.l., (c) BTO at 114 m a.s.l. and (d) SCO at 52 m a.s.l.

Table 10.1. Details of IARC radiation measurement programme

Instrument	Measurements	Spectral range
Izaña historical records (2373 m a.s.l.) Start date: Different dates		
Abbot silver-disk pyrheliometer	Direct Radiation (1916)	~ 0.3 to $\sim 3.0 \mu\text{m}$
Bimetallic pyranograph (analog.)	Global Radiation (Jan 1977)	~ 0.3 to $\sim 3.0 \mu\text{m}$
YES Multi Filter Rotating Shadow-band Radiometer	Global, diffuse and estimated direct radiation (Feb 1996)	300–1200 nm
K&Z CM5 pyranometer	Global radiation (Jan 1992)	310–2800 nm
Izaña BSRN Station (2373 m a.s.l.) Start date: March 2009		
Pyranometer K&Z CM-21, EKO MS-801, EKO MS-80S	Global and Diffuse Radiation	285–2600 nm

Pyrheliometer K&Z CH-1, EKO MS-56, EKO MS-57	Direct Radiation	200–4000 nm
Pyrgeometer K&Z CG-4, EKO MS-21	Longwave Downward Radiation	4500–42000 nm
Net Radiometer, EKO MR-60	Net Radiation	
Pyranometer K&Z UV-A-S-T, EKO MS-10S	UV-A Radiation	315–400 nm
Pyranometer Yankee YES UVB-1	UV-B Radiation	280–400 nm
Absolute Cavity Pyrheliometer PMO6	Direct Radiation	-
Spectroradiometer EKO MS-711	Spectral Direct Radiation	300–1100 nm
Spectroradiometer EKO RSB	Spectral Global and Diffuse Radiation	300–1100 nm
Spectroradiometer EKO MS-713	Spectral Global Radiation	900–2500 nm
EKO MS-321LR Sky Scanner	Luminance/Radiance	-
EKO Photon Sensor ML-020P	Photosynthetically Active Radiation (PAR)	400–700 nm
SPN1 Sunshine Pyranometer	Global and Diffuse Radiation	400–2700 nm
Izaña National Radiation Center (CNR) Station (2373 m a.s.l.) Start date: August 2005		
Pyranometer K&Z CM-21	Global and Diffuse Radiation	285–2600 nm
Pyrheliometer K&Z CH-1	Direct Radiation	200–4000 nm
Pyrgeometer K&Z CG-4	Longwave Downward Radiation	4500–42000 nm
Pyranometer Yankee YES UVB-1	UV-B Radiation	280–400 nm
Pyranometer K&Z PQS1	Photosynthetically Active Radiation (PAR)	400–700 nm
SCO (52 m a.s.l.) Start date: February 2006		
Pyranometer K&Z CM-11	Global and Diffuse Radiation	310–2800 nm
Pyrheliometer EPPLY	Direct Radiation	200–4000 nm
SPN1 Sunshine Pyranometer	Global and Diffuse Radiation	400–2700 nm
BTO (114 m a.s.l.) Start date: 2009		
Pyranometer K&Z CM-11	Global and Diffuse Radiation	310–2800 nm
TPO (3555 m a.s.l.) Start Date: July 2012		
Pyranometer K&Z CM-11, CM-21	Global and Diffuse Radiation	310–2800 nm
Pyranometer Yankee YES UVB-1	UV-B Radiation	280–400 nm
SPN1 Sunshine Pyranometer	Global and Diffuse Radiation	400–2700 nm



Figure 10.3. Radiation instrumentation installed at IZO

Radiation measurements are tested against physically possible and globally extremely rare limits, as defined and used in the BSRN recommended data quality control. Shortwave downward radiation (SDR) measurements are compared daily with SDR simulations, which are modelled with the LibRadtran model. This information has been created and shared on the web page <http://bsrn.aemet.es/>, where real time measurements of global, direct, diffuse and UV-B radiation are shown.

The radiation measurements have been complemented with spectral measurements of global, direct, and diffuse radiation, covering both the visible and infrared ranges, using the instruments described below.

10.2.1 EKO MS-711 spectroradiometer

Measurements of spectral direct solar radiation (spectral direct normal irradiance) are performed with an EKO MS-711 spectroradiometer (Figure 10.4) starting in 2016. This instrument covers a wavelength range from 300 to 1 100 nm, exhibiting a Full Width at Half Maximum < 7 nm. It is equipped with its own built-in entrance optics, and the housing is temperature-stabilized at $25^{\circ} \pm 5^{\circ}$ (Egli et al., 2016; García et al., 2020; 2021).



Figure 10.4. The EKO MS-711 spectroradiometer at IZO

The EKO MS-711 spectroradiometer is mounted on an Owel INTRA 3 sun-tracker (Figure 10.4), an intelligent tracker which combines the advantages of automatic-tracking operation (automatic alignment with the system of astronomical coordinates follows after a few days), and actively-controlled tracking (a 4-quadrant sun sensor). It is constructed for use under extreme weather conditions; its operational temperature range is between -10 and $+50^{\circ}\text{C}$.

It can sustain about 50 kg of a carefully balanced load. The tracker motors have a special grease for use in low temperatures. The drive unit has an azimuth rotation $>360^{\circ}$. It moves back to the start (morning) position at the corresponding midnight. The drive unit has a zenith rotation $>90^{\circ}$. The unit has an angular resolution $\leq 0.1^{\circ}$, an angular repeatability of $\pm 0.05^{\circ}$ and an angular velocity $\geq 1.5^{\circ}/\text{s}$ on the outgoing shafts. The maximum speed is $2.42^{\circ}/\text{s}$.

10.2.2 EKO RSB spectroradiometer

The spectral direct solar radiation measurements have been complemented since February 2020 by global and diffuse solar radiation measurements performed with an EKO RSB (Figure 10.5). This instrument covers a wavelength range from 300 to 1 100 nm.



Figure 10.5. The EKO RSB spectroradiometer at IZO

10.2.3 EKO MS-713 spectroradiometer

In 2022, IZO acquired a grating spectroradiometer EKO MS-713 (Figure 10.6) to complete the measures of the spectral global radiation in the near infrared wavelength range of 900 to 2500 nm.



Figure 10.6. The EKO MS-713 spectroradiometer at IZO

10.3 Other instrumentation and measurements

In late 2020, an EKO sky scanner model MS 321-LR was installed at IZO (Figure 10.7). This instrument is provided with two sensors, one measures the sky luminance (Kcd/m^2) and the other measures the sky radiance ($\text{W/m}^2\text{sr}$). The sensors are mounted on a tracker. Data from the sky scanner is obtained in 10 min. intervals during daylight (each scan takes up to 4.5 min.). The distribution of both luminance and radiance is obtained by dividing the sky dome in 145 patches with field of view of 11° .



Figure 10.7. The sky scanner EKO MS 321-LR installed at IZO

The atmospheric transmission is a data product that has been produced since 2014, it was also processed retrospectively back to 2009, and it has been updated until 31 December 2024 (Figure 10.8). It is available on the IZO BSRN web page. The atmospheric transmission is derived from broadband (0.2 to $4.0\ \mu\text{m}$) direct solar irradiance BSRN observations. Data are for clear-sky mornings between solar elevations of 11.3° and 30° .

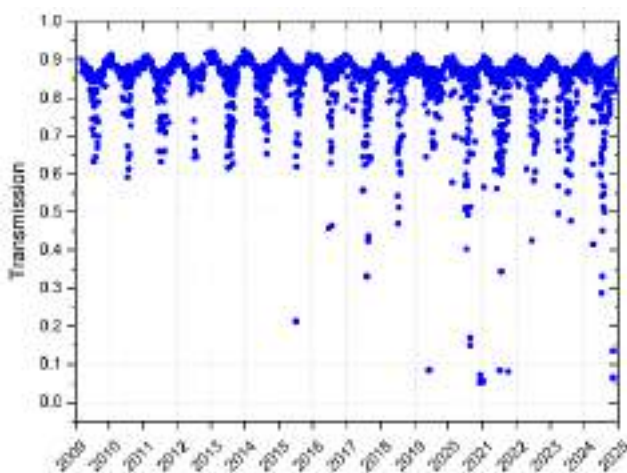


Figure 10.8. Daily atmospheric transmission data of direct solar irradiance at IZO computed for clear-sky mornings between solar elevations of 11.3° and 30° (2009–2024)

10.4 Participation in scientific projects and campaigns/experiments

10.4.1 Calibration campaign of BSRN instruments with a PMO6 Absolute Cavity Pyrheliometer

As part of the radiation quality assurance system a calibration campaign of BSRN pyranometers and pyrheliometer took place in summers 2023 and 2024 using an Absolute Cavity Pyrheliometer PMO6 as reference (Figure 10.9). The PMO6 was calibrated by the World Radiation Center, Davos. The BSRN instruments were calibrated following the ISO 9059:1990 (E) and ISO 9846:1993(E), delivering the corresponding official calibration certificates.



Figure 10.9. Absolute cavity radiometer (PMO6) installed at IZO during summers 2023 and 2024 on the BSRN sun-tracker

10.5 Summary of remarkable results during the period 2023–2024

González-Fernández et al. (2024) presented CNN-CMF, a new model based on convolutional neural networks (CNN) designed to retrieve solar shortwave irradiance by estimating the cloud modification factor (CMF) from daytime sky images captured by all-sky cameras. A total of 237 669 images, paired with SW irradiance measurements from pyranometers, were collected from three locations: Valladolid and Izaña in Spain, and Lindenberg in Germany (Figure 10.10).

The dataset was randomly divided into training and testing subsets, ensuring that the test data were not used during model training to allow for independent validation. Model predictions were compared to pyranometer measurements using scatter density plots, achieving a high coefficient of determination (R^2) of 0.99. Statistical evaluation showed a mean bias error (MBE) close to -2% and a standard deviation (SD) of around 9% , indicating a slight underestimation of irradiance by the CNN-CMF model. The model's generalization capabilities were further assessed at the Marambio station in Antarctica, a site excluded from the training dataset. In this case, the comparison yielded an R^2 of 0.95, an MBE of approximately 2% , and an SD near 26% . While the precision decreased at Marambio, the accuracy remained consistent with previous evaluations, showing a slight overestimation of SW irradiance. Finally, when

estimating daily SW irradiation values, the model's performance improved, reaching an R^2 of 0.99, with an MBE around 3% and an SD close to 11%.

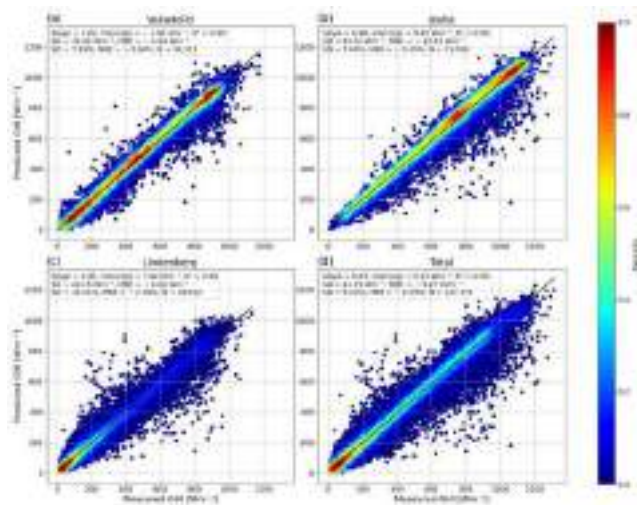


Figure 10.10. Density scatter plots between the shortwave global horizontal irradiance (GHI) predicted by the trained CNN-CMF model and the measured one with a pyranometer. Panels (a–d) correspond to the test dataset of Valladolid, Izaña, Lindenberg, and all stations together, respectively. The colour bar marks the density of the points ranging from 0.0 to 1.0. The black straight line represents the linear fit. The linear fit coefficients, the number of data used (N), the standard deviation (SD), and the mean bias error (MBE) values of the GHI differences between the CNN-CMF model and the measured values are also added (in relative and absolute values) for each panel (Reprinted from González-Fernández et al., 2024).

The main on-going and future activities of the radiation programme are focused on:

- Characterization of CIE standard sky types at IZO from sky scanner measurements.
- Accurate determination of cloud attenuation impact on global, direct and diffuse spectral radiation performed with EKO RSB spectroradiometer from SCO and IZO.
- Reconstruction and accurate analysis of a new long-term GSR data series (since 1916) in which newly recovered observation data are being incorporated. Long-term records of aerosols (AOD), cloudiness, and solar flux will be compared with GSR data.
- Accurate determination of cloud attenuation impact on global radiation using GSR from SCO and BTO.
- Accurate analysis of UV-B broadband data from the vertical transect formed by SCO (52 m a.s.l.), IZO (2 373 m a.s.l) and TPO (3 555 m a.s.l.) observatories, with complementary information on cloudiness, AOD and O_3 vertical profiles (ECC O_3 sondes).

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11 Differential Optical Absorption Spectroscopy (DOAS)

11.1 Main scientific goals

Differential Optical Absorption Spectroscopy (DOAS) and Multi Axis Differential Optical Absorption Spectroscopy (MAXDOAS) techniques allow the determination of atmospheric trace gases present in very low concentrations. The long-term monitoring of atmospheric trace gases is of great interest for trend studies and satellite validation. The detection of gases using DOAS or MAXDOAS technique allows the study of mutual interaction between gases even when detection limits of the gases are low.

The main scientific goals of the DOAS and MAXDOAS programme are:

- To improve the knowledge of the distribution, seasonal behaviour and long-term trends of minor constituents related to ozone equilibrium such as NO₂, BrO and IO and their distribution in the subtropical atmosphere.
- To obtain a climatology of stratospheric NO₂ and BrO in subtropical regions and to study its dependence on environmental and climate variables.
- To study the seasonal variations of NO₂, O₃, formaldehyde (HCHO) and IO in the free troposphere and their interaction with environmental factors such as Saharan dust amongst others.
- To contribute to validation of NO₂ and O₃ satellite products (GOME, GOME2, SCIAMACHY, OMI, TROPOMI) and in the improvement of the methodology to perform such comparisons.

11.2 Measurement programme

The DOAS technique (Platt and Stutz, 2008) is a method to determine the atmospheric trace gases column density by measuring their absorption structures in the near ultraviolet and visible spectral region.



Figure 11.1. DOAS instruments outdoor optics with sky trackers and indoor set up at IZO

The technique is based on measurement of atmospheric absorption of solar radiation at selected wavelength bands where the gas under consideration shows a structured and known absorption cross-section. For stratospheric observations the instrument is pointed at zenith during the twilights.

Although the DOAS technique was developed for stratospheric research, during the last few years it has been largely employed in tropospheric environment and pollution episodes studies. In particular, the so called Multi Axis Differential Optical Absorption Spectroscopy approach allows to infer vertical distribution of minor species from spectrometric measurements of solar scattered light at given angles of elevation (off-axis measurements). The analysis technique makes use of the Optical Estimation Method (Rodgers, 2000) by putting together the off-axis measurements and a radiative transfer algorithm to get the best solution for all used elevation angles.

The instruments (see Figure 11.1) automatically take spectra from an AM SZA = 96° to PM SZA = 96°, every day. As the instrument must work with a stabilized room temperature and also with a stabilized internal temperature and humidity, those parameters are monitored and recorded in data files. Calibration of the instrument grating is performed approximately every year. Calibration of the elevation angle is performed once a month. After the spectral inversion, a quality control of data is carried out. The acquired data are filtered on the basis of the analysis and instrumental error, aerosol optical thickness and the solar zenith angles, to ensure quality.

INTA has performed measurements of stratospheric O₃ and NO₂ at IARC since 1993. Data have been used for the study of stratospheric O₃ and NO₂ distribution in the subtropical region (Gil et al., 2008, Gil et al., 2012 and Yela et al., 2017) and for validation of satellite products (Hendrick et al., 2011, Robles-Gonzalez et al., 2016, Yela et al., 2017). In 2003, the installation of an ultraviolet DOAS spectrometer expanded the measurements of stratospheric gases to the near ultraviolet region, allowing the monitoring of stratospheric BrO and the estimation of the concentration of BrO in the free troposphere. In 2010, the instruments were adapted to MAXDOAS measurements, allowing the detection of free tropospheric trace gases, such as IO and NO₂ (Puentedura et al, 2012, Gomez et al., 2014, Gil-Ojeda et al., 2015) in the visible region and of BrO and HCHO in the ultraviolet region. Prior to the installation at IZO in 2009, the VIS-MAXDOAS instrument participated in the international blind NO₂ MAXDOAS intercomparison campaign CINDI (Cabauw Intercomparison campaign Nitrogen Dioxide measuring Instrument) (Peters et al., 2012, Pinardi et al., 2013). During the AMISOC campaign in 2013, extensive measurements of IO were performed at three different altitude levels on Tenerife.

11.3 Participation in scientific projects and campaigns/experiments

11.3.1 Contribution to NDACC database

The Network for Detection of Atmospheric Composition Change (NDACC, De Mazière et al., 2018) is one of the most important global networks which primary goal is to establish long-term databases for detecting changes and trends in the chemical and physical state of the atmosphere and to assess the coupling of such changes with climate and air quality. INTA, with DOAS measurements of O_3 and NO_2 at IZO, has contributed to NDACC since 1998. Participation in NDACC requires compliance with strict measurement and data protocols to ensure that the network data are of high

and consistent quality. O_3 and NO_2 results are shown in Figures 11.2 and 11.3.

11.3.2 Contribution to CAMS27

The Copernicus Atmosphere Monitoring Service (CAMS) is an integrated service within the Copernicus programme that provides information on the atmospheric composition. CAMS27 provides CAMS or high-quality atmospheric data in HDF GEOMS format within a few weeks after measurements acquisition from selected NDACC stations, such as the DOAS measurements at IARC from INTA.

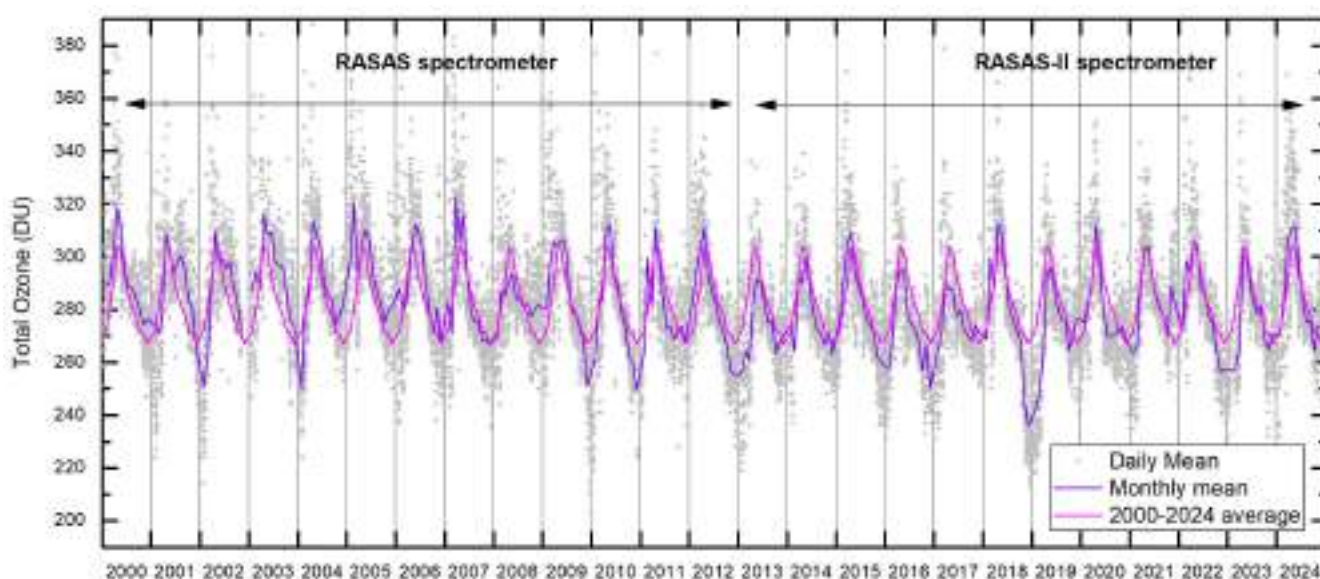


Figure 11.2. Time series of reanalysed stratospheric O_3 2000-2024

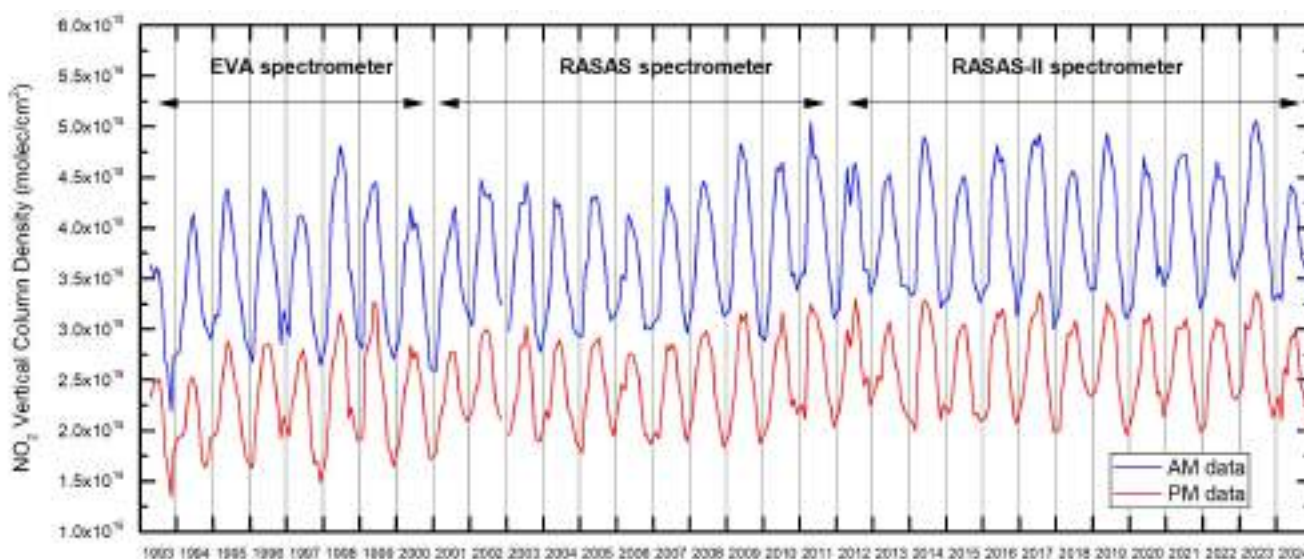


Figure 11.3. Time series of reanalysed stratospheric NO_2 1993-2024

11.3.3 Contribution to FRM4DOAS-2.0

Fiducial Reference Measurements (FRM) can be defined as a suite of independent, fully characterized, and traceable ground measurements that follow the guidelines outlined by the project Quality Assured Data for Earth Observation communities (QA4EO). These FRM provide the maximum return on investment for a satellite mission by delivering to users the required confidence in data products, in the form of independent validation of results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission. A number of FRM projects have been set up in the past by ESA to build up FRM for different satellites and measurement types.

FRM4DOAS2.0 (FRM for DOAS 2.0), led by BIRA-IASB, started in 2022 and will be completed in 2026, was designed as a continuation of the previous FRM4DOAS project. The main objectives of FRM4DOAS were the specification of best practices for the operation of MAXDOAS instrumentation, the evaluation of the different existing MAXDOAS analysis algorithms, and, finally, the development and implementation of a central and automatic near real-time processing system for the delivery of harmonized and quality-controlled MAXDOAS data products (NDACC MAXDOAS Service). FRM4DOAS-2.0 focuses on the consolidation of existing trace gas algorithms and the development of a new suite of products under the FRM MAX-DOAS activity.

The VIS-MAXDOAS instrument installed at IARC is part of the FRM4DOAS project providing NO₂ and O₃ DOAS/MAXDOAS data products.

11.3.4 CINDI-3 campaign

The Third Cabauw INtercomparison of UV-Vis DOAS Instruments (**CINDI-3**) campaign took place at the Cabauw Experimental Site for Atmospheric Research (CESAR), The Netherlands, from 21 May to 24 June 2024. CINDI-3 was organized under the umbrella of NDACC and conducted as part of the ACTRIS-CREGARS Topical Center for trace gas remote sensing with additional support from the European Space Agency and from the EU ATMO-ACCESS project.

The main objective of the exercise was to compare the performance of MAX-DOAS instruments when measuring NO₂, ozone, aerosols and several other reactive gases, such as formaldehyde, glyoxal and bromine monoxide. Following this intercomparison, the participating instruments can now reliably support the validation of space-borne instruments such as the current Sentinel-5p/TROPOMI and GeoKOMPSAT-2B/GEMS as well as future Copernicus instruments on Sentinel-4 and Sentinel-5 missions.



Figure 11.4. INTA MAXDOAS UV-VIS, CINDI-3 campaign, Kingdom of the Netherlands, 21 May to 24 June 2024

INTA successfully participated in this intercomparison using MAX-DOAS instrumentation identical to that installed at IARC. Figure 11.4 shows the outdoor optics of the INTA MAX-DOAS instrument used in the campaign.

11.4 Summary of remarkable results during the period 2023–2024

11.4.1 Fiducial reference measurements for air quality monitoring

In this paper, Van Roozendaal et al. (2024) presents the current status of the FRM4DOAS project. The centralized data processing system for MAXDOAS instruments, which was developed as part of the FRM4DOAS project, has already reached pre-operational status. It has demonstrated its ability to deliver quality-controlled atmospheric composition data products with a latency of one day. The system incorporates advanced algorithms, selected by the scientific community, for the retrieval of total ozone, lower tropospheric and stratospheric NO₂ vertical profiles and formaldehyde profiles.

Although it is still in pre-operational/demonstration mode, FRM4DOAS has already been used in several scientific and validation studies and has also been deployed to support field campaigns for the validation of the TROPOMI and GEMS satellite missions, such as the CINDI-3 campaign.

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12 Water vapour

12.1 Main scientific goals

The main scientific goals of this programme are:

- To conduct long-term water vapour monitoring and study its relationship with climate change.
- To study radiative forcing due to water vapour.

To achieve these goals, high-quality measurements are conducted with state-of-the-art instrumentation consisting of a microwave radiometer, Global Navigation Satellite System (GNSS) receiver network, radiosondes, photometers and a Fourier transform infrared spectrometer (see section 12.2 for more details). From these various measurement datasets, the following products are obtained:

- Precipitable water vapour (PWV) and liquid water (LW) total column content.
- PWV, LW, temperature and humidity vertical profiles.
- Intra-hourly and diurnal PWV variability.
- Diurnal and annual mean cycles of PWV.
- Monthly and annual PWV mean series, analysing their homogeneity and evaluating their anomalies and evolution over time to detect possible trends.

With these products, IARC contributes to the EUMETNET Profiling Programme (**E-PROFILE**) with measurements from the RPG-LHATPRO-G5 series microwave radiometer, installed at IZO on 11 May 2020 and the EUMETNET GNSS Water Vapour Programme (**E-GVAP**) through a network of GNSS receivers located at different places and altitudes in Tenerife and La Palma islands since July 2008.

12.2 Measurement programme

Several instruments and measurement techniques are used in this programme as detailed below. Comparisons of column-integrated water vapour (precipitable water) between different techniques and instruments have been carried out during the preceding years (e.g. Romero Campos et al., 2009, Schneider et al., 2010a, García et al., 2021a, García et al., 2021b). In December 2023, we published a technical document that incorporates and validates the column-integrated water vapour measurements obtained from the microwave radiometer with those of the other available techniques (Romero Campos et al., 2023).

12.2.1 Global Navigation Satellite System technique

The Global Navigation Satellite System technique consists in determining PWV in the atmospheric column from the observed delay in radio signals at two different frequencies emitted by a network of Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) satellites received by a GNSS receiver (Figure 12.1).



Figure 12.1. Global Navigation Satellite System receiver at IZO

Currently, the group works with 11 GNSS receiver stations (Figure 12.2) at different altitudes, ten of them in Tenerife and one in La Palma. Izaña Observatory in Tenerife and Roque de Los Muchachos in La Palma are the only sites on Canary Islands where ZTDs from precise GNSS orbits are processed. In the rest of the GNSS stations, the ZTDs are obtained from ultra-fast GNSS orbits.

The atmospheric pressure in places where the GNSS antennas are located is a key parameter for obtaining the PWV from the zenith total delay (ZTD) and zenith hydrostatic delay (ZHD). The Spanish National Geographic Institute (IGN) is in charge of managing the GNSS network and data acquisition, as well as the calculation of the ZTD from the GNSS signals, currently using the Bernese 5.4 software version applied for both ultra-fast and precise orbits. The ZHD calculation depends on the temperature and pressure at the GNSS antenna sites. However, atmospheric pressure plays a more important role in determination of PWV than temperature. An uncertainty of 1 hPa in pressure produces, approximately, the same uncertainty in determination of PWV (0.33 mm to 0.36 mm) as an uncertainty of 5K in temperature (Hagemann et al., 2003).

The PWV is calculated from ZTD and pressure values at the different GNSS stations. One of the most important tasks carried out is to estimate the pressure at the GNSS sites where surface pressure measurements are not available due to the absence of barometric sensors. To do this, based on the perfect gas law and the hydrostatic equation, a precise value of pressure as a function of altitude and temperature is calculated for each GNSS station using a grid of ten automatic meteorological stations equipped with barometric and temperature sensors, located at different altitudes (Figure 12.2).

The values of the PWV column in quasi-real time are obtained at each GNSS station from the ZTDs from ultra-fast GNSS orbits, which have a temporal resolution of 15 minutes and are available approximately every two hours.

Values are plotted as contour maps (Figure 12.3a). Together with these maps, profiles are obtained that represent the amount of PWV contained in layers located between GNSS stations (Figure 12.3b).

Similarly, using the predicted pressure, temperature, specific humidity and geopotential altitude fields from ECMWF we also obtain maps analogous to Figure 12.3a and Figure 12.3b with predicted PWV.

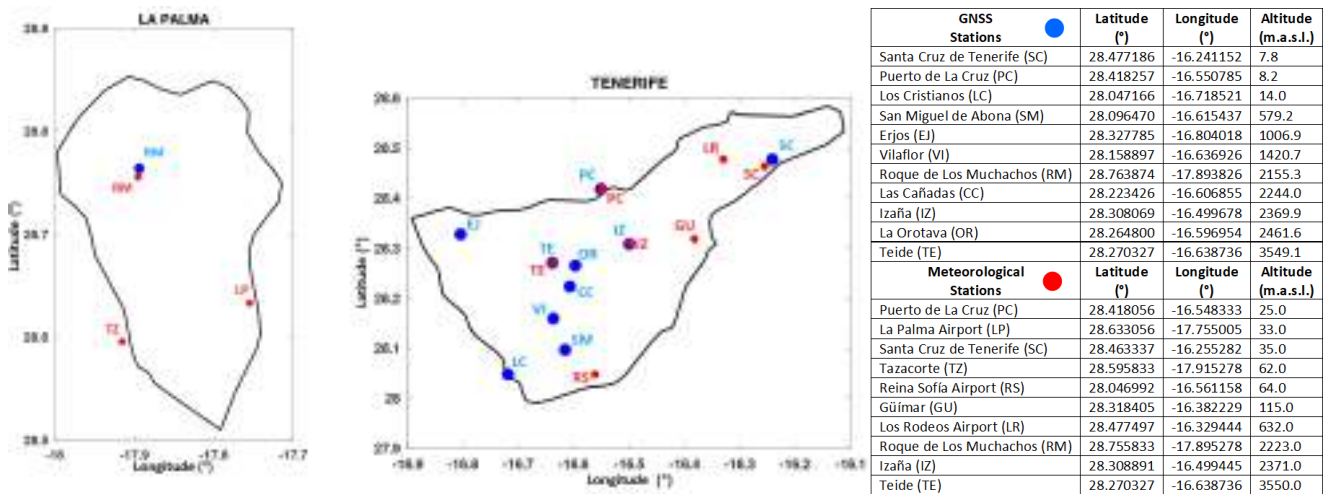


Figure 12.2. Locations of Global Navigation Satellite System stations and automatic meteorological stations in La Palma and Tenerife

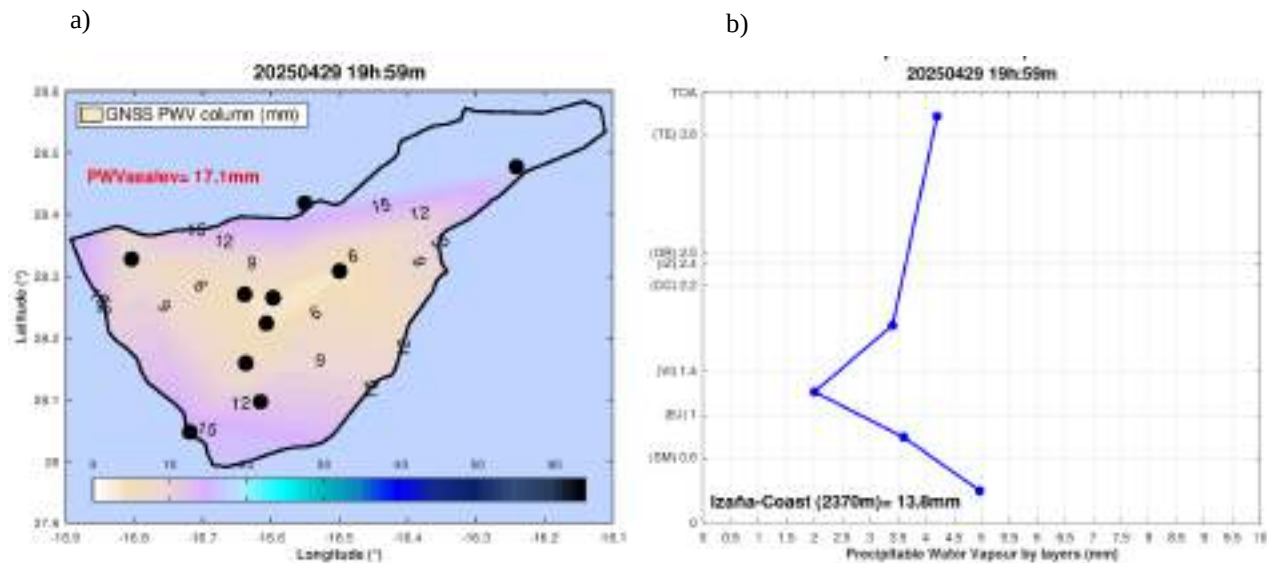


Figure 12.3. PWV at the GNSS stations in Tenerife obtained in quasi-real time at 19:59 UTC on 29 April 2025. a) PWV column values and b) PWV profile between stations

12.2.2 FTIR

The IARC FTIR programme is described in section 7, where details are given on the atmospheric composition observations conducted within the programme. To obtain column-integrated water vapour, the solar spectra acquired with the standard TCCON settings (Wunch et al., 2011; Schneider et al., 2010b) are used. These measurements are made between 4 000 and 9 000 cm^{-1} (corresponding to wavelengths between 1 111 and 2 500 nm) at a spectral resolution of 0.02 cm^{-1} .

12.2.3 Radiosondes Vaisala RS41

From the vertical profiles of relative humidity obtained with Vaisala RS41 radiosondes, precipitable water content in the atmospheric column is calculated by integrating numerically (using the trapezoidal rule) the density function of atmospheric water vapour for the base and top of each atmospheric layer. The integration is performed from ground level to 12 km altitude. By default, the PWV profile is supplied for the following layers: 1) from ground up to 1.5 km; 2) from 1.5 km to 3 km altitude in layers of 0.5 km

thickness; 3) from 3 km altitude up to 12 km in layers of 1 km thickness.

The use of RS41 radiosonde sounding started on Tenerife on 13 December 2017. During the radiosonde's ascent into the atmosphere, a vertical profile of meteorological data is taken and readings within the vertical profile have a temporal resolution of 1 s. Prior to 2017, RS-92 radiosondes were used from 1995–2017, with a temporal resolution of readings within the vertical profile of 2 s. The high temporal resolution of RS41 radiosondes provides a large number of levels in the vertical profiles of pressure, temperature, humidity and wind.

However, at high altitudes (~14 km in the stratosphere), we have occasionally detected a weak decrease in reported altitude in the RS41 Vaisala Tenerife radiosonde data. It could be due to the combination of an excessively high temporal resolution and longer response times and errors of the different meteorological sensors and GNSS. For these reasons, the erroneous records are filtered from the files before they are evaluated.

12.2.4 Photometric observations

Details of photometric observations conducted at IARC are given in section 9 (Column Aerosols programme). Since 2012, the CIMEL CE318-T sun-sky-lunar photometer has been utilized (Barreto et al., 2016). Column-integrated water vapour is obtained following the procedure described in Smirnov et al. (2004) with an uncertainty of 10%. According to Schneider et al. (2010a), this uncertainty varies depending on the humidity conditions, with values of 7% for humid conditions and 25% for very dry conditions (IWV < 2 mm).

12.2.5 EKO MS-711 Spectroradiometer

The IARC Radiation programme is described in section 10, where details are given on water vapour retrievals from spectral direct irradiance measurements with an EKO MS-711 spectroradiometer at IZO. These measurements and an intercomparison with other measurement techniques are also described in García et al. (2021a).

12.2.6 Microwave radiometer

In 2019, a high precision microwave radiometer (MWR) was acquired to measure tropospheric temperature and humidity vertical profiles, with high temporal resolution, at IZO (Figure 12.4). It was installed at IZO on 29 April 2020. The Low Humidity and Temperature Profiling (LHATPRO-G5 series) microwave radiometer (Radiometer Physics GmbH) is specially designed to make humidity measurements under low humidity conditions such as those in the free troposphere above IZO. The radiometer obtains vertical profiles of humidity and tropospheric temperature up to 10 km of height above its emplacement, with a spatial

resolution of 200 m to 400 m depending on the height level, with a temporal resolution of 1 second.

The microwave radiometer operates with two receivers. The first one has six channels at different frequencies: around the 183 GHz water vapour line for humidity and water vapour profiling and the second one works with seven channels around the 60 GHz oxygen absorption line for temperature profiling from the brightness temperature measurements.



Figure 12.4. MWR on the Izaña Observatory instrument terrace

The instrument is also equipped with a double channel coupled infrared radiometer (IRR), a GPS receiver and a conventional weather station with a rain sensor. Figure 12.5 shows an example of the main types of MWR measurements retrieved.

Through the radiometer's RPG software, using an artificial neural network (ANN) algorithm, derivative products can be obtained such as Absolute and Relative Humidity (HPC), Full Tropospheric Temperature Profile (TMP), the Liquid Water Path (LWP), Column Integrated Water Vapour (IWV), Hydrostatic and Wet Zenith Delays (DLY) of GPS signals, Infrared Temperatures (IRT), Atmospheric Stability Indices (STA), Cloud Base Height (CBH), Height (BLH) and Temperature Profiles of the Planetary Boundary Layer (TPB) and Atmospheric Attenuation (ATN).

The MWR is a robust instrument, with a high degree of autonomy, especially designed for outdoor measurements in high mountain conditions that require minimal maintenance. The most important maintenance task is calibration. The equipment requires absolute calibration with liquid nitrogen every six months. The last valid calibration at IZO took place on 8 May 2024, since the one on 21 November 2024 could not be carried out correctly due to the breakage of one of the liquid nitrogen targets. On the same day, the original radome sheet was substituted for a new one since the old one was deteriorated by use and the weather conditions.

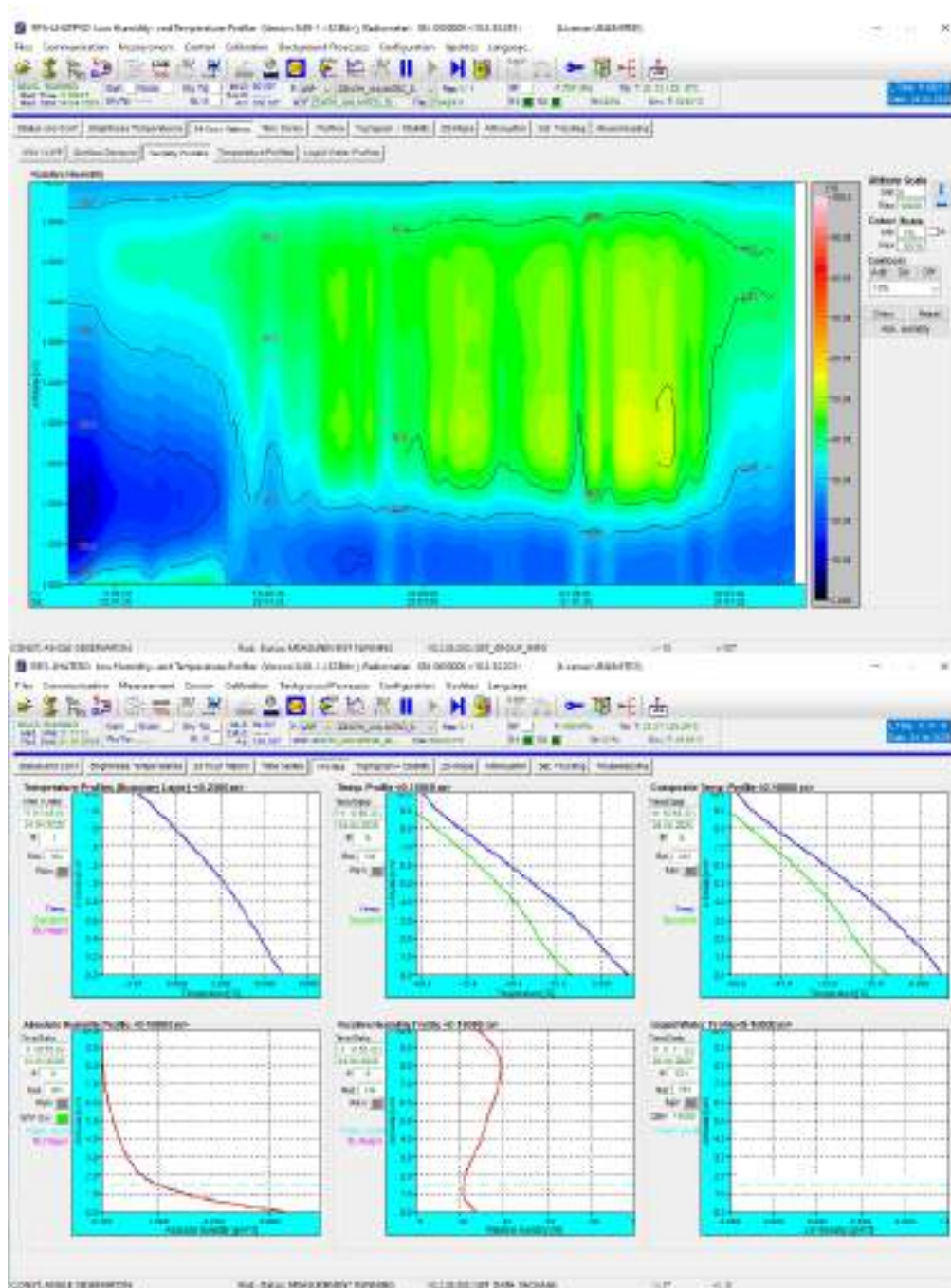


Figure 12.5. Example of the main types of measurements of the MWR on 24 April 2025 at the Izaña Observatory. Upper panel: 24-hour history of the absolute humidity taken at 11 UTC; lower panel: different vertical profiles at 11 UTC.

Figure 12.6 represents a comparison of the temperature and absolute humidity profiles between the MWR and the radiosondes measurements on 13 October 2024 at 11 UTC at IZO. These results demonstrate that while there is a reasonable agreement between the profiles measured by these two different measurement techniques, the indirect derivation from brightness temperature and the MWR inversion algorithms together with the lower spatial resolution mask certain thermal inversions as well as absolute humidity variations at different levels that the sounding does measure.

On 20 January 2021, we requested the incorporation of the microwave radiometer as a measurement instrument into the E-PROFILE Profiling Programme and on 11 March 2021, IZO was included in a list of potential stations of the new E-PROFILE MWR Network still under development and not operational to date. On 24 March 2023, the MWR was officially registered within E-PROFILE and raw data in hourly files is sent automatically and processed through a centralized hub as part of a pilot programme. Currently, Met Office and MeteoSwiss are working on L1 products and their dissemination improving the quality checks and setting up a daily monitoring based on observation and simulation for the brightness temperature.

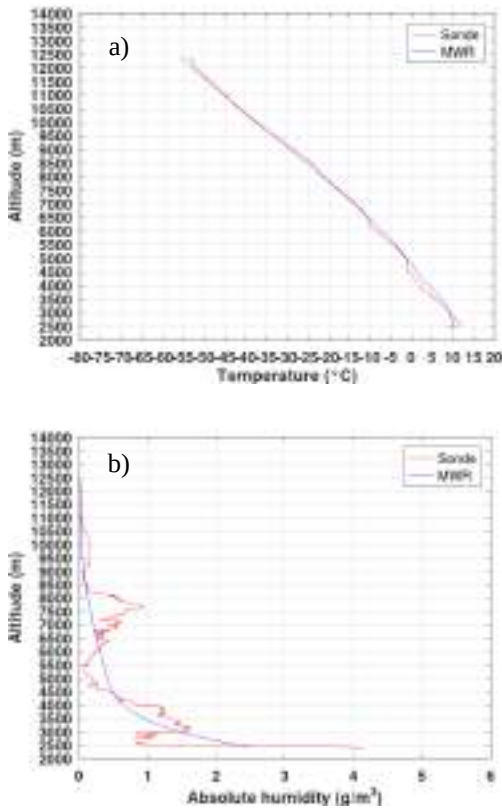


Figure 12.6. a) Temperature and b) absolute humidity profiles from radiosondes (red) and MWR (blue) on 13 October 2024 at 11 UTC at the Izaña Observatory

12.3 Updating the PWV series: 2023–2024

Following a similar procedure to that of other authors (Botey et al., 2013); diurnal, monthly and annual PWV averages are calculated when the data coverage is $\geq 60\%$.

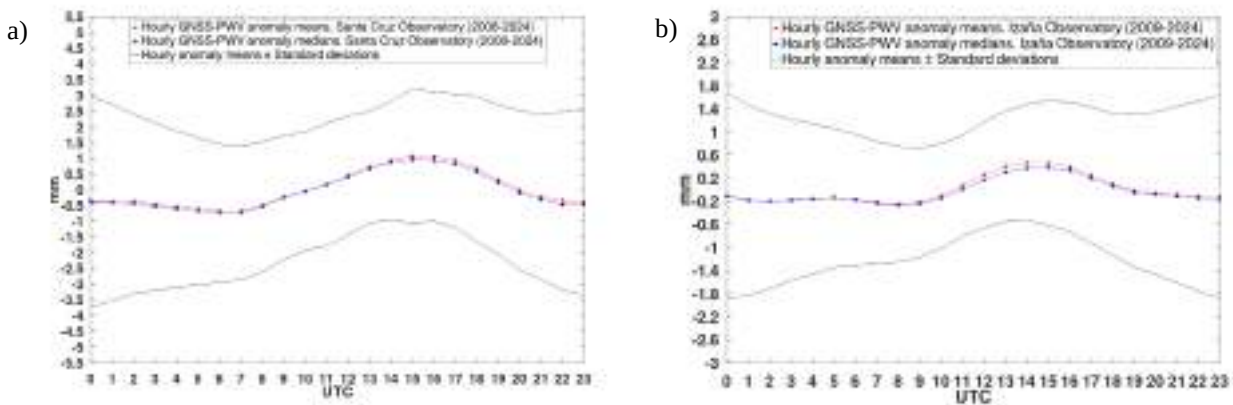


Figure 12.7. PWV mean daily cycle at a) SCO and b) IZO, from GNSS during 2008–2024 and 2009–2024 respectively

12.3.1 Daily mean cycle of PWV from GNSS

The averaged daily cycles of PWV are shown for GNSS stations at SCO (2008–2024) (Figure 12.7a) and at IZO (2009–2024) (Figure 12.7b). Ultrafast orbits (those available) have been used for SCO, and precise orbits were used at IZO. The daily cycles have been calculated from average hourly anomalies. For these statistics, we have selected only those hourly average values with at least 60% of high-quality intra-hours values, on days with at least 15 hourly means (60%). The daily time anomalies were obtained by subtracting the value of the corresponding daily average from the value of the hourly average: hourly mean - daily mean.

Then, for each hour, the averages for all the available data anomalies within the period of evaluation are calculated. A total of 5 663 daily records for IZO and 4 091 for SCO have been analysed for the period 2008–2024.

Daily variations are qualitatively similar in SCO and IZO but they are smoother in IZO than in SCO. The minimum of the mean daily cycle in SCO is reached around 6UTC–7UTC and in IZO around 8UTC, while the maximum occurs around 14UTC in IZO and around 15UTC in SCO. This suggests that although there is a synoptic cause that modulates the variations, there is also a local influence due to the geography and locations of both stations.

12.3.2 Monthly mean PWV data series from radiosondes, GNSS and MWR

PWV monthly means obtained from radiosondes, GNSS and MWR at IZO are shown for the period 1995–2024 at 12 UTC (Figure 12.8). These are the values of PWV calculated over the duration of the radiosonde flight (about 2 hours or so) from the time of its release (approximately 12 UTC), and assuming that, during this period of time, the PWV remains constant. An annual cycle with peak in summer-autumn and minimum values in winter is seen in the data. The series was subjected to the corrections for different types of sondes described in (Romero Campos et al., 2011). The results shown in Figure 12.8 seem to indicate a slight increase in the amount of PWV over IZO starting in 2020, which is noticeable in both the minimum and maximum annual values of the series. At the same time, we can observe how the MWR provides higher PWV values than the other two techniques, in agreement with the conclusions obtained in Romero Campos et al. (2023).

Using a 99% confidence level in the Wilcoxon-Mann-Whitney test (Lanzante, 1996), weak inhomogeneity was found in the median of the monthly series of the PWV in IZO at 12UTC in May 2020. The signal-to-noise ratio at the point of change was $0.054 > 0.05$. For the rest of the PWV monthly mean series, no lack of homogeneity was detected in the median at a confidence level $\geq 99\%$. No significant trends have been found in any of the series.

Given that the presence of water vapour above 12 000 m is very small (90% of the water vapour is concentrated in the troposphere below 12 000 m), the values obtained from radiosondes are comparable with those obtained with the GNSS technique. The agreement between the two techniques as depicted in Figure 12.8 is very good; the small differences observed can be attributed to the fact that the GNSS measurements are zenith, while the radiosondes do not measure vertically, rather its profile moves horizontally, at a greater or lesser distance, depending on weather conditions on launch day.

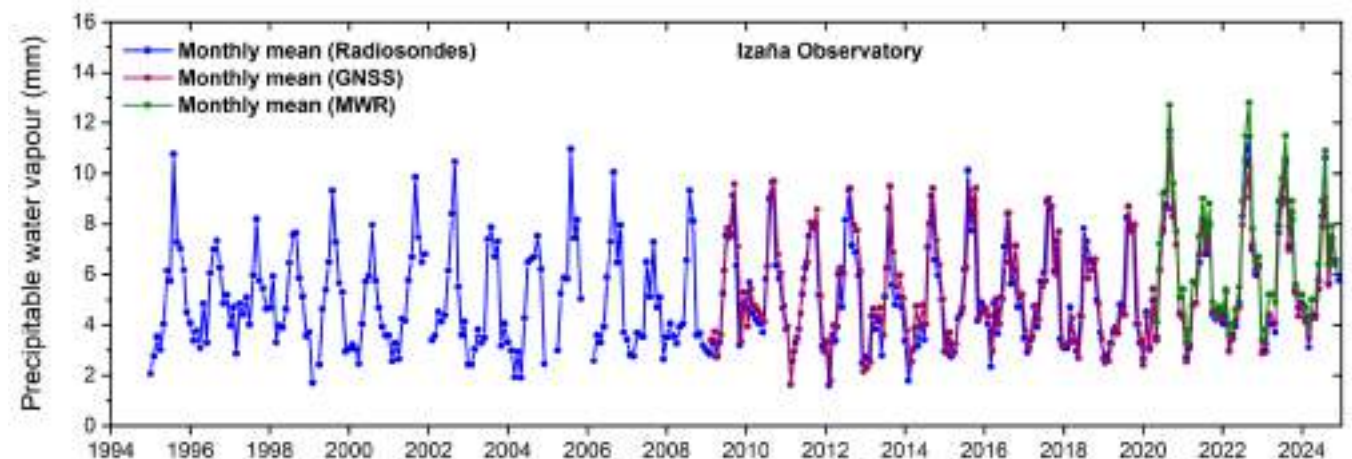


Figure 12.8 PWV monthly data series at IZO at 12UTC from radiosondes, GNSS and MWR for 1994–2024

12.3.3 Annual mean cycle of PWV from GNSS

The PWV annual cycles for SCO and IZO for the 2008–2024 and 2009–2024 period are shown in Figure 12.9 and Figure 12.10. The annual maximum of PWV in Santa Cruz is observed at the end of the summer (September), which represents a one-month delay with respect to Izaña, where the annual maximum is observed in August.

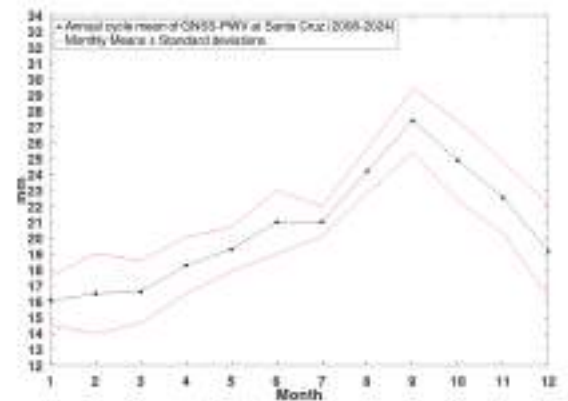


Figure 12.9. GNSS PWV mean annual cycle, SCO (2008–2024)

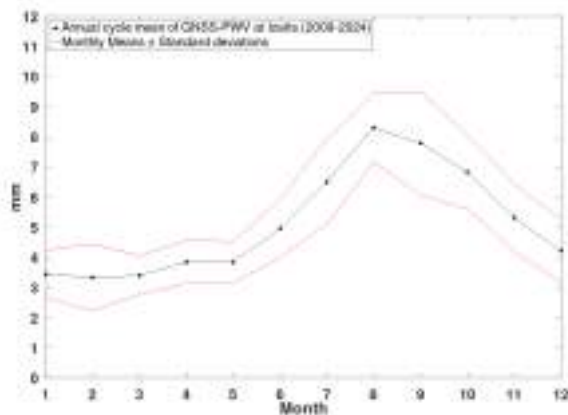


Figure 12.10. GNSS PWV mean annual cycle, IZO (2009–2024)

12.3.4 PWV vertical stratification monthly statistics

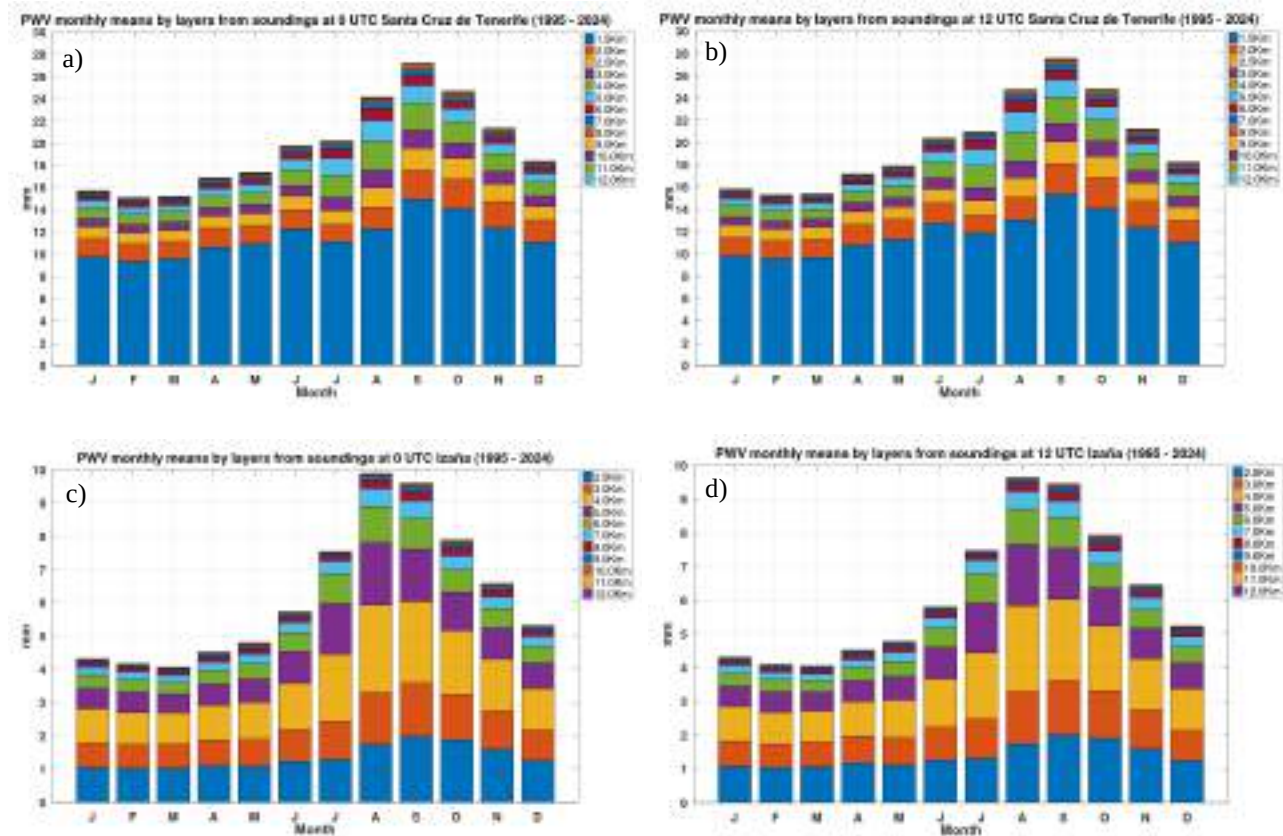


Figure 12.11. Monthly statistics of precipitable water vapour vertical distribution from Tenerife radiosondes for SCO a) 0UTC, b) 12UTC and IZO c) 0UTC and d) 12UTC (1995–2024)

The monthly average of PWV vertical distribution over Tenerife obtained from radiosondes data at 0 UTC and 12 UTC during the period 1995–2024, are depicted for SCO in Figures 12.11a-b and for IZO in Figures 12.11c-d. The total height of each column corresponds to the total monthly averaged PWV from the station level up to 12 km above sea level. No significant differences are found between 0 UTC and 12 UTC.

Most of the PWV is concentrated within the first 1.5 km altitude. There is a “wet” season from August to October, with a maximum in September (~27 mm) in the case of Santa Cruz, and August-September (~9.5 mm) in the case of Izaña. Similarly, we observe a “dry” season corresponding to the months of January to March at both sites with minimums in February–March of about (~4 mm) at Izaña and (~15 mm) at Santa Cruz. The rest are transition months between both seasons.

12.4 Additional activities

12.4.1 Intercomparison of PWV measurement techniques at IZO

In 2023, the Water Vapour group conducted an intercomparison between the PWV values obtained with the MWR and several other techniques and instruments (FTIR, CIMEL solar and lunar photometers, EKO MS-711 spectroradiometer, GNSS and radiosondes RS41) at IZO during different periods of time between May 2020 and April 2023. The precision, uncertainty, detection limits and compatibility between the different measurement techniques and the MWR were characterized. This study was published in Spanish as a Technical Document (Romero Campos et al., 2023) and is freely available [here](#).

Scatter plots of the PWV intercomparison during the daytime are shown in Figure 12.12. The linear fits are excellent, with correlation coefficients very close to 0.99, or even higher, indicating a very strong positive correlation in all cases. The slopes of all regressions are >1, indicating that the PWV values measured by the MWR are, on average, higher than those measured by any of the other techniques.

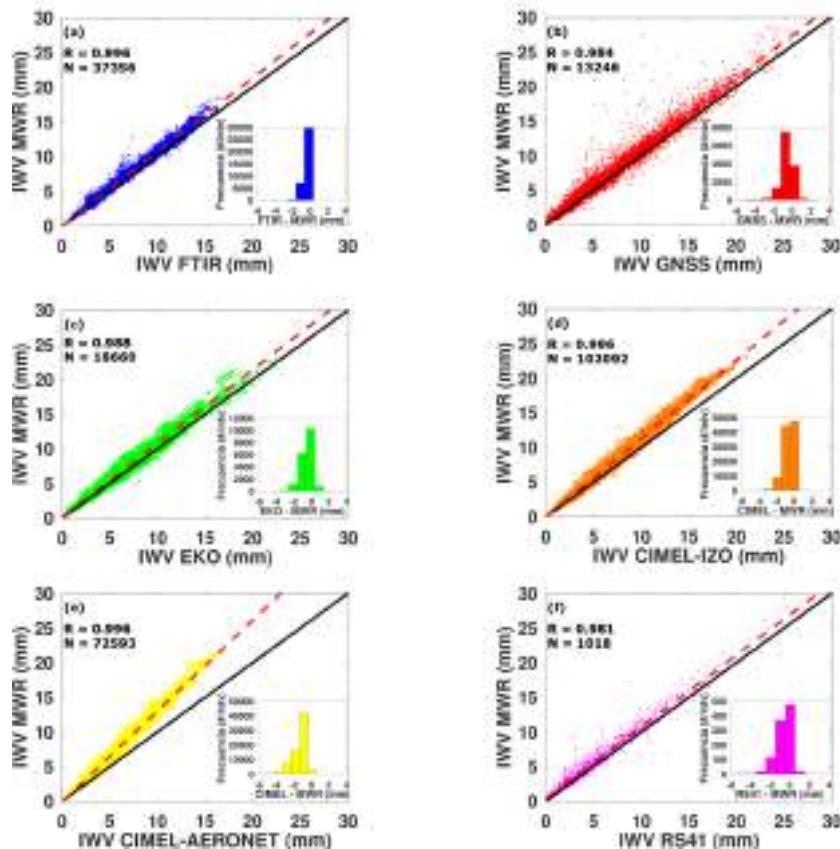


Figure 12.12. Scatter plot of daytime water vapour measured with (a) FTIR, (b) GNSS, (c) EKO MS-711, (d) CIMEL-IZO, (e) CIMEL-AERONET, and (f) RS41 compared to water vapour measured with MWR in different periods between May 2020 and April 2023. The dashed red line represents the linear fit of the measurements, the solid black line represents the diagonal ($x=y$). R is Pearson's correlation coefficient and N is the number of data points. The inserted histograms represent the distribution of the differences between the two measurements in mm ($X - \text{MWR}$). IZO 2020–2023. Reprinted from Romero Campos et al. (2023).

The results of the comparison indicate a high traceability of the MWR PWV, >90% with most of the techniques. The FTIR technique demonstrated the highest traceability during daytime (99%) and the radiosondes Vaisala RS41 demonstrated the highest traceability during the night-time (98%) (Figure 12.13). Note that the techniques which provide night-time measurements in this intercomparison are the MWR, lunar photometers, GNSS and radiosondes.

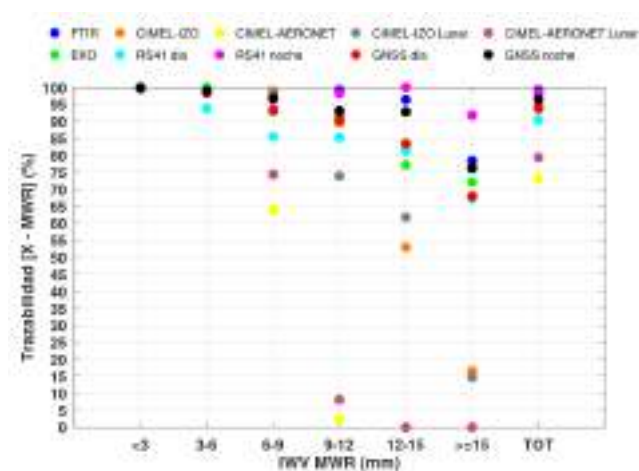


Figure 12.13. Traceability (%) of the differences in PWV between MWR and the different techniques. TOT is the total traceability of the MWR with each technique. IZO 2020–2023

The study has also allowed us to estimate the accuracy and precision of the PWV measurements, as well as the detection limit of the different techniques, confirming that the MWR and CIMEL IZO lunar techniques are the most accurate and precise with detection limits of 0.18 mm and 0.13 mm and maximum uncertainties of 0.77 mm and 0.93 mm, respectively. Another result of the analysis carried out is that the MWR instrument measures more PWV than any of the other techniques, both during the day and at night (between 4% and 22% more, depending on the technique).

It was also found that the differences between the PWV of the MWR and that of the other techniques show, in absolute value, a progressive linear increase with the water vapour content, both during the day and at night, a slight decrease with the solar zenith angle and a very weak increase with the lunar zenith angle.

Finally, a quality index (I_c) of 1.7 mm was established, which represents the maximum estimated difference for two simultaneous PWV measurements carried out in the same place by different instruments or techniques to be traceable.

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13 Meteorology

13.1 Izaña Observatory as a WMO Centennial Observing Station

Today, supercomputers and sophisticated models and satellites are important tools for climate scientists. However, long-term, high quality continuous observations from thermometers, rain gauges and other instruments remain essential. Without them, we could not be certain that the Earth has warmed by one degree centigrade over the past century. These long-term observations are vital to our scientific understanding of climate variability and change and essential for model and satellite validation activities.

To promote the recovery and continuation of these records, governments are nominating Centennial Observing Stations for formal recognition by WMO. Many Centennial Observation Stations are also of outstanding historical and cultural interest, recalling previous eras and the birth of modern meteorology. Taken together as a network, Centennial Observation Stations are uniquely able to tell the story of recent climate history.

Izaña Observatory, IZO, was recognized as a Centennial Observation Station by the WMO in 2017. More information about the WMO Centennial Observing Stations can be found [here](#).

13.2 Main scientific goals

The main goals of the meteorology programme are:

- To provide diagnosis and operational weather forecasting to support routine operation activities at the IARC observatories and issue internal severe weather alerts and special forecasts for planned field campaigns, outdoor calibrations, repairs, etc.
- To configure and operate High Resolution Numerical Weather Prediction Models capable of capturing the complex meteorology of the mountain observatory, as an aid to improve the supporting forecasts.
- To operate back-trajectory models on a monthly basis to keep a database available for other scientific projects up-to-date.
- To investigate the use of machine learning strategies to improve the forecasting of meteorological and air quality parameters.
- To maintain meteorological parameter observations according to WMO specifications, and in the framework of AEMET's Synoptic and Climatological Observation Networks.
- To measure conventional meteorological parameters at different stations on the island of Tenerife, to support other observation programmes.



Figure 13.1. Izaña Observatory (IZO) weather stations

- To develop non-conventional meteorological parameters programmes.
- To provide meteorological analysis information and technical advice to interpret and support results from other observation programmes and scientific projects, designing and implementing specific algorithms and databases to reach these goals.

13.3 Measurement programme

IARC directly manages six weather observation stations, located at IZO (3), SCO, BTO and TPO (see section 3 for more details).

13.3.1 Izaña Observatory

IZO has three fully automatic weather stations, two of them are located in the weather garden (C430E/60010 and Meteo-STD), which includes a network of five cloud observation webcams, and the third station is on the instrument terrace of the observation tower (Meteo-Tower) at 30 m above ground level. Instrumentation for manual observations (staffed by personnel, Figure 13.2) with temperature, humidity, pressure and precipitation analog recorders (bands), is also maintained at IZO in order to preserve the historical series that started at Izaña Observatory in 1916.



Figure 13.2. Izaña Observatory, manual meteorological instrumentation

13.3.2 Santa Cruz Observatory

SCO has a fully automatic weather station located on the instrument terrace.

13.3.3 Botanic Observatory

BTO has a fully automatic weather station installed at the ozonesounding station in the Botanic Garden in Puerto de la Cruz.

13.3.4 Teide Peak Observatory

TPO has an automatic very high-altitude weather station with temperature, humidity and pressure sensors, supplemented by data from a wind sensor installed at the Cable Car tower No.4, managed by the Cable car company.

The meteorology programme also has access to meteorological soundings data of pressure, temperature, humidity and wind from the Tenerife station (ID: WMO 60018) located in the town of Güimar. This station belongs to the AEMET upper-air observation network and is managed by the Meteorological Center of Santa Cruz de Tenerife (AEMET).

13.4 Meteorological resources

To accomplish the objectives of the meteorology programme we have the following tools.

13.4.1 Man Computer Interactive Data Access System (McIDAS)

LINUX Workstations (Fedora Core) with the Man Computer Interactive Data Access System (McIDAS) provide access, exploitation and visualization of meteorological information from different geo-referenced observations, modelling and remote sensing (satellite, radar) platforms.

The application provides access to all data in real time in the AEMET National Prediction System, including the following data and products:

- Global synoptic surface observation and upper-air networks.

- Outputs of numerical prediction models from ECMWF Integrated Forecasting System (IFS) and AEMET (HIRLAM).
- METEOSAT satellite imagery.
- Images of the AEMET Weather Radar Network.
- Data from the AEMET Electrical Discharge Detection network.
- Products derived from SAF (Satellite Application Facilities) Nowcasting Meteosat Second Generation (MSG) images.

Utilizing this application different automated processes for the exploitation of meteorological information have been developed, among which we can highlight:

1) Automatic generation of graphical products from specific model outputs and images from derived MSG products (RGB combinations), for consultation through an intranet website (Figure 13.3).

2) Calculation of isentropic back trajectories of air masses from analysis outputs (4 cycles per day) and prediction (every 12 hours and range up to 132 hours) for Tenerife at nine different vertical levels (Figure 13.4).

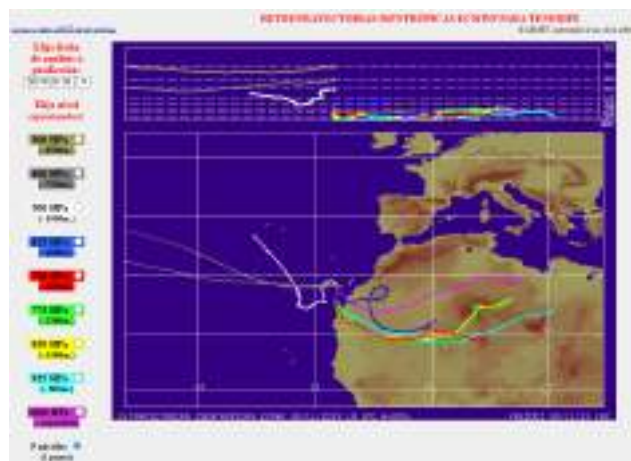


Figure 13.4. Screenshot of isentropic back-trajectories for Tenerife at nine levels on day 30/11/2024 18 UTC

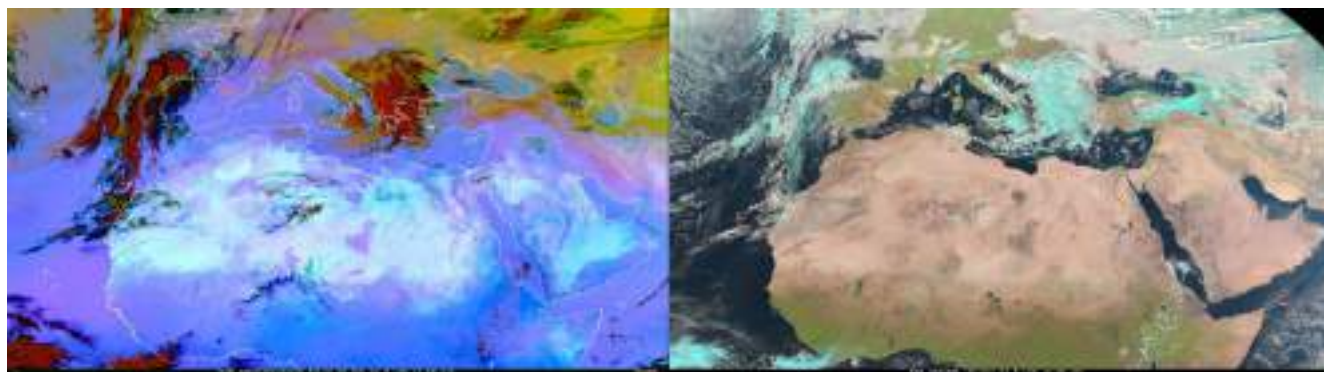


Figure 13.3. Two different RGB composite images from Meteosat-10 satellite on 30/11/2024 12:00 UTC. Left panel: dust (channels 7, 9 and 10), right panel: natural (channels 1, 2 and 3).

3) Lightning strikes in situ detection and AEMET lightning detection network warning system, for taking preventive action to avoid damages at the facilities.

4) Automatic seven-day Meteogram generation of temperature, humidity, wind, pressure and clouds for IZO using standard isobaric grid points interpolated to 2400 m a.s.l. The statistics have been weighted using the inverse distance to the validity forecast time taking into account the last five available model runs (Figure 13.5).

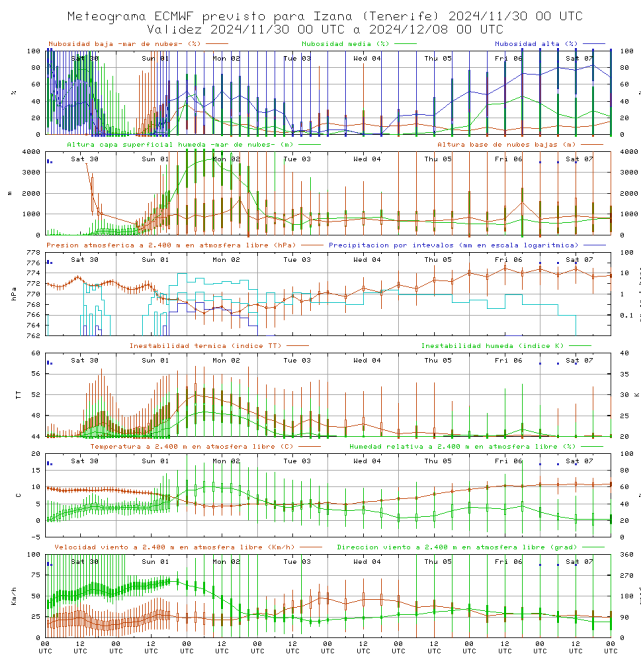


Figure 13.5. Ensemble week length meteogram forecast at IZO on 30/11/2024 at 00 UTC

13.4.2 EUMETCast receiving system

The EUMETCast real-time receiving system for aerial imagery and meteorological satellite data distributed by EUMETSAT has its own internal web interface for displaying images received, and mass storage system for archiving images of compressed MSG segments in native format.

13.4.3 EUMETSAT Data Center

We have access to the EUMETSAT Data Center for retrieval of images and historical products of Meteosat satellites.

13.4.4 AEMET Server Meteorological Data System

We have access to numerical model databases, observations, bulletins, satellite and radar images available on the AEMET Server Meteorological Data System (SSDM).

13.4.5 ECMWF products and MARS archive

In addition, we have access to the European Centre for Medium-Range Weather Forecasts (ECMWF) computer systems and extractions of the Meteorological Archival and

Retrieval System (MARS), which is the archive of all operational products generated in ECMWF. From this system we have developed different exploitation processes such as:

- Routine extraction in two cycles per day of meteorological analysis and prediction fields of the ECMWF IFS model, which are decoded in a compatible format for exploitation from McIDAS and input of initial and boundary conditions for the integration of high-resolution models running locally on our computer systems.
- Monthly extraction of ERA-Interim reanalysis outputs for updating large data series for different projects.
- Extraction of previous analysis fields for computing back trajectories with FLEXTRA.
- Routine extraction in two cycles per day from CAMS system (Figure 13.6).

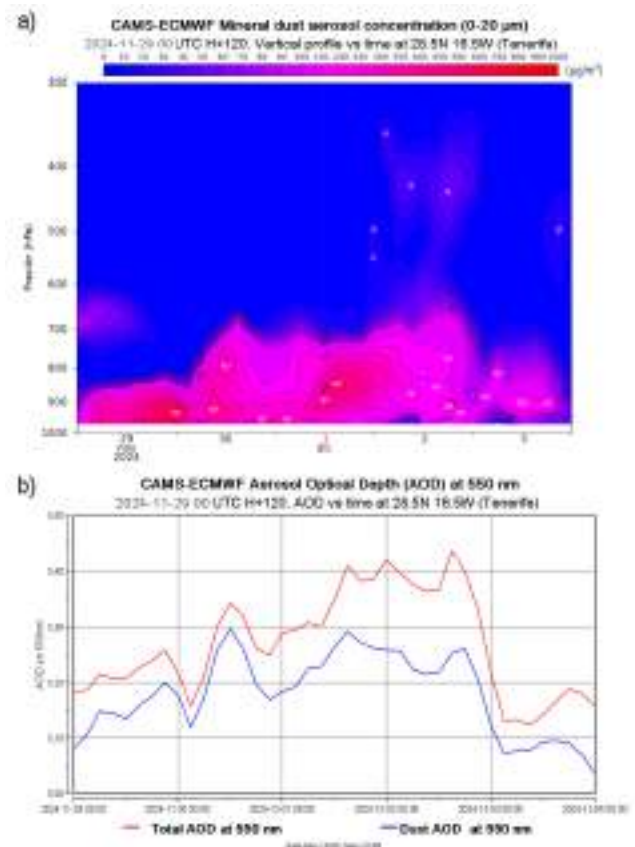


Figure 13.6. Examples of routine output cycles from CAMS. Forecast evolution of a) vertical profile of mineral dust aerosol concentration and b) Aerosol Optical Depth at 550 nm on 29/11/2024 00:00 UTC H+120 for 28.5N 16.5W (Tenerife).

13.4.6 AEMET National Climatological Database (BDCN)

We have access to the AEMET National Climatological Database (BDCN) for data extraction of observations from the AEMET principal and secondary climatological networks.

13.5 Numerical models and meteorological and environmental tools

13.5.1 Statistical forecasting model

A statistical forecasting model using the analog method estimates the likelihood of pollution episodes. Furthermore, meteorological data for a fixed location in the northeast of the Canary Islands (29.25°N, 15.75°W) are colour-coded by quartile position relative to historical records, providing a quick visual indication of unfavorable weather conditions within a 108-hour forecast window (see Figure 13.7; refer to Milford et al., 2008 for further information).

DATE	HOURL	DIR	DIR	WS	EPI	BLH	B ALT	T ALT	B TEM	C TEM	MEDIAN	PER99	>%70	>%80
05-06-2024	00	008	N	6.3	1.7	947	1108	1953	11.9	15.2	*****	*****	**	**
05-06-2024	06	011	NNE	5.9	1.5	762	1222	1781	10.5	14.1	*****	*****	**	**
05-06-2024	12	010	N	4.5	1.9	574	1225	1786	12.6	13.9	10.0	140.0	22	16
05-06-2024	18	005	N	4.8	1.8	536	1225	1785	12.8	14.1	*****	*****	**	**
06-06-2024	24	035	NE	2.1	1.9	534	1350	1784	12.1	13.9	*****	*****	**	**
06-06-2024	30	018	NNE	6.3	2.1	849	1347	1781	12.0	14.0	*****	*****	**	**
06-06-2024	36	268	W	3.0	1.9	859	1349	1784	12.0	14.3	10.0	61.0	09	06
06-06-2024	42	249	WSW	4.0	1.9	748	1226	1485	13.3	13.7	*****	*****	**	**
07-06-2024	48	222	SW	6.1	2.6	346	*****	*****	*****	*****	*****	*****	**	**
07-06-2024	54	256	WSW	5.4	2.3	324	*****	*****	*****	*****	*****	*****	**	**
07-06-2024	60	274	W	3.1	2.1	545	*****	*****	*****	*****	11.0	61.0	22	13
07-06-2024	66	291	WNW	5.7	1.9	666	*****	*****	*****	*****	*****	*****	**	**
08-06-2024	72	286	WNW	5.9	2.0	739	1950	2126	10.9	11.0	*****	*****	**	**
08-06-2024	78	298	WNW	4.2	2.0	867	1947	2123	11.1	11.2	*****	*****	**	**
08-06-2024	84	306	NS	3.4	2.2	468	*****	*****	*****	*****	10.0	147.0	26	20
08-06-2024	90	334	NSW	4.4	2.1	622	1112	1228	14.1	14.2	*****	*****	**	**
09-06-2024	96	000	N	3.2	1.8	587	1226	1630	12.5	13.3	*****	*****	**	**
09-06-2024	102	005	N	4.8	1.9	829	1347	1625	10.9	13.6	*****	*****	**	**
09-06-2024	108	346	NSW	4.6	1.6	702	1347	1627	11.7	13.6	12.0	287.0	40	33

Figure 13.7. Overview of weather variables and likelihood of SO₂ threshold exceedances: wind characteristics (direction and speed), EPI (Integrated Stability Potential), Boundary Layer Height (BLH), inversion layer metrics (height and temperature), analog-based percentiles (median and 99th), and probabilities of surpassing the 70th and 80th historical percentile levels.

13.5.2 Meteorological variables: 10-day forecast

A 10-day forecast of meteorological variables is generated every 12 h from a simulated weather sounding using ECMWF data at the same coordinates as the previous statistical forecasting model (29.25°N, 15.75°W) (Figure 13.8). The forecast includes a broader set of variables derived from vertical profiles. These include: 2-m temperature; 850 hPa temperature; Integrated Stability Potential (EPI); accumulated precipitation; BLH; maximum RH; mean RH in the first 3 km; the first altitude where 75% humidity is reached and the last altitude where it is reached again (providing an estimate of the moist layer thickness and the inversion top when it is not clearly defined thermally). We also include wind speed and direction at the boundary layer base, as well as altitude, temperature, and humidity at the base and top of the first thermal inversion, along with wind speed and direction at its base.

This provides a quick overview of expected meteorological conditions over the next ten days, highlighting periods of stable and unstable weather, which are then analysed in more detail using available high-resolution numerical models.

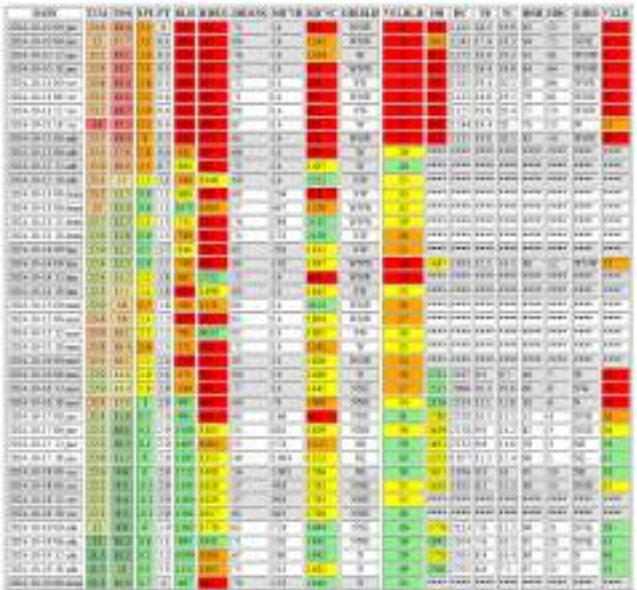


Figure 13.8. Example summary table of 10-day forecast of key meteorological variables at location: 29.25°N, 15.75°W, updated every 12 hours using ECMWF data (10–20 October 2024). The entries are colour-coded by quartile position relative to historical records, as in Figure 13.7. Only T2M and T850 use a different colour scaling, applied solely to highlight temperatures relative to the maximum and minimum values over the entire period.

13.5.3 The PSU/NCAR mesoscale model (MM5)

The meteorology programme utilizes a cluster system running in a LINUX environment with parallel processors to execute a high-resolution, non-hydrostatic weather model (MM5) for the Canary Islands. Initial and boundary conditions are provided by the ECMWF IFS model, and the system generates nested grids at 18 km, 6 km, and 2 km resolutions, with forecast ranges extending up to 144 hours.

Base Time: Mon 23DEC2024 00Z Valid Time: Mon 23DEC2024 07Z
1=L 2=L+H 3=L+M 4=M 5=M+H 6=H >6=L+M+H

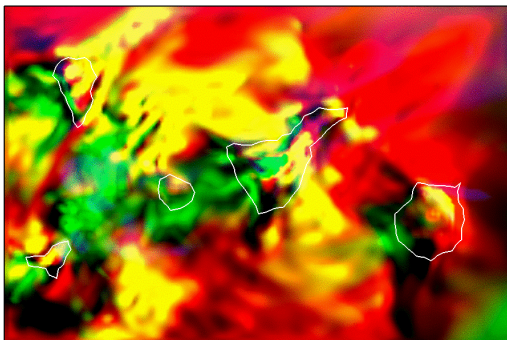


Figure 13.9. Example of a graphical representation of total cloud fraction (combined low, medium, and high clouds), based on MM5 model output for 23 December 2023 at 07 UTC

13.5.4 The Weather Research and Forecasting (WRF) model

A high-performance workstation equipped with a Xeon Phi KNL processor (72 cores at 1.5 GHz), 64 GiB of RAM, and running CentOS 7.3 with Intel Parallel Studio XE (Fortran

and C++ compilers) is used to run the Weather Research and Forecasting – Advanced Research WRF (WRF-ARW) model at very high resolution. The model is initialized and forced at the boundaries using data from the ECMWF IFS model. Nested domains with horizontal resolutions of 6 km, 2 km, and 1 km are generated, providing forecasts up to 72 hours. A high-mountain gust parameterization was implemented in WRF, significantly improving wind gust forecasts at both IZO and TPO (Figures 13.10 and 13.11).

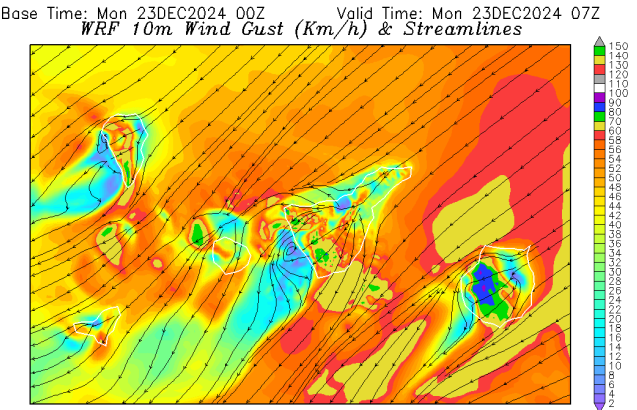


Figure 13.10. Example plot showing forecasted wind gust speeds, represented with colour shading, overlaid with streamlines during a high wind event on 23 Dec 2024 at 07 UTC

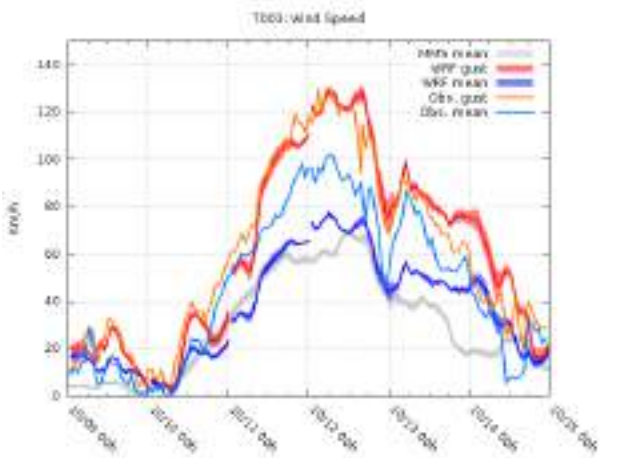


Figure 13.11. Validation plot showing observed and forecasted wind and gust speeds from 10 to 15 October 2024 for the Teide Peak Observatory. MM5 wind speed is also displayed.

13.5.5 Post-processed numerical results

The outputs of these models offer the added value of dynamic downscaling of the IFS model predictions for the complex topography of the Canary Islands. Various types of post-processed numerical fields permit a better understanding of the atmospheric situations. In addition to these outputs an artificial neural network has been implemented that improves the prediction of local temperature and wind at the observatory, granting additional accuracy to the in situ forecast (Figure 13.12). All these results are presented using a web server installed in the cluster.

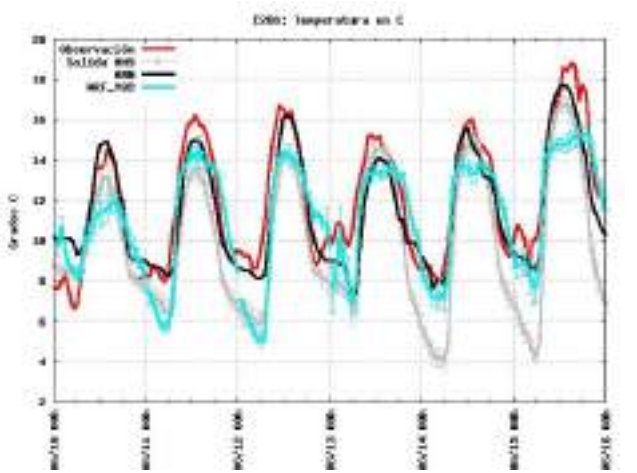


Figure 13.12. Example of the improvement in 2 m temperature forecasts using an Artificial Neural Network (ANN) from 10–16 June 2024. The black lines show ANN predictions, while red, grey, and blue lines correspond to observations, and raw outputs from MM5 and WRF, respectively.

13.5.6 FLEXible TRAjectory (FLEXTRA) model

The FLEXible TRAjectory (FLEXTRA) model is installed on a dedicated server and simulates 10-day back-trajectories arriving at IZO, calculated at multiple altitudes. These back-trajectories provide valuable information on the transport pathways and source regions of air masses influencing the various components and parameters measured at IZO. They have been computed and archived at six-hour intervals for the 1979–2024 period.

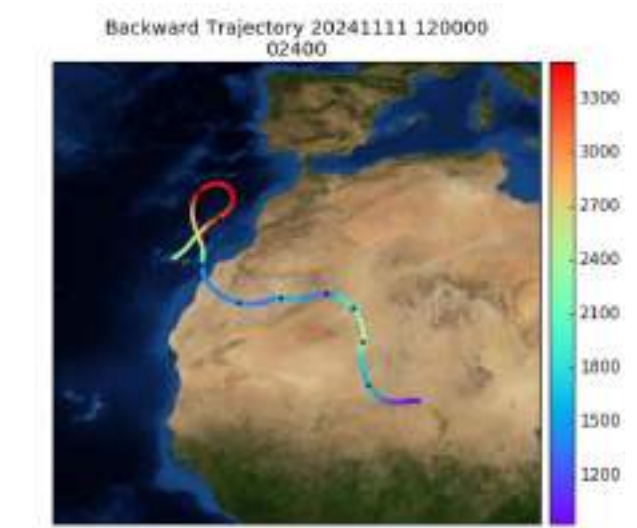


Figure 13.13. Image representing the track and height of a FLEXTRA back-trajectory with track ending on 11/11/2024 at 12 UTC

Additional graphical information representing the track and its height is shown using a web server as a quick reference in order to select particular episodes (Figure 13.13). A later more exact representation can be requested using a McIdas web-based server (Figure 13.14).

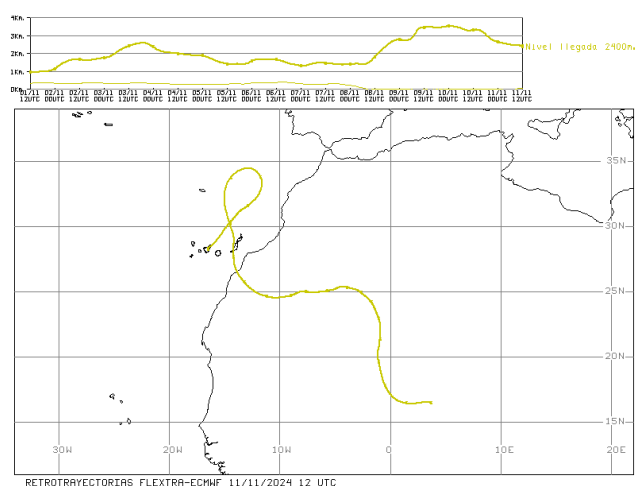


Figure 13.14. Detailed plot of a FLEXTRA back-trajectory with track ending on 11/11/2024 at 12 UTC

13.5.7 Uncertainty in back-trajectories

The calculation of back-trajectories using FLEXTRA involves inherent uncertainties that are strongly influenced by the prevailing meteorological patterns. Some synoptic situations are more stable and lead to consistent trajectory paths, while others introduce greater variability and result in significant divergence over short distances or time intervals.

To better characterize this intrinsic uncertainty, we developed a method to quantify variability in the ERA5-based trajectories. Specifically, 60 trajectories were generated daily from slightly perturbed initial conditions: five spatial points centered around a reference point at 2 400 m a.s.l. (including points 200 m above and below), and for each of the four synoptic hours (00, 06, 12, and 18 UTC). These trajectories were then grouped using K-means clustering into four clusters that minimize spatial variance within each group. For each day from 2010 to the present, this analysis yields the relative frequency of trajectories per cluster, offering insight into the dominant transport pathways and their associated uncertainties. The mean trajectory of each cluster serves as its representative path. All results are available through an interactive website that provides graphical access to the trajectory data (Figure 13.15).



Figure 13.15. Plot showing the average paths of the four back-trajectory clusters for 18 April 2024. The legend indicates the proportion of elements within each group, while line transparency reflects the transport altitude.

13.5.8 HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model

To estimate SO_2 concentrations near emission sources, the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model was also deployed on the cluster system, running in dispersion mode with parallel configuration and using MM5 output data (Figure 13.16). Separately, HYSPLIT was installed on the same server as the FLEXTRA model to simulate 10-day back-trajectories based on input from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS). These back-trajectories were computed and archived, at six hourly intervals for the entire 1949–2024 period.

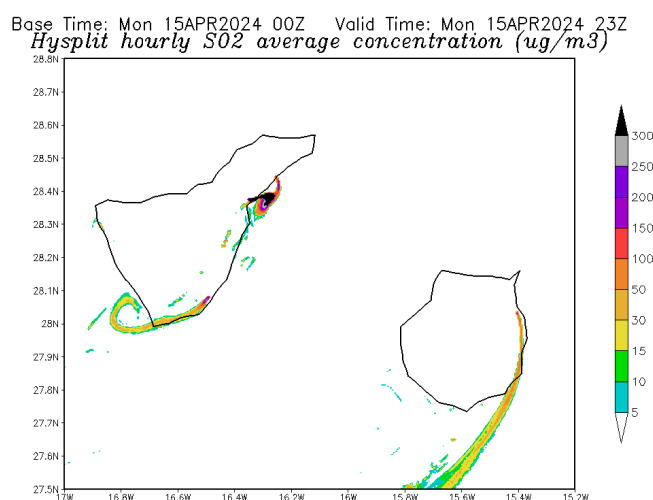


Figure 13.16. Average Hysplit SO_2 concentration forecasted on day 15/04/2024 at 23 UTC

13.5.9 Enhanced short-term PM_{10} dust forecasts over Canary Islands

The dust forecast systems participating in the model intercomparison of the WMO Barcelona Dust Regional Center (see section 20) include dust surface concentrations relevant to health, climate, aviation, and other sectors. These dust forecasted surface concentrations are often overestimate or underestimate with respectr observed PM_{10} levels over Canary Islands. To increase the accuracy of the predicted dust surface concentrations over the region, IARC developed a statistical correction using the multi-model median ensemble of the models participating the regional intercomparison of the WMO Barcelona Dust Regional Center, interpolated to the locations of the observation network stations in the Canary Islands. The correction was based on model–observation differences over a past reference period. The resulting adjusted forecasts are presented on a dedicated web platform using summary statistics that facilitate rapid interpretation. This product provides more realistic estimates of PM_{10} levels during African dust intrusions over the Canary Islands.

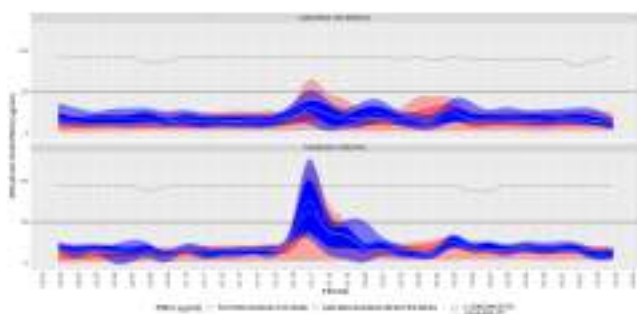


Figure 13.17. Statistically corrected PM₁₀ percentiles (05–95) from the WMO dust multi-model ensemble, interpolated to station locations in the Canary Islands. Red shading shows model percentiles (25–75 in dark red, 05–25 and 75–95 in light red); blue shows observations with the same scheme. The dotted line indicates data availability. Upper panel: western islands; lower panel: eastern islands. Data shown from 3 March to 3 April 2024.

13.5.10 PM₁₀ levels recorded at all Canary Islands stations

To present PM₁₀ data and its distribution across all monitoring stations in the Canary Islands, we have developed a web application that allows users to define a time window of a specified number of days to display PM₁₀ values throughout the archipelago (Figure 13.18). An outlier filter is included to remove noisy data. The web application accesses the complete historical PM₁₀ database, enabling the evaluation of past events such as dust intrusions from Africa and supporting the validation of other related products.



Figure 13.18. PM₁₀ data and its distribution across all monitoring stations in the Canary Islands, the datapoints are colour-coded by island. An outlier filter has been applied to avoid anomalous data points, data shown from 12–28 December 2024.

13.5.11 Real-time tracking of PM₁₀ levels in the Canary Islands

To enable real-time monitoring of PM₁₀ levels across the Canary Islands, a dedicated platform displays daily data for each monitoring station, showing the evolving daily average as a horizontal dotted line that updates throughout the day. Users can explore detailed information by hovering over individual data points or the average line (see Figure 13.19). The tool serves as a valuable resource for tracking PM₁₀ concentrations and offers researchers new insights into air quality trends in the region.

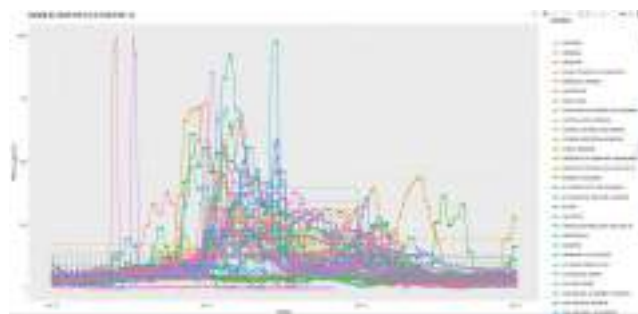


Figure 13.19. Interactive chart of semi-hourly PM₁₀ measurements from the Canary Islands Air Quality Monitoring Network. The dashed line represents the daily average, and the dots represent the semi-hourly measurements taken from 10–13 April 2024.

13.5.12 Real-time monitoring of atmospheric gases in La Palma

Air quality data from the Canary Islands Air Quality Monitoring Network (AQMN) is collected from a server every 30 minutes for the following components: SO₂, CO, PM₁₀, PM_{2.5}, NO, NO₂, NO_x, O₃, HR, DD, TMP, and VV. These data are ingested and presented on a dedicated website for all stations installed in La Palma (Figure 13.20), enabling continuous, near real-time monitoring of air quality on the island. The system remains fully operational and supports ongoing environmental surveillance and research activities.



Figure 13.20. Air quality parameters measured on 3 June 2024 at the stations located in La Palma and belonging to the Canary Islands Air Quality Monitoring Network

13.5.13 MERRA-2

The MERRA-2 dataset includes an aerosol component derived from the Goddard Aerosol Assimilation System (GAAS), implemented within the GEOS-5 model framework. This system assimilates observational data from multiple satellite instruments—such as AVHRR, MODIS (Aqua and Terra), MISR—and ground-based sources like AERONET, with bias corrections applied to aerosol optical depth (AOD) values. The Global Modeling and Assimilation Office (GMAO) is responsible for generating the MERRA-2 aerosol analysis, which provides a consistent, observation-informed record of AOD from 1980 to the present. Aerosol composition is modelled using the GOCART module.

MERRA-2 aerosol data were retrieved from NASA's Giovanni online visualization and analysis platform. The complete dataset was downloaded and subsequently processed at IARC. The processed data, from 2010 to the present, are presented here in a format optimized for accessibility and ease of interpretation, facilitating broader use in atmospheric research and environmental monitoring (Figure 13.21).

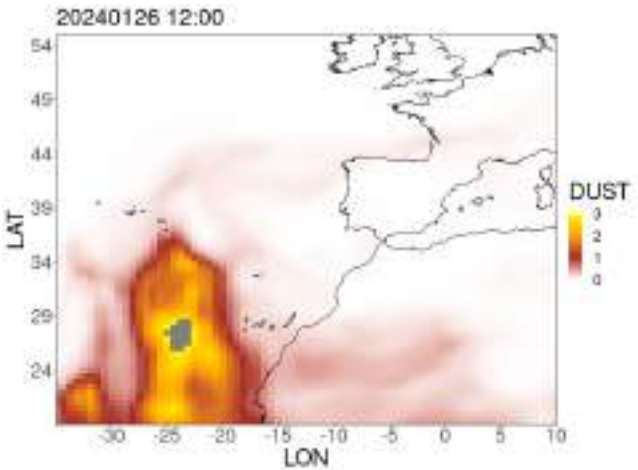


Figure 13.21. Aerosol Optical Depth (AOD) on 26 January 2024 at 12:00 UTC, indicating a strong dust intrusion originating from Africa and moving west of the Canary Islands

13.5.14 Electric field in Izaña

The Previstorm electric field monitoring system is currently operational at IZO. Real-time measurements are statistically characterized using optimized time intervals, with data presented as percentiles (min, p25, p50, p75, max) for intervals ranging from 1 second to 5 minutes. The results are accessible through an interactive web interface, enabling users to explore and interpret electric field variations efficiently (Figure 13.22). This ongoing monitoring provides valuable information for the Canary Islands, supporting enhanced forecasting and management of weather-related phenomena.

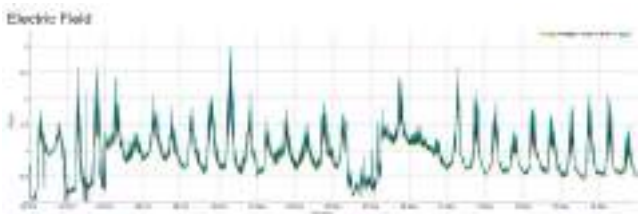


Figure 13.22. Interactive graph of electric field measured with Previstorm every 5 minutes and corresponding percentile statistics (0%, 25%, 50%, 75% and 100%) based on 1 second raw data resolution (November 2023)

13.5.15 Web platform for the presentation of products developed by the Meteorology Group

In order to showcase the large number of products we have available online, we have developed a web platform (Figure 13.23) that provides access to the various products, including explanations of their functionality and graphical interfaces to facilitate their identification.



Figure 13.23. Web interface for accessing and identifying meteorological products

13.6 Summary of activities during the period 2023–2024

13.6.1 Meteorological long-term records

The series of average temperature, accumulated precipitation, sunshine duration and average atmospheric pressure at IZO have been updated for the years 2023 and 2024 (Figure 13.24). This constitutes over a century of meteorological data and is the oldest uninterrupted climate series in the Canary Islands.

In the series of annual mean temperature at IZO (Figure 13.24a), the rate of rise in temperature has increased slightly to 0.16 °C per decade, still consistent with the global warming trend. This series is especially relevant since the station is at altitude and is representative of conditions of quasi free troposphere. The annual mean temperature of 2023 and 2024 have exceeded the upper quintile of the 1961–90 reference series, with a classification of extremely warm; 11.2 °C for 2023 and 12.1 °C for 2024, the highest annual mean temperature ever recorded since measurements began in 1916.

Regarding total annual precipitation (Figure 13.24b), both 2023 and 2024 have precipitation rates less than the 1961–90 median value and both are classified as extremely dry (below the minimum of the reference series). The 2023 total annual precipitation was 117.4 mm (the 3rd lowest since 1916), while in 2024 the total annual precipitation was 150.0 mm (the 5th lowest since 1916).

The total annual sunshine duration series has also maintained a significantly increasing trend of 42.5 h per decade (Figure 13.24c). In 2023 and 2024, the total annual sunshine duration was 3 808.9 h and 3 883.6 h, respectively.

The evolution of the annual mean atmospheric pressure (13.24d) shows a sustained slight increase in the last decade, with the data for 2023 and 2024 similar at 771.2 and 771.1 hPa, respectively.

An analysis was conducted to compare the meteorology of 2023 and 2024 at IZO to the long-term meteorological records. For example, March 2023 and August 2024 broke the records of highest monthly mean temperature and 2024, as already mentioned, was the highest annual mean temperature ever recorded since measurements began in 1916. In addition, 7 June 2023 registered an anomalous precipitation intense summer event (Table 13.1).

Table 13.1. Meteorology of 2023 and 2024 at IZO in comparison with 1916–2020 meteorological records

Extreme Event	Data	Date
Highest March monthly mean temperature	15.2 °C	Mar 2023
Highest June precipitation intensity	15.6 mm/h	7 Jun 2023
Highest of daily minimum temperatures	21.4 °C	12 Jul 2024
Highest August monthly mean temperature	20.6 °C	Aug 2024
Highest annual mean temperature	12.1 °C	2024

To ensure quality and continuity of observations within national and international meteorological and climatological observation networks in which IARC participates it is required to keep constant maintenance and vigilance of meteorological instrumentation and subsequent quality checking of meteorological data from IZO, SCO, BTO and TPO.

The networks in which IARC participates are the Synoptic Observation Network (WMO Region I, ID: 60010), included in the surface observation network of Global Climate Observing System (GCOS), the AEMET Climatological Monitoring Network (ID C430E) and the Baseline Surface Radiation Network (BSRN; station # 61).

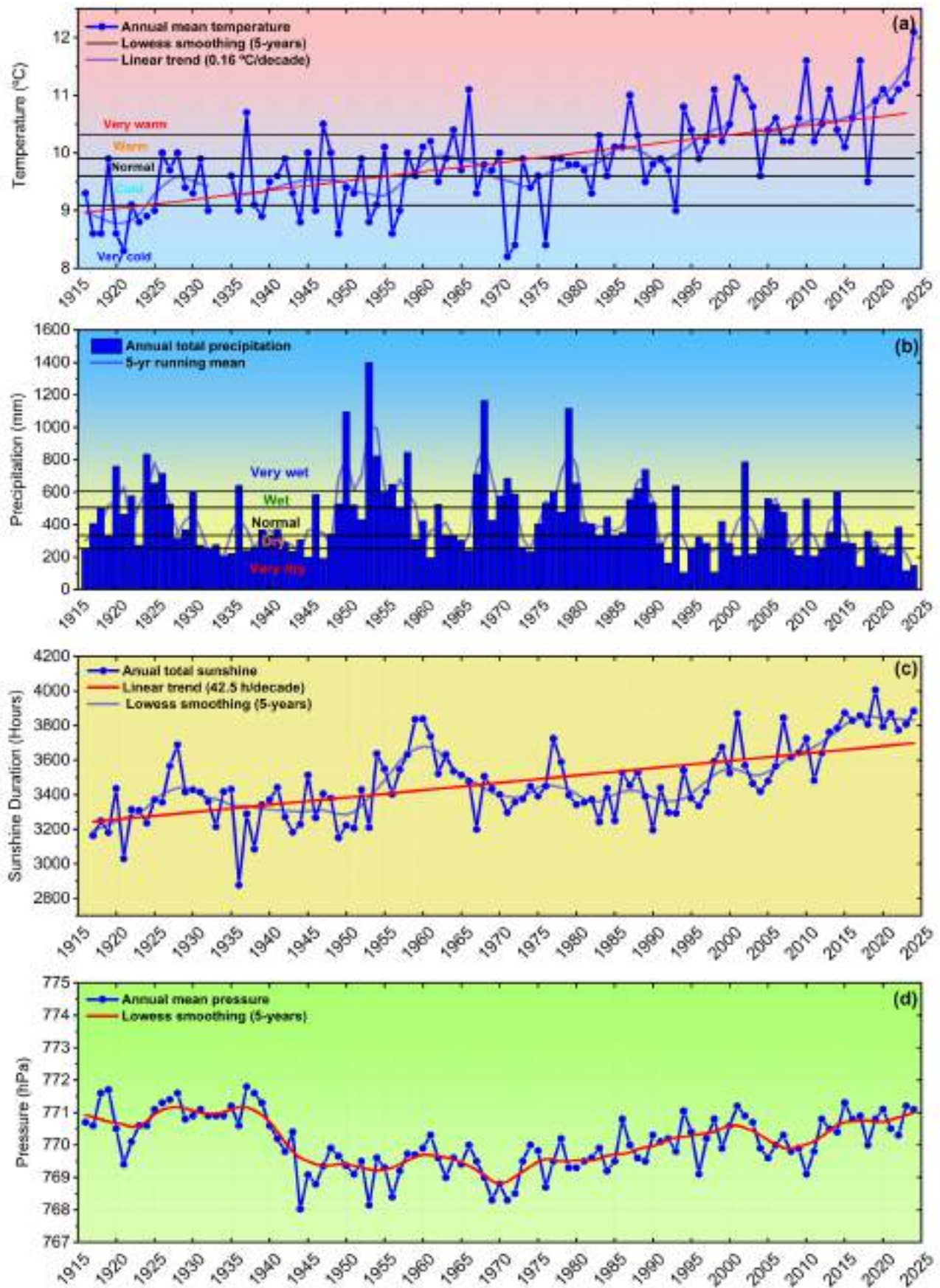


Figure 13.24. Time series (1916–2024) of a) annual mean temperature, b) total annual precipitation, c) annual sunshine duration and d) annual mean pressure at Izaña Observatory

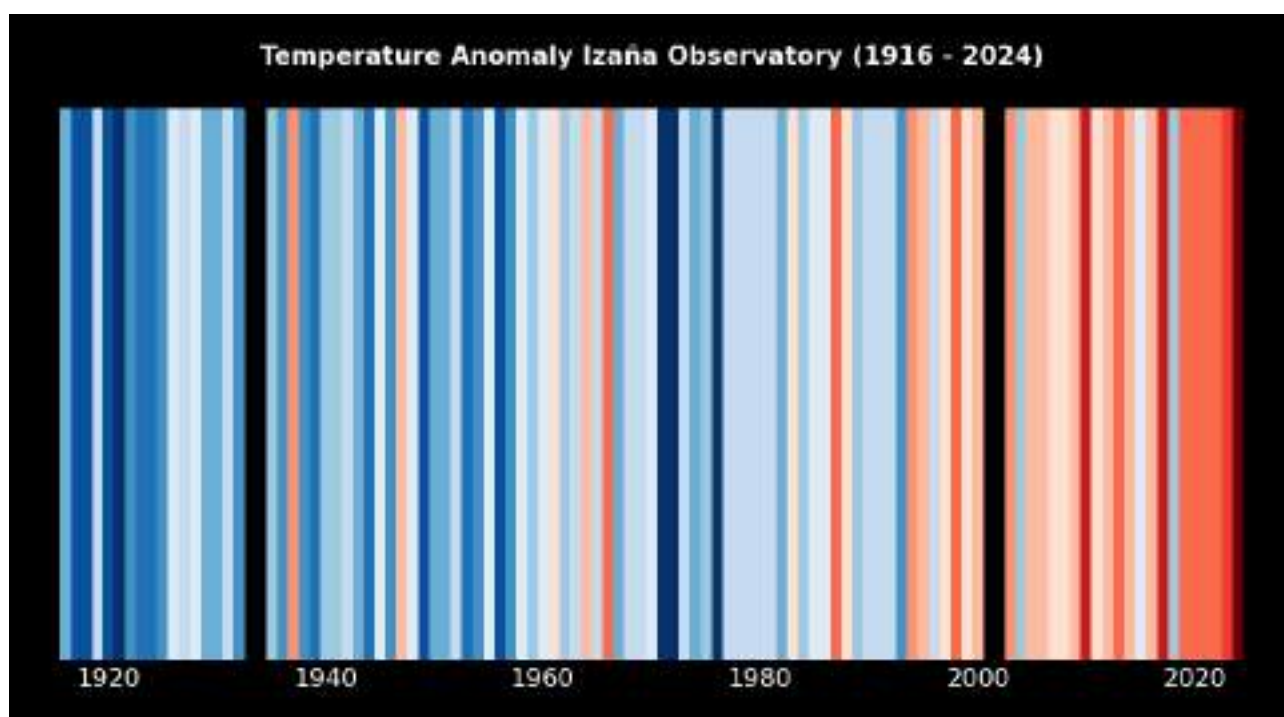


Figure 13.25. Average annual temperature anomaly time series from 1916 to 2024 at Izaña Observatory

Another representation of the series of average temperature is shown in Figure 13.25, this shows the average annual temperature anomaly time series at IZO for the years 1916 to 2024.

13.6.2 Prediction and analysis of severe weather events

Additional activities of the Meteorology programme include prediction and subsequent analysis of severe weather events that may affect operations of the various observation programmes at the four IARC observatories. We highlight some of the most important episodes during 2023–2024.

On 6–7 June 2023 the named storm “Oscar” produced strong winds with 95 km/h maximum gust, and an anomalous late spring precipitation event (Figure 13.26).

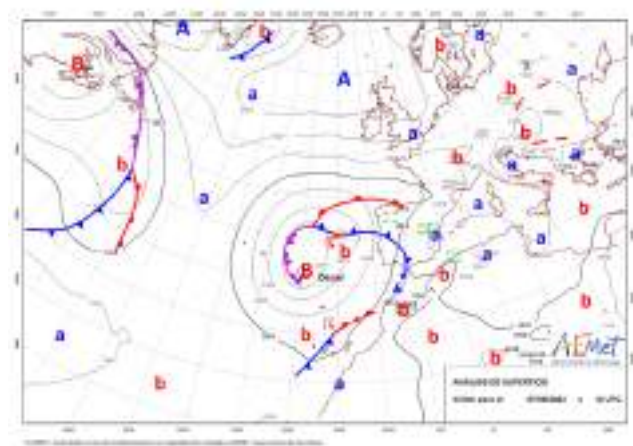


Figure 13.26. Surface pressure analysis and fronts, 07/06/2023 12 UTC

On 16 January 2024 the approximation of named storm “Irene” produced a strong wind event with a 119 km/h maximum wind gust (Figure 13.27).

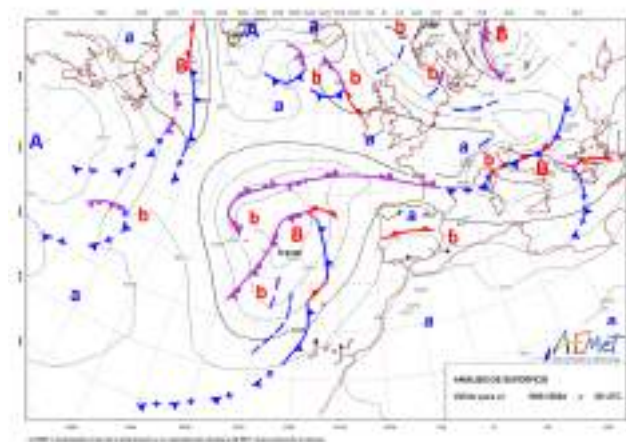


Figure 13.27. Surface pressure analysis and fronts, 16/01/2024 00 UTC

On 28–29 March 2024 the external circulation of large storm named “Nelson” centered over the North Atlantic produced a strong wind event with a 130 km/h maximum wind gust (Figure 13.28).

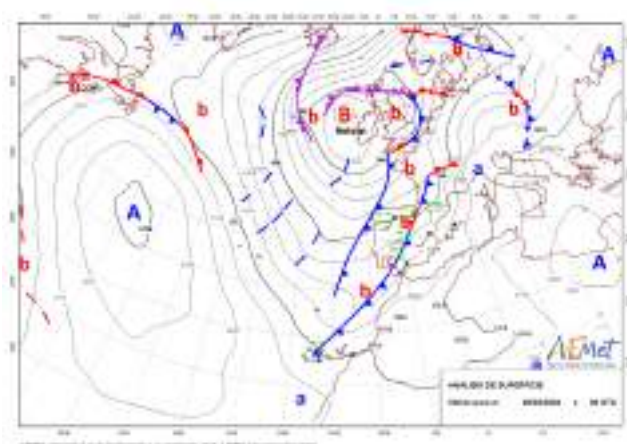


Figure 13.28. Surface pressure analysis and fronts, 29/03/2024 00 UTC

On 11–12 October 2024 the storm “Berenice” produced a strong wind event with a 120 km/h maximum wind gust (Figure 13.29).

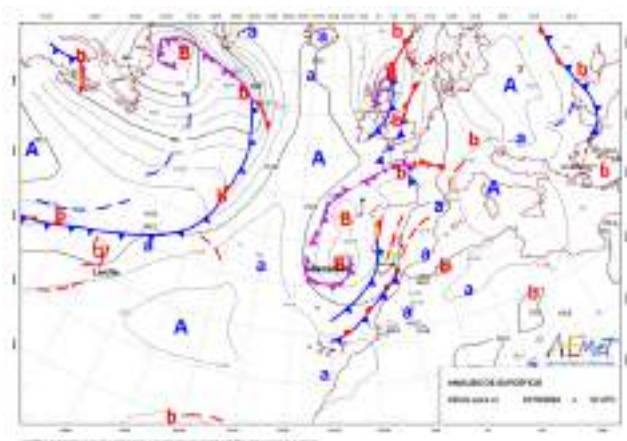


Figure 13.29. Surface pressure analysis and fronts, 12/10/2024 12 UTC

On 15–16 December 2024 the storm “Dorothea” produced a strong wind event with a 111 km/h maximum wind gust and an accumulated rainfall of 26.2 mm (Figure 13.30).

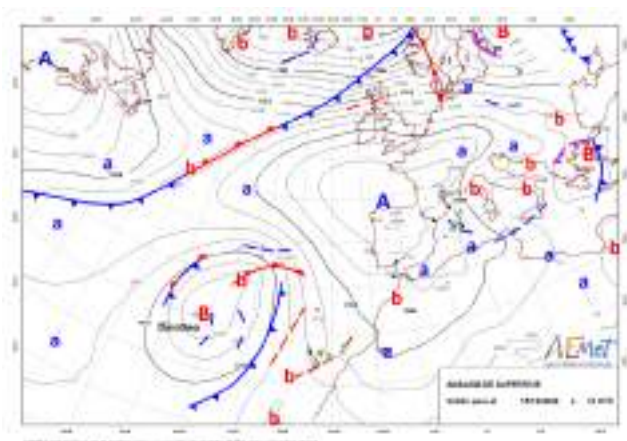


Figure 13.30. Surface pressure analysis and fronts, 15/12/2024 12 UTC

On 21–23 December 2024 the high-level cut-off low (DANA) produced a cold event with strong winds, hail and snow with temperature below 0°C, maximum wind gust of 104 km/h and a total precipitation amount of 43.2 mm. (Figure 13.31).



Figure 13.31. Image from the tower of IZO on 22 December 2004

Other activities of the Meteorology programme include the following.

13.6.3 Contribution to the study "Spectral aerosol radiative forcing and efficiency of the La Palma volcanic plume over the Izaña Observatory"

A study conducted by García et al. (2023a) quantifies the spectral direct radiative forcing (ΔF) and efficiency (ΔF_{eff}) of aerosols associated with the La Palma volcanic eruption that began on 19 September 2021. Using solar radiation measurements from the Izaña Observatory in Tenerife, together with ground-based (lidar), satellite (Sentinel-5P TROPOMI), and reanalysis data (MERRA-2), the study characterizes three aerosol scenarios: volcanic, Saharan dust, and mixed volcanic-dust events. As a contribution to the study, backward air mass trajectories were computed using the FLEXTRA model and ERA5 reanalysis data, providing crucial information to identify the origin and nature of the aerosols impacting IZO during the key events. This analysis highlights the distinct radiative impacts of each aerosol type and demonstrates the value of multidisciplinary observations in assessing atmospheric responses to volcanic activity. This work was also presented at the EGU General Assembly 2023 (García et al., 2023b).

13.6.4 Contribution to the study "Impact of the 2021 La Palma volcanic eruption on air quality: Insights from a multidisciplinary approach"

The study investigating the impact of the 2021 La Palma volcanic eruption on air quality (Milford et al., 2023) mentions the use of meteorological information as part of its multidisciplinary approach. It describes the computation of forward trajectories using the FLEXTRA model and ERA5 reanalysis data, starting from the eruptive centre, to examine plume transport. The study also states that back trajectory information (along with lidar and reanalysis data) was utilized to identify Saharan air mass episodes.

13.6.5 Contribution to the study "New insights into the 2021 La Palma eruption degassing processes from direct-sun spectroscopic measurements"

The study conducted by Taquet et al. (2025) analyzes the chemical composition and degassing of the Tajogaite volcanic plume during the 2021 La Palma eruption using ground-based FTIR and DOAS measurements, petrological data, and satellite SO₂ fluxes. Atmospheric transport was modelled with HYSPLIT, supported by high-resolution meteorological data from the meteorology group's operational WRF-ARW model, converted into ARL format for compatibility. ERA5 data were also included to enhance simulations. The group aided in installing, compiling, and configuring HYSPLIT, enabling accurate plume age and dispersion estimates. This integrated approach allowed detailed characterization of volcanic emissions and plume transport over long distances.

13.6.6 Contribution to the COCCON-Spain project

As part of the COCCON-Spain project, which aims to establish a national network for the observation of GHG in Spain, the modelling component focuses on estimating emissions of CO₂, CH₄, and CO in the cities of Madrid and Barcelona. These estimates are based on atmospheric measurements and the use of transport models. While the CAPE model was initially considered as a preliminary tool to estimate CH₄ fluxes in Madrid using data from the MEGEI-MAD I campaign, the current approach involves using the Harmonie meteorological model in combination with the XSTILT transport model to estimate emissions across all campaigns conducted in Madrid, and eventually in Barcelona. This work is carried out in collaboration with the AEROLAB group at the University of Reims, among other partners. Our contribution to the project involved the complex process of extracting data from AEMET's big data archive. We programmed the retrieval of a large set of variables from the high-resolution Harmonie model covering the entire duration of the measurement campaigns.

13.6.7 Atmospheric transport support for the ATMO-ACCESS campaign at Izaña

As part of the collaboration with the University of Helsinki under the ATMO-ACCESS project, efforts to study new particle formation processes at IZO include careful sampling strategies to avoid contamination from boundary layer air, indicating a focus on understanding the origin of observed aerosols. These studies typically rely on back trajectory analyses to trace air mass origins. In this context, we provided air mass back trajectory data using both HYSPLIT and FLEXTRA models, supporting the interpretation of aerosol measurements under clean, free-tropospheric conditions (see section 8 for more details).

13.6.8 Contribution to the ICaRO Cosmic Rays Observatory

The ICaRO Cosmic Rays Observatory was installed in February 2023 at the IZO through a collaboration between AEMET and the University of Alcalá. It measures secondary cosmic rays—mainly neutrons and muons—and fills a key gap in the Global Neutron Monitor Network. Additionally, a portable neutron monitor campaign is being conducted at different altitudes in Tenerife to study the influence of atmospheric pressure on cosmic ray detection, for more details see section 22.

Our contribution has consisted of automating the transmission of electric field statistics from the Previstorm monitoring system at the observatory, providing real-time data every 5 minutes. This electric field is monitored because it has a significant influence on the cosmic ray measurements performed at the site.

13.6.9 Additional activities

In addition to the activities described in this section, we participated as co-authors in the following studies and publications: Fraile-Nuez et al. (2024a, b), García et al. (2023c) and Taquet et al. (2024a, b).

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13.8 Staff

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14 Aerobiology

The Aerobiology programme at the IARC is carried out jointly by IARC and the Laboratori d'Anàlisis Palinològiques (LAP) of the Universidad Autònoma de Barcelona (UAB). This programme started in 2004 at SCO with the aim of improving the knowledge of the pollen and spore content in the air of SCO and its relation to the prevalence of respiratory allergy. A second aerobiological station was implemented at IZO thanks to the financial support of the Research and development (R+D) National Plan CGL-2005-07543 project ("Origin, transport and deposition of African atmospheric aerosol in the Canaries and the Iberian Peninsula based on its Chemical and Aerobiological Characterization"). These two projects also contribute to improvement of knowledge of the biological fraction of aerosols within the GAW Programme.

14.1 Main scientific goals

The main scientific goals of this programme are:

- To produce high quality standardized data on the biological component of the atmospheric aerosol.
- To establish the biodiversity and quantity of pollen and fungal spores registered in the air of Santa Cruz de Tenerife and Izaña.
- To establish the distribution pattern over the course of the year of the airborne pollen and fungal spores at Santa Cruz de Tenerife and Izaña, through the daily spectra.
- To put the Canary Islands on the map of the global aerobiological panorama, along with the Spanish networks (REA; SEAIC) and the [Worldwide Pollen Map](#).
- To provide information useful for medical specialists and allergic patients.
- To set up the list of the allergenic pollen and spore taxa in the air of Santa Cruz de Tenerife and Izaña that will help doctors to diagnose the allergy aetiology and to rationalize the use of the medication.
- To produce weekly alerts on allergenic pollen and spores for the days ahead to help doctors in the allergy detection and to help people suffering from allergies with a better planning of their activities and to improve the quality of their life.

A detailed description of this programme can be found in Belmonte et al. (2010).

14.2 Measurement programme

The sampling instrument is a Hirst, 7-day recorder VPPS 2000 spore trap (Lanzoni S.r.l.) (Figure 14.1) and the analysing instrument is a Light microscope, 600 X (Table 3.2). The pollen and spore analysis are conducted using palynological methods following the recommendations of the Spanish Aerobiology Network and those of the European Aerobiology Society (Galán et al. 2017) and the norm CEN (2019). The sampling programme at SCO is continuous throughout the year, whereas samples are only collected at IZO part of the year because of adverse meteorological conditions during the rest of the year. In 2023 they were collected from May to September.



Figure 14.1. Hirst, 7-day recorder VPPS 2000 spore trap at SCO (left) and at IZO (right)

14.3 Summary of remarkable results during the period 2023–2024

The annual dynamics of the total pollen and total fungal spores taxa in SCO and IZO are shown in Figures 14.2 and 14.3. The plots show mean and absolute maximum weekly concentrations of historical data (2004/2006–2022) and data from 2023

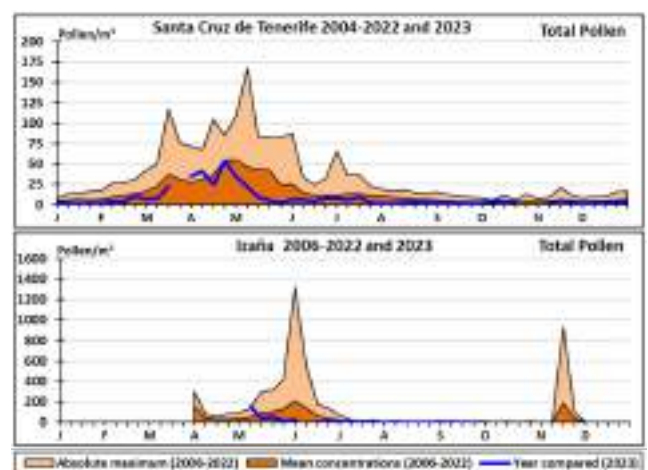


Figure 14.2. Dynamics of the mean weekly Total Pollen concentrations in Santa Cruz de Tenerife (upper panel) and Izaña (lower panel) during 2023 in comparison with 2004/2006–2022 mean and maximum loads

Table 14.1. Airborne pollen and spore spectrum for SCO, year 2023

SANTA CRUZ DE TENERIFE

1 January 2023 - 31 December 2023

	YEAR		WEEK		DAY	
	Integral P*day/m ³	Percentage %	Maximum P/m ³	Week nr. Nr.	Maximum P/m ³	Date of the Maximum dd/mm/yyyy
TOTAL POLLEN	2757	100	53,9	16,0	126,0	29/03/2023
POLLEN FROM TREES	1141	41,4	34,0	16	69,3	18/04/2023
<i>Acacia</i>	0	0,0	0,0		0	
<i>Alnus</i>	1	0,0	0,1	51	0,7	21/12/2023
<i>Ainus</i>	4	0,1	0,2	2	1,4	13/01/2023
<i>Castanea</i>	13	0,5	0,7	26	2,8	14/07/2023
<i>Casuarina</i>	10	0,4	0,5	6	2,1	09/02/2023
CUPRESSACEAE	113	4,1	2,7	16	11,2	07/04/2023
<i>Eucalyptus</i>	34	1,2	1,2	14	7,7	03/04/2023
<i>Ilex</i>	1	0,0	0,1	21	0,7	27/05/2023
MORACEAE	51	1,9	1,1	24	7,0	13/06/2023 - 28/09/2023
<i>Myrica</i>	266	9,6	9,4	14	28,0	06/04/2023
OLEACEAE	191	6,9	8,8	15	39,9	16/04/2023
PALM TREES	132	4,8	3,1	28	14,7	14/07/2023
<i>Pinus</i>	55	2,0	1,3	16	6,3	21/04/2023
<i>Platanus</i>	11	0,4	0,4	10	2,1	08/03/2023
<i>Populus</i>	1	0,0	0,1	11	0,7	13/03/2023
<i>Quercus</i> total	164	5,9	14,5	16	41,3	18/04/2023
<i>Salix</i>	3	0,1	0,3	6	2,1	07/02/2023
<i>Schinus</i>	90	3,3	1,9	28	7,0	03/05/2023
<i>Tilia</i>	0	0,0	0,0		0,0	
<i>Ulmus</i>	0	0,0	0,0		0,0	
Other pollen from trees	4	0,1	-	-	-	
POLLEN FROM SHRUBS	347	12,6	19,3	13	74,9	29/03/2023
CISTACEAE	1	0,0	0,1	14	0,7	09/04/2023
ERICACEAE	319	11,6	19,2	13	74,2	29/03/2023
<i>Ricinus</i>	18	0,7	0,4	11	1,4	23/03/2023 - 16/03/2023 - 16/04/2023
<i>Pistacia</i>	0	0,0	0,0		0,0	
Other pollen from shrubs	10	0,4	-	-	-	
POLLEN FROM HERBS	1178	42,7	18,1	16	28,7	03/05/2023
COMPOSITAE total (incl. <i>Artemisia</i>)	334	12,1	8,4	16	21,0	03/05/2023
<i>Artemisia</i>	326	11,8	8,3	16	21,0	03/05/2023
BORAGINACEAE	8	0,3	0,4	15	2,8	15/04/2023
CYPERACEAE	13	0,5	0,3	14	1,4	07/04/2023
CRASSULACEAE	2	0,1	0,2	16	1,4	19/04/2023
CRUCIFERAE	18	0,6	0,5	8	2,1	24/02/2023
<i>Euphorbia</i>	2	0,1	0,1	18	0,7	07/05/2023
GRAMINEAE (Grasses)	249	9,0	2,9	11	9,1	29/03/2023
<i>Mercurialis</i>	50	1,8	1,4	11	4,2	24/02/23 - 13/03/23
<i>Plantago</i>	96	3,1	2,4	16	5,6	20/04/2023
<i>Rumex</i>	71	2,6	3,6	11	7,0	19/03/2023
AMARANTHACEAE	129	4,7	2,1	42	13,3	21/10/2023
URTICACEAE	178	6,4	4,1	8	12,6	26/02/2023
Other pollen from herbs	38	1,3	-	-	-	

	YEAR		WEEK		DAY	
	Integral S*day/m ³	Percentage %	Maximum S/m ³	Week nr. Nr.	Maximum S/m ³	Date of the Maximum dd/mm/yyyy
TOTAL SPORES	58898	100,0	573,5	48	1531,6	01/12/2023
<i>Alternaria</i>	1439	2,4	26,0	15	61,6	11/04/2023
Ascospores	22604	38,4	373,8	48	1330	01/12/2023
<i>Aspergillus/Penicillium</i>	1974	3,4	50,8	9	336,0	03/03/2023
<i>Clostridium</i>	21493	36,5	358,4	25	910,0	23/06/2023
<i>Ustilago</i>	3895	6,6	48,0	2	280,0	10/01/2023
Other fungal spores	7493	12,7	-	-	-	

Table 14.2. Airborne pollen and spore spectrum for IZO, year 2023

IZAÑA

01 May 2023 - 24 September 2023

	YEAR		WEEK		DAY	
	Integral P*day/m ³	Percentage %	Maximum P/m ³	Week nr. Nr.	Maximum P/m ³	Date of the Maximum dd/mm/yyyy
TOTAL POLLEN	2144	100,0	152,6	18	291,9	07/05/2023
POLLEN FROM TREES	312	14,5	26,1	18	113,4	01/05/2023
<i>Acacia</i>	0	0,0	0,0		0,0	
<i>Alhambus</i>	0	0,0	0,0		0,0	
<i>Alnus</i>	0	0,0	0,0		0,0	
<i>Castanea</i>	23	1,1	2,5	24	9,1	12/06/2023
<i>Casuarina</i>	1	0,0	0,1	34	0,7	24/08/2023
CUPRESSACEAE	4	0,2	0,3	22	1,4	02/06/2023
<i>Eucalyptus</i>	0	0,0	0,0		0,0	
<i>Ilex</i>	0	0,0	0,0		0,0	
MORACEAE	1	0,1	0,1	18	0,7	06/05/2023 - 25/06/2023
<i>Myrica</i>	153	7,1	18,9	18	98,7	01/05/2023
OLEACEAE	20	0,9	2,6	19	7,7	09/05/2023
PALM TREES	4	0,2	0,2	22	1,4	31/05/2023
<i>Pinus</i>	102	4,7	7,0	18	14,7	01/05/2023
<i>Platanus</i>	0	0,0	0,0		0,0	
<i>Populus</i>	0	0,0	0,0		0,0	
<i>Quercus</i> total	4	0,2	0,5	19	2,1	09/05/2023
<i>Salix</i>	0	0,0	0,0		0,0	
<i>Schinus</i>	1	0,0	0,1	19	0,7	09/05/2023
<i>Tilia</i>	0	0,0	0,0		0,0	
<i>Ulmus</i>	0	0,0	0,0		0,0	
Other pollen from trees	0	0,0	-	-	-	
POLLEN FROM SHRUBS	8	0,4	0,4	18,0	1,4	07/05/2023 - 08/05/2023
CISTACEAE	0	0,0	0,0		0,0	
ERICACEAE	6	0,3	0,4	18	1,4	07/05/2023 - 08/05/2023
<i>Ricinus</i>	1	0,0	0,1	36	0,7	05/09/2023
<i>Pistacia</i>	0	0,0	0,0		0	
Other pollen from shrubs	1	0,1	-	-	-	
POLLEN FROM HERBS	1702	79,4	124,1	18,0	284,2	07/05/2023
COMPOSITAE total (incl. <i>Artemisia</i>)	11	0,5	0,5	18	2,1	02/05/2023 - 15/05/2023
<i>Artemisia</i>	11	0,5	0,5	18	2,1	02/05/2023 - 15/05/2023
BORAGINACEAE	1	0,1	0,2	22	0,7	29/05/2023 - 30/05/2023
CYPERACEAE	15	0,7	0,5	38	2,1	24/09/2023
CRASSULACEAE	0	0,0	0,0		0,0	
CRUCIFERAE	1539	71,8	120,6	18	282,8	07/05/2023
<i>Euphorbia</i>	0	0,0	0,0		0,0	
GRAMINEAE (Grasses)	20	0,9	0,5	24	2,1	22/05/2023
<i>Mercurialis</i>	1	0,0	0,1	26	0,7	29/06/2023
<i>Plantago</i>	2	0,1	0,1	18	0,7	01/05/2023 - 19/05/2023 - 25/07/2023
<i>Rumex</i>	13	0,6	0,5	22	2,1	31/05/2023
AMARANTHACEAE	25	1,1	1,1	36	2,8	09/09/2023
URTICACEAE	62	2,9	2,2	18	7,0	02/05/2023
Other pollen from herbs	13	0,6	-	-	-	

	YEAR		WEEK		DAY	
	Integral S*day/m ³	Percentage %	Maximum S/m ³	Week nr. Nr.	Maximum S/m ³	Date of the Maximum dd/mm/yyyy
TOTAL SPORES	12844	100,0	399,6	38	1240,4	20/09/2023
<i>Alternaria</i>	591	4,6	12,8	22	19,6	29/05/2023
Ascospores	5659	44	328,4	38	1072,4	20/09/2023
<i>Aspergillus/Penicillium</i>	406	3,2	24,0	30	168,0	24/07/2023
<i>Cladosporium</i>	3629	28,3	113,4	24	266,0	15/06/2023
<i>Ustilago</i>	882	6,9	34,7	34	165,2	25/08/2023
Other fungal spores	1678	13,1	-	-	-	

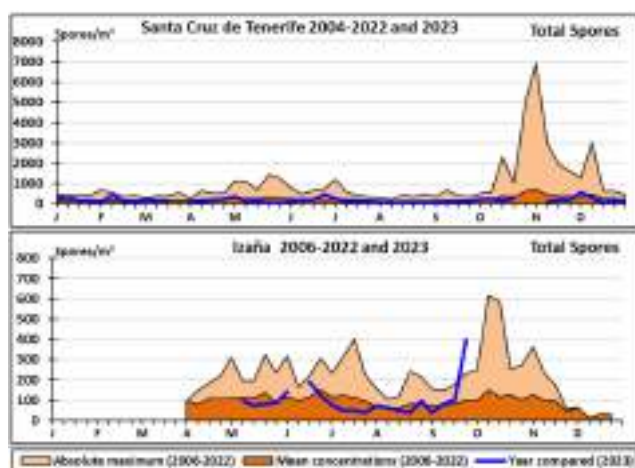


Figure 14.3. Dynamics of the mean weekly Total Fungal Spore concentrations in Santa Cruz de Tenerife (upper panel) and Izaña (lower panel) during 2023 in comparison with 2004/2006–2022 mean and maximum loads

The plots show that the seasonal cycle of total concentration of pollen and fungal spores at SCO is very different from that observed at IZO. It is also a subject of great interannual variability that depends on weather conditions such as temperature and precipitation. In SCO, concentration of pollen shows a broad maximum covering an extensive spring season (March to early June), that in 2023 occurred from March to mid-May. While in IZO, higher pollen concentrations during the measurement period happen in two months (usually from May to late June) but centered in early May in 2023. Usually, pollen concentration values are somewhat higher for IZO than for SCO (Figure 14.2). Main pollen taxa in SCO are *Artemisia*, *Erica*, *Myrica*, grasses (Poaceae or Gramineae), Oleaceae, Urticaceae, *Quercus*, Palm trees, Amaranthaceae and Cupressaceae. In IZO, Brassicaceae (Cruciferae) pollen is highly predominant, followed by *Myrica*, *Pinus*, Urticaceae, Amaranthaceae, *Castanea*, Oleaceae and grasses (Poaceae) as more abundant (Tables 14.1 and 14.2).

The total concentration of fungal spores shows a contrasting seasonal variation to that of total pollen. In 2023, in SCO, the concentrations showed small peaks in February, May, June, and in November-December but they did not reach higher values than the mean values of the period 2004–2022. At IZO, in 2023, fungal spore concentrations were similar than the mean values for the period 2006–2022 but higher than the mean in June and over the absolute maxima in September, when the sampling was stopped. Fungal spore concentrations are higher in SCO than in IZO (Figure 14.3). Main fungal spore taxa are *Ascospores*, *Cladosporium* and *Ustilago*, followed by *Alternaria* and *Aspergillus/Penicillium* (Tables 14.1 and 14.2).

The results presented here are a summary of the detailed information generated. However individual taxa might have quite a different seasonal behaviour at each station (see Tables 14.1 and 14.2 and graphs that can be generated on the [webpage](#)).

A number of products, such as current levels and forecasts of the main allergenic pollens and fungal spores, historical and current data and pollen calendar for SCO can be found at the Tenerife Aerobiology information (Proyecto EOLO-PAT) [web page](#).

14.4 Future activities

- Continuation of pollens and fungal spores sampling, and aerobiological data analysis.
- Update of the airborne pollen and spores databases.
- Improvement of the information provided through the [webpage](#) and services to its users.
- Trend analysis.
- Internannual variability versus meteorology.

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International Cooperation Programmes

15 Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS)

The Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) is the pan-European research infrastructure (RI) producing high-quality data and information on short-lived atmospheric constituents and on the processes leading to the variability of these constituents in natural and controlled atmospheres (simulation chambers).

ACTRIS enables access to high-quality long-term atmospheric data through a single-entry point. It offers access to world-class facilities providing researchers, from academia as well as from the private sector, with the best research environments and expertise promoting cutting-edge science and international collaboration.

ACTRIS is composed of ten connected elements: distributed National Facilities (Observational platforms and Exploratory platforms) both in Europe and globally, and eight Central Facilities (Head Office, Data Centre and six Topical Centres) (Figure 15.1).



Figure 15.1. ACTRIS research infrastructure core components

ACTRIS research infrastructure works towards:

- reducing uncertainties in quantification of emission sources, improved understanding of deposition processes that remove short-lived constituents from the atmosphere and quantification of their potential impacts on ecosystems.
- bringing essential information for understanding global biogeochemical interactions between the atmosphere and ecosystems, and how climate-ecosystem feedback loops may change atmospheric composition in the future.
- supporting the development of the required level of understanding of sources of the air pollutants that negatively affect human health.
- complementing Earth Observations from space with the necessary observations, providing unique ground-truthing of remote sensing information collected by current and future satellite missions.

15.1 ACTRIS-Implementation Phase Project

ACTRIS was included in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap in 2016. In April 2023, ACTRIS was legally recognized as a European Research Infrastructure Consortium (ERIC) with the official establishment of the ACTRIS ERIC by the European Commission. After many years of community building, design phase, and three years of the ACTRIS Preparatory Phase Project (ACTRIS PPP), ACTRIS is now immersed in an implementation phase (Figure 15.2). While many services are already accessible, the infrastructure is expected to reach full operational capacity by 2026. This process was funded as the ACTRIS Implementation Project (ACTRIS IMP), through the EU Horizon 2020 Coordination and Support Section.

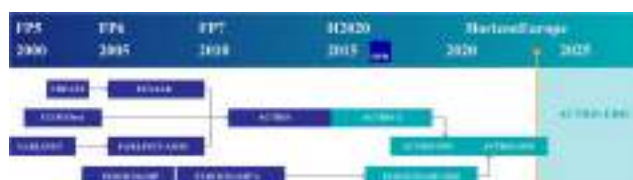


Figure 15.2. The Integrating Activities of the Infrastructure Program of the European Commission, funded under the fifth, sixth, and seventh (H2020) and now Horizon Europe Framework Programmes, leading to establishing ACTRIS ERIC in 2023. Reprinted from Laj et al. (2024)

This current phase is dedicated to constructing and upgrading the National Facilities and Central Facilities, setting-up the user access and service provision, working on the governance and management tasks, increasing the connection with new users and member countries, further developing strategies within ACTRIS and for international collaboration and partnerships, and integrating ACTRIS at different strategic levels (national, European and internationally). The key bodies, their roles, and the mechanisms that guide the strategic and operational management of ACTRIS are presented in Figure 15.3.

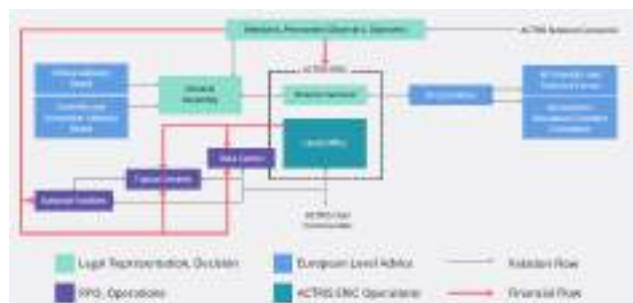


Figure 15.3. Key bodies, roles, and mechanisms guiding the strategic and operational management of ACTRIS. Reprinted from ACTRIS ERIC (2025).

15.2 Centre for Aerosol Remote Sensing

- 1) National Institute of Research and Development for Optoelectronics (INOE), Romania.
- 2) Meteorological Institute of the Ludwig-Maximilians-University (LMU-MIM), Germany.
- 3) Consiglio Nazionale delle Ricerche (CNR), Italy.
- 4) Hohenpeissenberg Meteorological Observatory, Deutscher Wetterdienst (HPB-DWD), Germany.
- 5) CNRS-Laboratoire d'Optique Atmosphérique (CNRS-LOA), Lille University, France.
- 6) Atmospheric Optic Group, University of Valladolid (UVA-GOA), Spain.
- 7) Izăna Atmospheric Research Center (AEMET), Spain.

- The CARS activities related to the measurement technique Automatic Sun/sky/polarised/lunar Photometers (CARS-ASP) are provided by CNSR-LOA (Lille, France), UVA-GOA (Valladolid, Spain) and IARC (Izaña, Spain) (see Figures 15.4 and 15.5). A new ASP unit has been incorporated in 2025 (ASP-PMOD).



IZO provides a unique facility for absolute calibration of Master Cimel instruments. For more details about the early AERONET-EUROPE Calibration Service, which is incorporated into CARS-ASP, see previous IARC Activity Reports (e.g Cuevas et al., 2022). The joint activity of IARC and UVA-GOA in the frame of AERONET EUROPE constitute AEROSPAIN (<https://aerospain.aemet.es/>).

Quality-assured data from ACTRIS and AERONET-EUROPE are widely used by modelling and satellite communities through several European programmes and initiatives (CAMS, ESA, EUMETSAT, AEROCOM, etc). In the period 2023–2024, ~ 57 sun-photometers were



CARS offers operational support to ACTRIS National Facilities, as well as specialized services to ACTRIS users:

calibrated by IARC in the frame of AERONET, ACTRIS and CARSNET.

During 2023–2024, IARC participated in various meetings and conferences within ACTRIS, for example, in ACTRIS Week 2023 held in Crete (Greece) in October 2023 (Figure 15.6) and ACTRIS Week 2024 held in Matera (Italy) in November 2024 (IARC staff attended online).



Figure 15.6. Group picture of participants of ACTRIS Week 2023 held in Heraklion (Crete), 24–27 October 2023

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Solano, J., Parra, F., Pérez de la Puerta, J., Rodríguez-Valido, M., Sálamo, C., Santana, D., Santo-Tomás, F., Sepúlveda, E. and Serrano, A.: Izaña Atmospheric Research Center Activity Report 2019–2020. (Eds. Cuevas, E., Milford, C. and Tarasova, O.), State Meteorological Agency (AEMET), Madrid, Spain and World Meteorological Organization, Geneva, Switzerland, NIPO: 666-22-014-0, WMO/GAW Report No. 276, <https://doi.org/10.31978/666-22-014-0>, 2022.

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16 ATMO-ACCESS

The ATMO-ACCESS project (Solutions for Sustainable Access to Atmospheric Research Facilities), funded under the European Union's Horizon 2020 research and innovation programme, aims to develop sustainable and harmonized solutions for access to European atmospheric research infrastructures (RIs). Its objective is to establish a long-term framework for open, coordinated access to facilities, services, and data, and to define governance and funding models that can ensure the continuity of transnational access beyond the current EU funding period.

Building on the progress achieved during the first years of the project (2021–2022), ATMO-ACCESS has continued advancing towards a sustainable and efficient model for physical, remote, and virtual access across atmospheric RIs. IARC remains actively involved in the initiative, contributing through two main Work Packages:

WP8: Sustainable and strategic framework for access to distributed atmospheric Research Infrastructures: led by the University of Valladolid – Atmospheric Optics Group. This activity contributes to identifying and testing the most appropriate mechanisms to ensure the long-term sustainability of transnational access.

WP9: Implementing access through Trans-National Access (TNA) activities: which coordinates the provision of access to a network of European atmospheric research facilities.

Within this framework, IARC continues to offer access under two complementary components:

Izaña Subtropical Access Facility for Observations (ISAF-Obs), providing synergistic in situ and remote-sensing observations of aerosols, trace gases, meteorology, and radiation. Activities include intercomparisons with operational instruments (reporting to global networks such as WMO GAW and NDACC), studies of atmospheric composition under pristine and dust-influenced conditions, and participation in field campaigns addressing phenomena such as new particle formation, desert dust, or long-range transport.

Izaña Subtropical Access Facility for Calibration (ISAF-Cal), offering a unique calibration site for photometric techniques under pristine conditions using Langley-based procedures. A calibration certificate is provided, along with the opportunity to compare and optimize photometers against reference instruments.

More information can be found on the ATMO-ACCESS [website](#) and the Izaña ATMO-ACCESS [webpage](#).

The following access activities were performed at the Izaña Atmospheric Research Center during 2023–2024:

Regular access:

1) Visit of the COCCON Travel Standard to the TCCON site in Izaña (COCCON Travel)

A mobile Fourier Transform Spectrometer (FTS) was deployed at the Izaña TCCON station to perform side-by-side measurements with the local high-resolution FTIR system. Date of access: 1–30 April 2023, Institution: Karlsruhe Institute of Technology (Germany).

Purpose and impact of the access: Validation and consistency assessment of TCCON network measurements by comparing COCCON and TCCON data. Contributes to maintaining global traceability and harmonization within the TCCON network.

2) Iron Salt Atmospheric Methane Oxidation in Sahara Dust Mixed with Sea Spray Aerosol (ISAMO)

Field sampling and analysis of air to test the hypothesis that methane oxidation by chlorine radicals originates from photocatalytic reactions in mixed sea-salt and Saharan dust aerosols. Date of access: 2023–2024. Institutions: Utrecht University, University of Copenhagen, Oceans X, Acacia Impact Innovation BV.

Purpose and impact of the access: Aims to reduce uncertainties in the role of Cl as a CH₄ sink, with implications for global climate models. Izaña serves as a high-altitude reference site expected to remain unaffected by low-level Cl sources.

Fast Track TNA (Trans-National Access urgent requests) access:

Following the volcanic eruption at Mauna Loa Observatory (Hawaii) in late 2022, which disrupted operations, IARC temporarily assumed the role of global calibration centre for several reference instruments and networks. These emergency actions were supported under the ATMO-ACCESS “Fast Track” access scheme.

The following activities were performed:

Calibration of reference photometers from NASA and PHOTONS-LOA (France), ensuring continuity of the AERONET and AEROSPAIN calibration chains.

Hosting of world reference Brewer and Dobson spectrophotometers for absolute ozone calibration campaigns in collaboration along with:

- Environment and Climate Change Canada (ECCC) — Absolute calibration of Brewer world reference #187 (July–August 2023).
- National Oceanic and Atmospheric Administration Global Monitoring Laboratory (USA) — Calibration of Dobson world standard D083 (July–August 2023).

For more details see section 9 and 17.

17 Regional Brewer Calibration Center for Europe (RBCC-E)

17.1 Background

In November 2003 the WMO GAW Regional Brewer Calibration Center for Europe (RA-VI region) (RBCC-E) was established at IZO. The RBCC-E reference is based on three double Mark-III Brewer spectrophotometers (the IZO triad): a Regional Primary Reference (Brewer 157), a Regional Secondary Reference (Brewer 183) and a Regional Travelling Reference (Brewer 185). In 2021, AEMET procured three new brewers as a new Triad for the RBCC-E (serial numbers #256, #257, and #258). As described in section 3.1, IZO is located in a subtropical region (28°N) on a mountain plateau (2373 m a.s.l.) with pristine skies and low ozone variability. This location allows routine absolute calibrations of the reference instruments under conditions similar to the Mauna Loa Observatory (MLO), Hawaii, USA. The establishment of the RBCC-E Triad allows the implementation of a self-sufficient European Brewer calibration system that respects the world scale but works as an independent WMO GAW Network infrastructure.

There are two European Calibration Centers for the two types of ozone spectrophotometers in use: Dobson and Brewer. The Regional Dobson Calibration Center for Europe (RDCC-E) is located at the Meteorological Observatory Hohenpeissenberg (Germany).

17.2 Objectives

The main objectives of this cooperation programme are:

- To implement a system for routine absolute calibrations of the European Brewer regional reference instruments at IZO, fully compatible with absolute calibrations of the world reference triad at MLO.
- To perform periodical intercomparison campaigns using the Regional Primary Reference B157 (during intercomparisons held at IZO) and the Regional Travelling Reference B185 spectrophotometer (traceable to B157) in continental campaigns (Figures 17.1 and 17.2).
- To perform regular comparisons of the Regional Brewer Primary Reference B157 with the Regional Dobson Reference D074 to monitor the relationship between both calibration scales in the WMO Regional Association VI - Europe.
- To study the sources of errors of the absolute calibrations and to determine the accuracy of total ozone measurement achievable by the Brewer

spectrophotometer under different atmospheric conditions or instrumental characteristics.



Figure 17.1. Participants at the 19th RBCC-E Intercomparison campaign held at Davos in 2024

17.3 Tasks

The main tasks of this cooperation programme are:

- To develop quality control protocols and Standard Operating Procedures (SOPs) for establishment of traceability of measurements to the reference standards.
- To maintain laboratory and transfer standards that are traceable to the reference standards.
- To perform regular calibrations and audits at WMO GAW sites.
- To provide, in cooperation with QA/Science Activity Centres, training and technical assistance to stations.



Figure 17.2. Images of the instrument terrace during the 18th RBCC-E Intercomparison campaign held at El Arenosillo in 2023

Table 17.1. Differences, in %, between the travelling reference Brewer #185 and other reference instruments during the blind days of RBCC-E campaigns, 2008–2024

Site	Year	IOS #017 (*)	K&Z #158	ECCC #145/190	JMA #174	Reference
Arosa	2008	-0.6				Redondas and Rodriguez-Franco (2008)
Huelva	2009	-0.6	0.8	-0.1		Rooszendaal et al. (2012)
Arosa	2010	-0.6				Rooszendaal et al. (2013)
Huelva	2011	-0.1	-0.2	-0.6		Rooszendaal et al. (2014)
Arosa	2012		-0.1			Redondas et al. (2015)
Huelva	2013	-1.0	0.7			Redondas and Rodriguez-Franco (2015a)
Izaña	2014			-2.2		Redondas et al. (2014b)
Arosa	2014	-1.2	1.5			Redondas and Rodriguez-Franco (2015b)
Huelva	2015	-0.5	-0.5			Redondas et al. (2018)
Arosa/Davos	2016					In preparation
Izaña	2016	-1.6 (-3.5)				Cuevas et al. (2017)
Huelva	2017	-0.7				Redondas et al. (2019a)
Izaña	2017		1.0			Redondas et al. (2017)
Arosa	2018		0.7			Redondas et al. (2019b)
Huelva	2019	-0.8		-0.9	-2.5	Redondas et al. (2021)
Davos	2021		-1.4			Redondas et al. (2024a)
Huelva	2021					Redondas et al. (2024b)
Davos	2022		-0.6	-0.8		Redondas et al. (2025)
Izaña	2023					In preparation
Huelva	2023		-1.1			Redondas et al. (2024c)
Sta Maria	2024					Redondas et al. (2024d)
Davos	2024		-0.9			Redondas et al. (2024e)
Izaña	2024					In preparation

International Ozone Services (IOS), Kipp & Zonen (K&Z), Environment and Climate Change Canada (ECCC), Japan Meteorological Agency (JMA).

In earlier years, RBCC-E activities were funded mainly by ESA projects such as “CEOS Intercalibration of Ground-Based Spectrometers and Lidars,” involving the two European calibration centers (RBCC-E and RDCC-E). Currently, AEMET provides most campaign funding, complemented by the WMO GAW Programme support for developing countries.

During the RBCC-E Brewer intercomparison campaigns, the travelling standard #185 is compared with other reference instruments when it is possible (Table 17.1). These reference instruments are: 1) International Ozone Services (IOS) travelling reference #017; 2) Brewers #145 and #190, operated by Environment and Climate Change Canada (ECCC); 3) the Kipp & Zonen travelling reference

#158 and 4) Brewer #174 operated by Japan Meteorological Agency (JMA).

The first three instruments (Brewers #017, #145 and #190), provide a direct link to the World Brewer Triad (WBT). A report of the comparison between references can be found in Redondas et al. (2018). As suggested by WMO GAW the link to the WBT is conducted by joint Langley campaigns at Mauna Loa or IZO stations. The last available comparison with the IOS reference Brewer is from 2019. No data from their instrument has been made available for the subsequent RBCC-E campaigns. The most recent intercomparison between the WBT and the RBCC-E Triad was held in Izaña in September 2024 (see section 17.4.8).

17.4 Main activities of the RBCC-E during the period 2023–2024

17.4.1 Comparison between the RBCC-E Reference Triads

After some mechanical adjustments, the New Triad instruments (#256, #257 and #258) have been operational since September 2022. The Original Triad and New Triad (#256, #257 and #258) have remained at the Izaña Observatory from then until May 2024, except for the time when Brewers #185, #256, and #258 have travelled to participate in calibration campaigns at El Arenosillo (Spain), Santa Maria (Brazil), Cabauw (The Netherlands) and Davos (Switzerland). During this period of approximately one and a half years, the two Triads have been both separately and cross analysed.

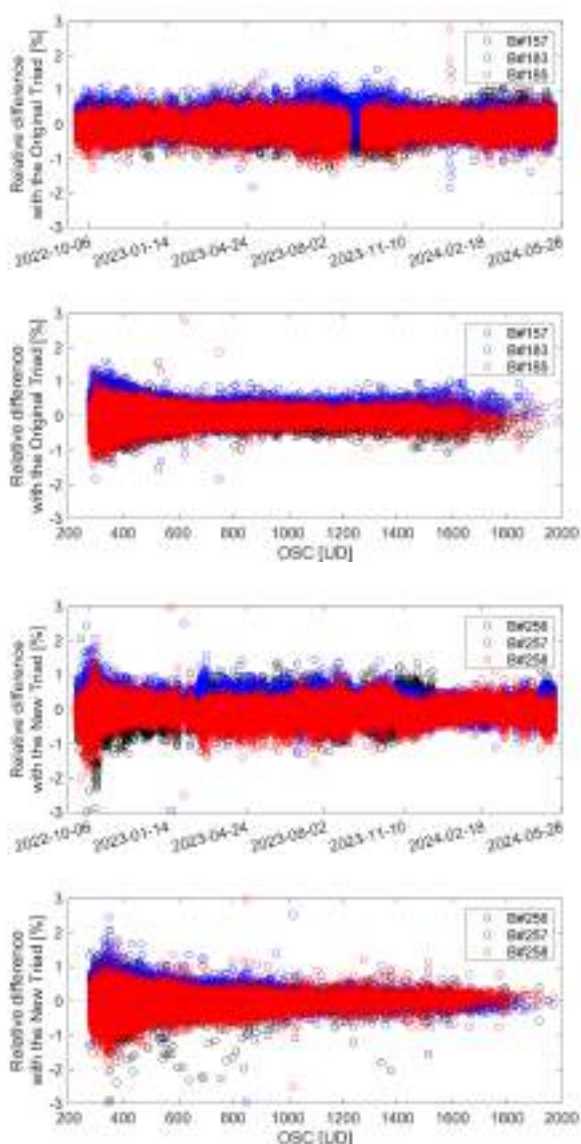


Figure 17.3. Separate analysis of the Original and New RBCC-E Triad

In the separate analysis (Figure 17.3), the relative differences between Eubrewnet L1.5 ozone of each Brewer with its Triad are shown. The average relative differences are between 0.03% and 0.10%, with standard deviations around 0.3%. From this analysis, it can be seen that the behaviour of the two triads are very similar.

The cross-analysis (Figure 17.4) shows the relative differences of each Brewer with respect to the other Triad. In this case, averages increase up to 0.37%, with standard deviations around 0.5%. No significant dependencies are found in any case with the ozone slant column (OSC), although in the case of cross-analysis there is a slight deviation from zero.

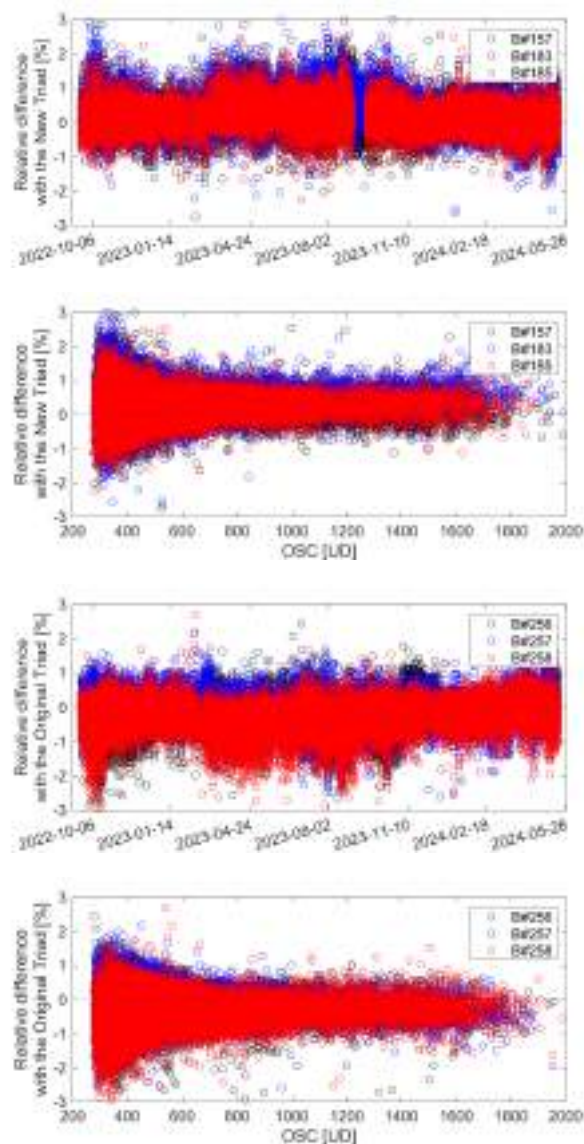


Figure 17.4. Cross-analysis of the Original and New RBCC-E Triad

The comparison between the triads (Figure 17.5) shows a mean difference of 0.3% with a standard deviation of 0.4%.

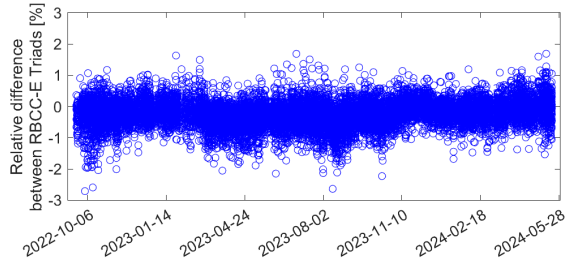


Figure 17.5. Difference between the Original and New RBCC-E Triad

17.4.2 Estimation of the uncertainty of RBCC-E Triads

Uncertainty of the Total Ozone Column provided by Eubrewnet has been implemented using the following expressions for both level 1.0 and level 1.5.

$$u_{O_3(L1.0)}^2 = \left(\frac{\delta O_3}{\delta etc}\right)^2 u_{etc}^2 + \left(\frac{\delta O_3}{\delta MS9}\right)^2 u_{MS9}^2 + \left(\frac{\delta O_3}{\delta A1}\right)^2 u_{A1}^2 + \left(\frac{\delta O_3}{\delta B}\right)^2 u_B^2 + \left(\frac{\delta O_3}{\delta P}\right)^2 u_P^2 + \left(\frac{\delta O_3}{\delta mR}\right)^2 u_{mR}^2 + \left(\frac{\delta O_3}{\delta mO_3}\right)^2 u_{mO_3}^2 + \left(\frac{\delta O_3}{\delta etc}\right)^2 u_{etc}^2 + \left(\frac{\delta O_3}{\delta etc}\right)^2 u_{etc}^2 + \left(\frac{\delta O_3}{\delta etc}\right)^2 u_{etc}^2 \quad (1)$$

$$u_{O_3(L1.5)}^2 = u_{O_3(L1.0)}^2 + u_{StandardLamp}^2 + u_{StrayLight}^2 + u_{Filter}^2 \quad (2)$$

Level 1.0 takes into account the uncertainty of the extraterrestrial constant (ETC), the measurement (MS9), the ozone absorption coefficient (A1), the Rayleigh coefficient (B), the pressure (P) and the optical air masses of Rayleigh (mR) and ozone (mO3). For the uncertainty of the level 1.5 product, the effect of the Standard Lamp, Stray Light, and Neutral Filter correction is also considered. The implementation in Eubrewnet is done without considering correlations between the different components, although work is currently underway to implement the effect of these correlations. The relative uncertainty of the six RBCC-E Brewers at Izaña between September 2022 and May 2024 is shown in Figure 17.6. The average uncertainty value is 1.2%, reaching up to 1.3% for angles greater than 70°.

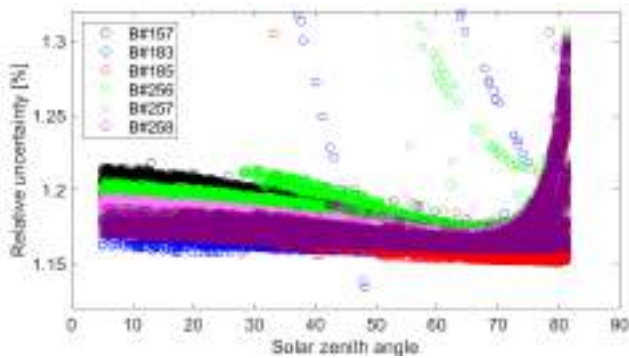


Figure 17.6. Relative uncertainty of the six RBCC-E Brewers at Izaña between September 2022 and May 2024

The principal uncertainty components (A1, ETC, MS9, B, P, mR and mO3) versus solar zenith angle for Brewer #157 are shown in Figure 17.7. The principal component is that associated with the absorption coefficient, A1, due to the error associated with the Bass and Paur cross-section used in the algorithm, which is independent of the Brewer. A detailed description of the whole calculation can be found in Redondas et al. (2020) and Redondas et al. (2022).

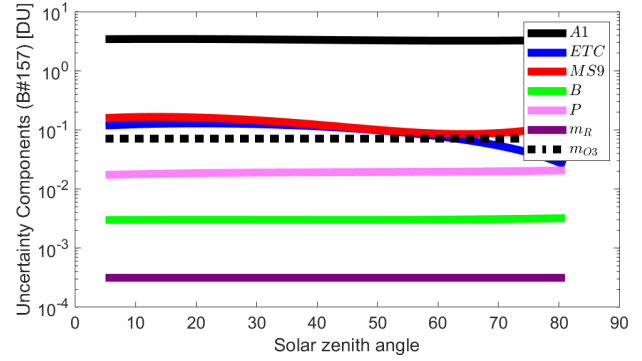


Figure 17.7. Principal uncertainty components (A1, ETC, MS9, B, P, mR and mO3) versus solar zenith angle for Brewer #157

17.4.3 Stability of the RBCC-E Triad

In the case of the RBCC-E Triads, the ETC is calculated by the Langley plot method. To determine the uncertainty associated to the ETC, both the uncertainty obtained from the linear fit (using the York method to consider the uncertainty of the optical air mass) and the uncertainty due to the dispersion of the obtained ETCs have been considered. In practice, the uncertainty due to the linear fit is less than 5% of the uncertainty associated with the dispersion of the ETCs, so it is considered negligible, and the uncertainty of the ETC is considered to be the standard error of the mean.

$$u_{etc}^2 = \sum_i^n \frac{u_{etc_i}^2}{n^2} = \sum_i^n \frac{u_{York}^2 + u_{std}^2}{n^2} \approx \sum_i^n \frac{u_{std}^2}{n^2} \quad (3)$$

The WMO GAW in 2011 authorized RBCC-E to conduct the transference of its own absolute calibration, based on Langley analysis at IZO. The link to the world reference in this case can be assured either by direct intercomparison with the world triad in Toronto or by common Langley campaigns at MLO or at IZO (Redondas 2014).

At present, the RBCC-E maintains a triad of reference instruments (see section 17.1). Each spectrophotometer is calibrated independently with the standard Langley method at IZO and since 2011 transfers their own total ozone calibration at regular calibration campaigns. These instruments are also regularly compared with the Toronto Triad.

Redondas et al. (2016) and León-Luis et al. (2018) studied the stability of the RBCC-E Triad during the period 2005–2015, using a mathematical method where the ozone values

are fitted to a 2nd grade polynomial (Fioletov et al., 2005) or an extended 3rd grade polynomial (Stübi et al., 2017). Redondas et al. (2016) and León-Luis et al. (2018) took into account two conditions: a) only days with at least 15 measurements distributed around the solar noon and with standard deviation < 0.5 were selected and b) measurement data obtained from Travelling Reference Brewer #185 during campaigns were removed.

In addition to this study, the stability of the RBCC-E Triad during the period 2005–2024 is presented in this report. The distribution of the difference between the ozone daily mean obtained by each Brewer with respect to the Triad mean O_3 value (O_{3_mean}) was calculated as follows:

$$O_{3_mean} = (O_{3_157} + O_{3_183} + O_{3_185})/3. \quad (4)$$

A good Gaussian profile can be observed in the distribution of the differences (Figure 17.3) which confirms the stability of the IZO Brewer Triad during the period 2005–2024.

Figure 17.4 shows the relative deviations from the RBCC-E Triad monthly mean TOC for each individual Brewer. This plot is used as a benchmark to identify if an instrument of the RBCC-E Triad needs to be recalibrated or for checking that a current calibration applied to a Brewer is good enough. The standard deviation of the relative deviations from the RBCC-E Triad monthly mean have values of 0.21%, 0.24% and 0.19% (Brewer#157, Brewer#183 and Brewer#185) for the period 2005–2024, 54% and 48% less than those reported for the MkII Canada Triad in Fioletov et al. (2005) and in Zhao et al. (2020), and 33% less than the MkIII Canada Triad (Zhao et al., 2020).

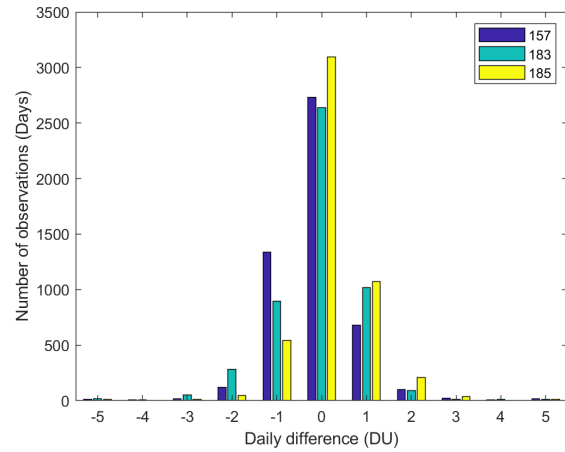


Figure 17.8. Distribution of the differences between the ozone daily mean obtained by each Brewer in the Triad with respect to the mean O_3 value of the RBCC-E Brewer Triad located at IZO for the period 2005–2024

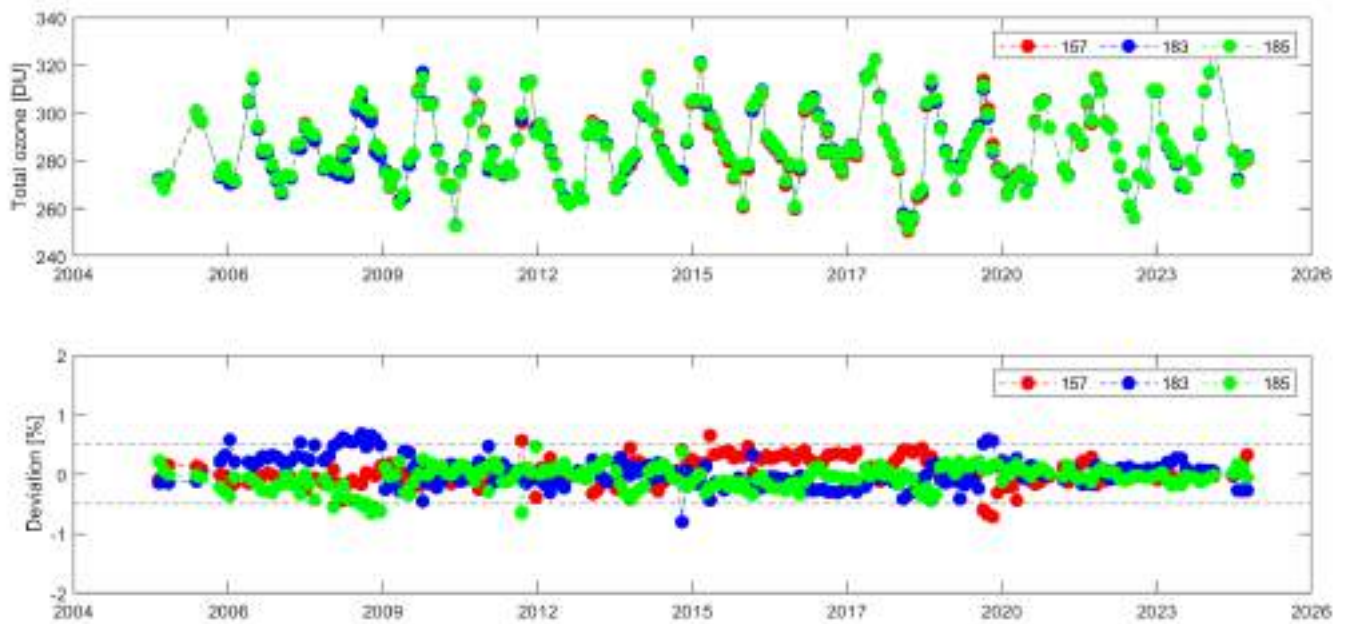


Figure 17.9. a) Monthly mean Total Ozone Column values measured at Izaña Observatory by the RBCC-E Triad and b) Relative deviation of each Brewer from the monthly mean of the RBCC-E Triad during the 2005–2024 period

17.4.4 RBCC-E intercomparison campaigns



Figure 17.10. Brewers participating in the 18th RBCC-E Intercomparison campaign at the El Arenosillo station, 5–15 September 2023 (Photo: A. Berjón)



Figure 17.11. Images of the 19th RBCC-E intercomparison campaign held at Davos, 19 – 28 August 2024

Brewer intercomparisons are held annually, alternating between Davos in Switzerland and the El Arenosillo Sounding Station of INTA (Huelva, Spain). The aim is to collect simultaneous ozone data from a number of Brewers from invited organizations so that their calibration constants can be transferred from the reference instruments. During the period of this report, two campaigns took place, the 18th RBCC-E intercomparison campaign held in El Arenosillo on 5–15 September 2023 (Fig 17.10) and the 19th RBCC-E intercomparison campaign held in Davos on 19–28 August 2024 (Fig 17.11).

The number of calibrations performed by the RBCC-E every year is shown in Figure 17.12. In 2023, 18 calibrations were performed (15 in El Arenosillo and 3 in IZO), while in 2024, 13 calibrations were performed (10 in Davos and 3 in IZO). These routine intercomparison campaigns provide the Brewer community with the opportunity to assess the status of the European network instruments.

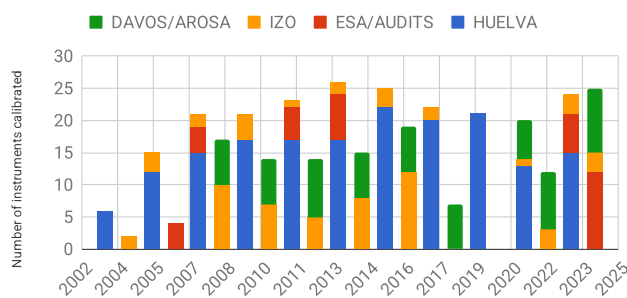


Figure 17.12. Calibrations performed by the RBCC-E per year.



Table 17.2. Participants at the 18th RBCC-E Intercomparison campaign held at El Arenosillo in 2023

Institution	Participants	Instrument	Country
Arenosillo 2023 (Spain, 5 – 15 September 2023) RBCC-E			
Izaña Atmospheric Research Center-AEMET & TRAGSATEC	Alberto Redondas Virgilio Carreño Alberto Berjón Javier López Solano	Brewer #185-MKIII Brewer #256-MKIII	Spain
AEMET	Ana María Díaz José María San Atanasio José Luis Hernández Pérez Patricia Fernández de Cos	Brewer #033-MKIV Brewer #070-MKIV Brewer #117-MKIV Brewer #151-MKIV Brewer #166-MKIII Brewer #186-MKIV	Spain
Instituto Nacional de Técnica Aeroespacial (INTA)	Jose Manuel Vilaplana	Brewer #150-MKIII	Spain
OTT Hydromet & Kipp & Zonen	Pavel Babal	Brewer #158-MKIII	The Netherlands
University of Manchester	Richard Kift John Rimmer	Brewer #075-MKIV Brewer #126-MKII Brewer #172-MKIII	United Kingdom
World Radiation Center (WRC)	Franz Zellinger	QUASUME	Switzerland
KNMI	Nis Jepsen Guisella Gacitúa	Brewer #202-MKIII Brewer #228-MKIII	Denmark
IOS	Volodya Savastiouk	Technical Support	Canada
Universidad de Extremadura	Antonio Serrano Pérez Alba Flores Jesús Zarza Belmonte María de los Ángeles Obregón	UV broad band calibration	Spain
AFC Ingenieros SA	Samuel Murcia Muñoz Óscar Peláez Lozano	Technical support	Spain

Table 17.3. Participants at the 19th RBCC-E Intercomparison campaign held at Davos in 2024.

Institution	Participants	Instrument	Country
Davos 2024 (Switzerland, 19–28 August 2024) RBCC-E			
Izaña Atmospheric Research Center-AEMET & TRAGSATEC	Alberto Redondas Virgilio Carreño Alberto Berjón	Brewer #185-MKIII Brewer #258-MKIII	Spain
World Radiation Center (WRC) & MeteoSwiss	Franz Zellinger Julian Gröbner Luca Egli Rolf Ruefenacht Eliane Maillard Barras	Brewer #040-MKIII Brewer #072-MKIII Brewer #156-MKIII Brewer #163-MKIII	Switzerland
Kipp & Zonen (K&Z)	Pavel Babal	Brewer #158-MKIII	The Netherlands
DWD	Voltaire Velazco Heiner Michael	Brewer #226-MKIII	Germany
CHMI	Martin Stanek		Czech Republic
BOKU-Met	Daniel Rauter	Brewer #093-MKIV	Austria

17.4.5 18th RBCC-E intercomparison results

During the blind comparison of the 18th RBCC-E Intercomparison Campaign, with the reference instrument Brewer #185, all Brewers had a mean difference of less than 1.0% except for Brewers #150 and #186, for which the difference was 1.1%. For eight of the twelve Brewers with blind days (67%) the difference was less than 0.5%. (Figure 17.13).

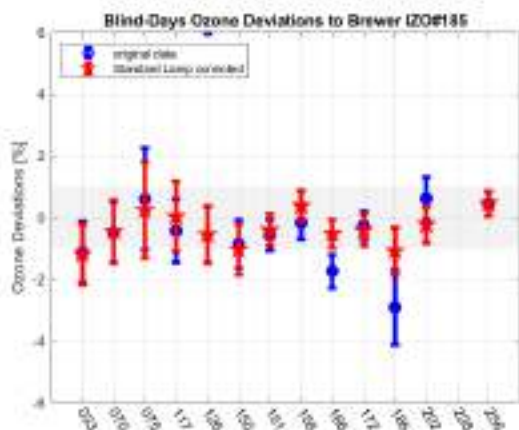


Figure 17.13. Initial period ozone relative percentage differences of all El Arenosillo 2023 participating instruments to RBCC-E travelling standard IZO#185. Ozone measurements collected during the blind period are reprocessed using the original calibration constants, with (red) and without (blue) Standard Lamp correction. Error bars represent the standard deviation.

Deviations of ozone values for all the participating instruments from the RBCC-E travelling standard Brewer IZO#185 are shown in Figure 17.14. We recalculated the ozone measurements using the final calibration constants, with and without Stray Light correction in the case of single Brewer instruments.

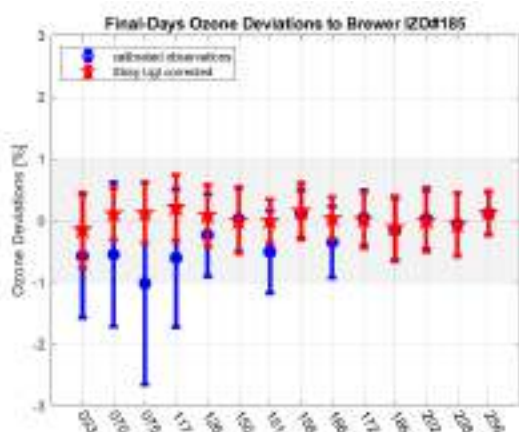


Figure 17.14. Final period, ozone relative percentage differences of all El Arenosillo 2023 participating instruments with respect to the RBCC-E travelling standard IZO#185. Ozone measurements collected during the final period are reprocessed using the proposed calibration constants, with (red plots) and without (blue plots) Stray Light correction. Error bars represent the standard deviation.

17.4.6 19th RBCC-E intercomparison results

The blind comparison with the reference instrument Brewer #185, shows that, after SL correction, all Brewers have an average difference of less than 1.0%, except for Brewer #226, for which the difference was slightly above this value. (Figure 17.15).

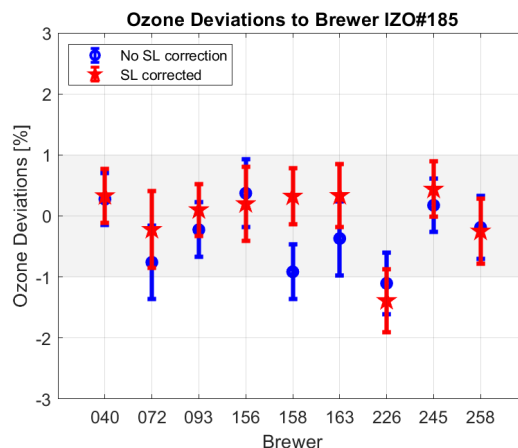


Figure 17.15. Ozone relative percentage differences of all Davos 2024 participating instruments to RBCC-E travelling standard IZO#185. Ozone measurements collected during the blind period are reprocessed using the original calibration constants, with (red) and without (blue) Standard Lamp correction. Error bars represent the standard deviation.

Deviations of ozone values for all the participating instruments from the RBCC-E travelling standard Brewer IZO#185 are shown in Figure 17.16. We have recalculated the ozone measurements using the final calibration constants, with and without Stray Light correction in the case of single Brewer instruments. The ozone is underestimated due to the effect of the Stray Light in single monochromator Brewers.

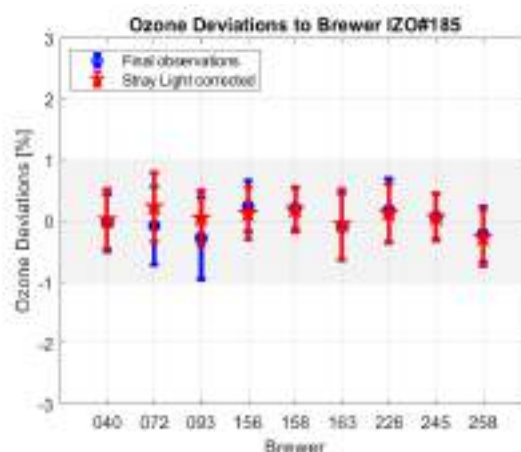


Figure 17.16. Ozone relative percentage differences of all Davos 2024 participating instruments with respect to the RBCC-E travelling standard IZO#185. Ozone measurements collected during the final period are reprocessed using the proposed calibration constants, with (red plots) and without (blue plots) Stray Light correction. Error bars represent the standard deviation.

17.4.7 Ibero-American campaign for Brewer spectrophotometer calibration and intercomparison

The “First Ibero-American Campaign for Brewer Spectrophotometer Calibration and Intercomparison” took place in Santa Maria, Brazil, from 19 February to 8 March 2024 (Fig 17.17). This exercise represented an unprecedented collaboration involving AEMET (Spain), the Federal University of Santa Maria (UFSM, Brazil), Instituto Nacional de Pesquisas Espaciais (INPE, Brazil), and the WMO GAW Programme, setting new standards for intercontinental atmospheric research and calibration. The campaign promoted high-precision recalibration, regional capacity-building, and operational training in ozone and ultraviolet measurements. Activities were conducted in structured phases, Week 1: Equipment refurbishment and calibration setup; Week 2: Operator training and Week 3: Intercomparison experiments and calibrations.

The equipment restoration was specifically targeted to the Brazilian Brewers (#068, #073 and #081) that had not been operational for nearly five years, providing essential hardware refurbishment and the installation of new NiSO₄ filters, as well as configuration and data recovery support. In addition, most of the participants lacked a recent calibration. Brazilian and Bolivian Brewers had not been calibrated since 2007, a gap of seventeen years, while other regional instruments received calibrations eight or more years ago. Only Spain’s Brewer #256 and Brazil’s Brewer

#167 had recent calibrations (2023 and 2022, respectively). The campaign successfully recalibrated all instruments, enabling real-time data transmission through EUBREWNET and restoring scientific quality to the entire network.

The instruments have been serviced and calibrated using the global reference provided by the RBCC-E. This reference is shared with the Toronto Centre, managed by Environment and Climate Change Canada (ECCC), which also participated remotely in the campaign.

The following operations were performed by the RBCC-E during the intercomparison:

- 1) Ozone calibration against the RBCC-E travelling reference (B#256).
- 2) Compilation of the calibration histories of the instruments.
- 3) Evaluation of the Level 2 Eubrewnet ozone data for the period between intercomparisons.

During this intercomparison, the RBCC-E transferred its own absolute ozone calibration, obtained by the Langley method at the Izaña Observatory with the new instrument of the triad (B#256). All the participating instruments were provided with a provisional calibration at the end of the campaign, which can be considered final calibration constants for most of them. A detailed calibration report for each instrument is available online. The list of participants is presented in Table 17.4.



Figure 17.17. First Ibero-American Campaign for Brewer Spectrophotometer Calibration and Intercomparison, 19 February–8 March 2024, Santa Maria, Brazil

Table 17.4. Participants at the First Ibero-American Campaign for Brewer Spectrophotometer Calibration and Intercomparison, held in Brazil in 2024

Institution	Participants	Instrument	Country
Santa María 2024 (Brazil, 19 February–8 March 2024) RBCC-E			
Izaña Atmospheric Research Center-AEMET	Alberto Redondas Virgilio Carreño	Brewer #256-MKIII	Spain
Instituto Nacional de Pesquisas Espaciais (INPE)	Gabriela Dornelles Maria Paulete Pereira Francisco Raimundo José Valentin Bageston	Brewer #068-MKIV Brewer #073-MKIV Brewer #081-MKIV	Brazil
Universidad Mayor de San Andres	Decker Guzmán	Brewer #056-MKII	Plurinational State of Bolivia
Instituto Antartico Argentino	Nazareno Tintes	Brewer #162-MKIV	Argentina
IOS	Martin Stanek	Technical support	Czech Republic
Universidad de Magallanes	Claudio Casicia	Brewer #180-MKIII	Chile
Universidade Federal de Santa Maria	Damaris Piñeiro	Brewer #167-MKIII	Brazil
Instituto de Investigaciones Científicas y Técnicas para la Defensa	Facundo Orte Cristian Laino	Brewer #229-MKIII	Argentina
Instituto Nacional de Meteorología e Hidrología	David Tonato	Brewer #218-MKIII	Ecuador

The results of the blind comparison with the reference instrument Brewer #256 can be seen in Figure 17.18. Brewers #068, #073 and #081 have not been included in the analysis of the blind days as they were serviced at the beginning of the campaign and are therefore considered as new instruments. Four instruments show an agreement better than 1%.

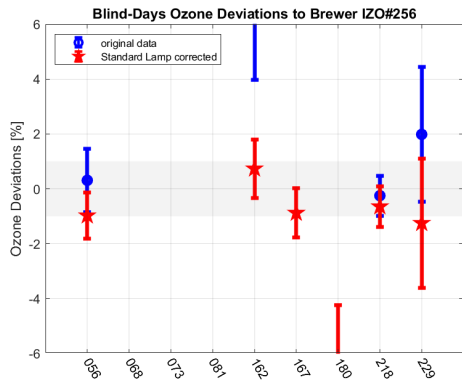


Figure 17.18. Ozone relative percentage differences of all participating instruments with respect to the RBCC-E travelling standard IZO#256. Ozone measurements collected during the final period are reprocessed using the proposed calibration.

A good agreement with the reference instrument Brewer#256 using the final calibration constants, within the range $\pm 0.5\%$, is achieved for most instruments (see Figure 17.19).

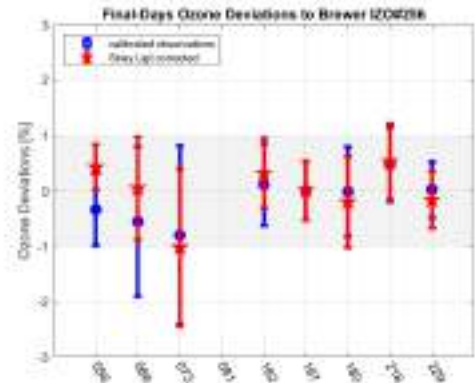


Figure 17.19. Ozone relative percentage differences of all participating instruments with respect to the RBCC-E travelling standard IZO#256. Ozone measurements collected during the final period are reprocessed using the proposed calibration. Brewer #081 could not be calibrated during the campaign.

17.4.8 Absolute ozone calibration campaigns at Izaña Observatory in 2023 and 2024

Table 17.5. Participants of absolute ozone calibration campaigns held at Izaña Observatory in 2023 and 2024

Institution	Participants	Instrument	Country
Izaña Observatory 2023 (Spain, 31 July–17 August 2023) RBCC-E			
Izaña Atmospheric Research Center-AEMET & TRAGSATEC	Alberto Redondas Virgilio Carreño Alberto Berjón Javier López Solano	RBCC-E reference triad Brewer #157 Brewer #183 Brewer #185	Spain
Environment and Climate Change Canada	Xiaoyi Zhao Reno Sit Michael Brohart	Brewer #187	Canada
National Oceanic and Atmospheric Administration, Global Monitoring Laboratory	Glen McConville Miyagawa Koji	Dobson world standard D083	USA
National Institute for Aerospace Technology	Jose Manuel Vilaplana	Dobson D120	Spain
Izaña Observatory 2024 (Spain, 9–24 September 2024) RBCC-E			
Izaña Atmospheric Research Center-AEMET & TRAGSATEC	Alberto Redondas Virgilio Carreño Alberto Berjón Javier López Solano	RBCC-E reference triad Brewer #157 Brewer #183 Brewer #185	Spain
Environment and Climate Change Canada	Reno Sit	Brewers #190, #191	Canada

Following the volcanic eruption at Mauna Loa Observatory (Hawaii) in late 2022, which disrupted operations, the Izaña Observatory hosted the world reference Brewer and Dobson spectrophotometers for absolute ozone calibration campaigns in collaboration with Environment and Climate Change Canada and the National Oceanic and Atmospheric Administration Global Monitoring Laboratory (Table 17.5).

In 2023, the absolute ozone calibration campaign was held at IZO from 31 July – 17 August 2023 (Fig 17.20), with Environment and Climate Change Canada and the absolute calibration of the Brewer world reference #187 and NOAA-GML (USA) absolute calibration of the Dobson world standard D083. The Spanish National Institute for Aerospace Technology also participated in the campaign with the Dobson D120.

In 2024, the absolute ozone calibration campaign was held at IZO from 9 – 24 September 2024 (Fig 17.21), with Environment and Climate Change Canada and the absolute calibration of Brewers #190 and #191.

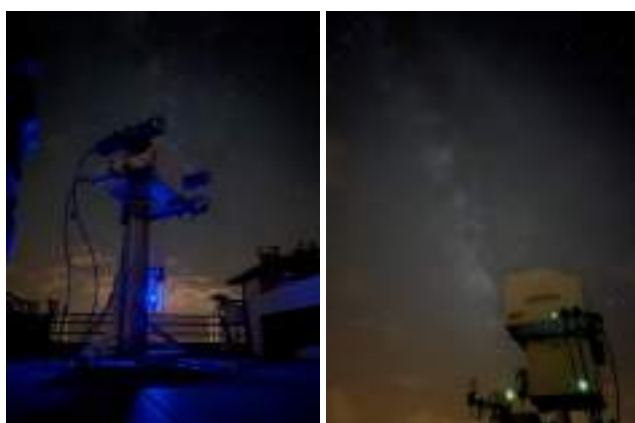


Figure 17.20. Absolute ozone calibration campaign held at IZO, 31 July – 17 August 2023

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Figure 17.21. Absolute ozone calibration campaign held at IZO, 9–24 September 2024

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18 Integrated Carbon Observation System (ICOS)

The Integrated Carbon Observation System (ICOS) is a European Research Infrastructure Consortium (ERIC) that provides high-precision, long-term observations essential for understanding the carbon cycle and the Earth system's response to climate change driven by greenhouse gases. ICOS delivers standardized and openly available data from nearly 180 measurement stations distributed across 16 European countries (as of 2024).

These stations monitor in situ GHGs concentrations in the atmosphere, the terrestrial biosphere, and the ocean. Accordingly, ICOS is structured into three scientific domains: **Atmosphere**, **Ecosystem** and **Ocean**. Each domain is coordinated by a Thematic Centre, which ensures data quality and provides technical and scientific support to the associated stations. In addition, ICOS includes the Central Analytical Laboratories (CAL), which are responsible for high-precision gas analyses and the provision of certified calibration gases. Figure 18.1 illustrates the organizational structure of ICOS and the data processing workflow within the network.

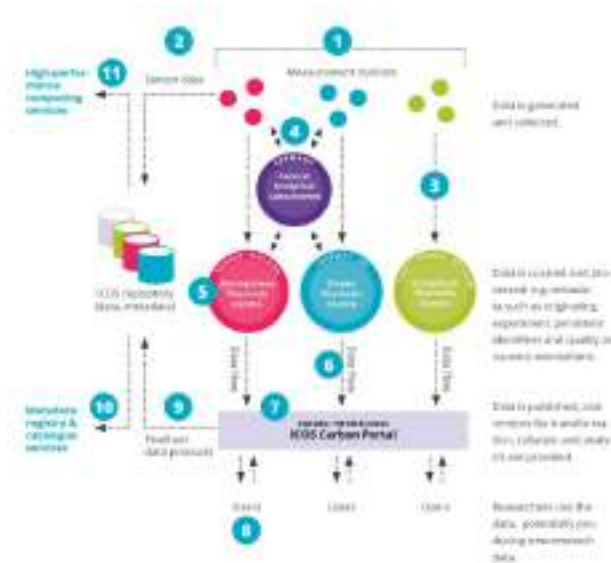


Figure 18.1. ICOS organizational structure and data workflow

Source: ICOS-ERIC website

The ICOS research community comprises more than 600 scientists and over 120 universities and research institutes across Europe. ICOS plays a central role in international efforts to improve the measurement, reporting, and verification of GHGs emissions. For example, it collaborates with WMO in the development of the Integrated Global Greenhouse Gas Information System (IG³IS) which helps countries verify their emissions using atmospheric observations.

Since 2019, ICOS has been officially recognized as an observer organization to the United Nations Framework

Convention on Climate Change (UNFCCC). This status enables ICOS to provide scientific input to the Convention's Subsidiary Body for Scientific and Technological Advice (SBSTA) and to organize side events during the annual Conferences of the Parties (COP), where global climate negotiations take place. Furthermore, ICOS is also an observer organization to the Intergovernmental Panel on Climate Change (IPCC), which allows the ICOS scientific community to contribute to the preparation of IPCC Assessment Reports.

To be included in the ICOS network, a station must undergo a rigorous labelling process carried out by the relevant Thematic Centre. This process is divided into three steps:

- The first step is to evaluate the site, the location, and other characteristics of the station.
- The second step assesses compliance with ICOS protocols, including measurement setup, data transfer, and data quality.
- The third step is the approval of the station by the General Assembly, based on the evaluation report prepared by the corresponding Thematic Centre and the recommendation of the Director General.

Each ICOS domain (Atmosphere, Ecosystem, and Ocean) has defined a set of mandatory and desirable variables to be measured by its stations. Depending on the extent to which these variables are monitored in accordance with ICOS standards, stations are classified as Class 1 (full compliance, including desirable variables) or Class 2 (minimum compliance, covering all mandatory variables).

Additionally, the Ecosystem network is complemented by a set of associated stations, which operate under less stringent requirements regarding the number of variables to be monitored.

18.1 Coordination of ICOS-Spain by IARC

AEMET, through IARC, is in charge of coordinating ICOS-Spain, one of the ICOS National Networks. Carlos Torres, IARC Director, serves as the national Focal Point. As such, AEMET (and particularly IARC) play a central role in the coordination of ICOS-Spain and its representation within the broader ICOS framework.

Spain's membership application was approved by the ICOS General Assembly on 17 November 2020. As of the end of 2024, the ICOS-Spain network comprised six official stations, distributed across the three ICOS domains (Atmosphere, Ecosystem, and Ocean). Each station is led by a Principal Investigator (PI), who is responsible for the scientific and technical operation of the site and participates in the Monitoring Station Assembly (MSA), coordinated by the corresponding Thematic Centre. A total of seven institutions are currently in charge of operating the ICOS-

Spain stations (see Table. 18.1). The current distribution of ICOS-Spain stations is as follows:

Atmospheric domain:

- Izaña Atmospheric Station, IZO (Tenerife). Class 2.
- El Arenosillo Atmospheric Station (Huelva). Class 2.
- Centro de Investigación de la Baja Atmósfera (CIBA) Atmospheric Station (Valladolid). Class 2.

Ecosystem domain:

- Majadas de Tiétar Associated Ecosystem Station (Cáceres). Associated.

Ocean domain:

- Estación de Series Temporales en el Océano de las Islas Canarias (ESTOC) Oceanic Station (fixed oceanic site north of Gran Canaria). Class 1.
- CanOA Oceanic Station (Ship of Opportunity between Gran Canaria and Barcelona). Class 1.

The main difference between the two oceanic stations lies in their operational mode: ESTOC is a permanent time-series station, moored at a fixed location north of Gran Canaria and dedicated to continuous in situ measurements of local oceanic parameters. In contrast, CanOA is implemented on a Volunteer Observing Ship (VOS) that regularly sails between Gran Canaria and Barcelona, collecting oceanic data along this route. Table 18.1 summarizes the most relevant details and institutional support of each station, while Figure 18.2 shows their locations.

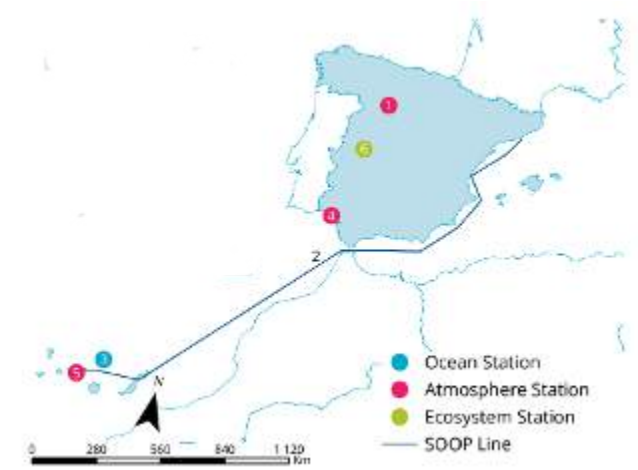


Figure 18.2. ICOS-Spain station network. Numbers on the map correspond to those listed in Table 18.1. Reprinted from: ICOS Handbook 2024.

Between 2023 and 2024, ICOS-Spain achieved several significant milestones that strengthened its integration within the ICOS Research Infrastructure. As shown in Table 18.1, three new stations were incorporated, and important progress was made in the certification process of the six stations currently comprising the network. IARC provided technical and logistical support throughout these processes, organizing regular coordination meetings with the entire ICOS-Spain community, as well as bilateral meetings with specific stations when necessary.

The ICOS Science Conference 2024 was held in Paris (France) from 9 to 12 September 2024. Researchers from various institutions within ICOS-Spain took part in the event.

Table 18.1. ICOS-Spain stations and current status in the ICOS certification process

Station (host institution)	PI	Station domain	Year officially admitted	ICOS labelling process stage	Number in Figure 18.2
CIBA (University of Valladolid and AEMET)	Abel Calle Montes	Atmosphere (Class 2)	2024	Step 1 approved on 23/5/2024	1
CanOA-VOS (ULPGC)	Melchor González Dávila	Ocean (Class 1)	2021	Labelling process completed on 15/11/2023	2
ESTOC (PLOCAN, IEO and ULPGC)	Melchor González Dávila Eric Delory	Ocean (Class 1)	2023	Step 2 on track (last update 05/03/2024)	3
El Arenosillo (INTA)	Jose Antonio Adame	Atmosphere (Class 2)	2022	Step 2 on track (last update 23/10/2024)	4
Izaña Observatory (IARC)	Pedro Pablo Rivas Soriano	Atmosphere (Class 2)	2021	Labelling process completed on 23/5/2023	5
Majadas de Tiétar (CEAM)	Arnaud Carrara	Ecosystem (associated)	2023	Labelling process completed on 15/11/2023	6

For a definition of the acronyms used in the above table, see section 30

A total of five posters and one oral presentation were delivered by scientists from ICOS-Spain. The corresponding titles can be found in the [conference programme](#). IARC researchers led two of the posters, which presented analyses based on data from various ICOS-Spain sites.

The first poster (León Luis et al., 2024a) reported anomalously high concentrations of CO and CO₂ measured at IZO and El Arenosillo stations in June 2023. Back-trajectories calculated by IARC staff using the FLEXTRA model (Stohl et al., 1995; Stohl and Seibert, 1998) and ERA5 meteorological data (Hersbach et al., 2020) revealed that the air masses reaching both stations during the event originated from Canada, coinciding with a major episode of wildfires. This study illustrates how long-range atmospheric transport can significantly alter local atmospheric composition, highlighting the sensitivity of ICOS atmospheric stations to global-scale events.

The second poster (León Luis et al., 2024b) focused on comparing the growth rate of detrended CO₂ time series (i.e., the trend obtained after removing the annual cycle following the approach of Thoning et al., 1989) from the ESTOC and IZO stations. Both observatories have long-standing CO₂ measurement records, starting in 1994 (ESTOC) and 1984 (IZO), well before their integration into the ICOS network. By fitting both time series, the authors found that the rate of increase in CO₂ concentrations measured at IZO appears to be accelerating over time, while the ESTOC data showed an approximately constant growth rate. They concluded that these results support the hypothesis that the ocean will likely continue to act as a CO₂ sink in the coming years.

IARC also played a key role in coordinating the national network's application to the [Redes de Investigación 2024](#) funding call from the Agencia Estatal de Investigación, under the Spanish Ministry of Science, Innovation and Universities. In collaboration with other institutions from ICOS-Spain (most notably the ULPGC), IARC submitted a proposal entitled: “*Consolidación y crecimiento de la red de observación de gases de efecto invernadero ICOS-España*”.

IARC as coordinator of the activities of the national network has collected the necessary information from its partners to collaborate in the edition of different documents such as the ICOS financial report, ICOS annual report and ICOS handbook. For more details of ICOS-Spain and the activities at the different stations see Cuevas et al. (2023a, b). In addition, the [ICOS-Spain](#) webpage disseminates the activities of the national node.

ICOS-Spain has also contributed to the ICOS ERIC Obspack compilations of atmospheric carbon dioxide, methane and nitrous oxide data from ICOS and non-ICOS European stations (ICOS RI et al., 2024b, 2024c, 2024d).

18.2 IZO-ICOS atmospheric station

IZO was the first ICOS Atmospheric Station established and certified in Spain. It is equipped with two specialized instruments ([Picarro G2401](#) and [Los Gatos Research-LGR-907-0015](#)) which were specifically acquired to measure CO₂, CH₄, CO and N₂O in compliance with ICOS standards. Both instruments were tested by the [ATC Metrology Laboratory](#) to ensure they meet the high-quality data requirements set by ICOS.

In November 2023, ICOS-ERIC published a feature article about IZO entitled “[The station above the clouds](#)” in its ExploreICOS series. The piece, produced on-site with journalist Charlotta Henry and photographer Pekka Pelkonen, highlighted IZO's strategic location, its instrumental capabilities, and its contributions to global GHGs monitoring. It included drone and ground-based photographs (Figure 18.3), as well as interviews with IARC research staff. A video complement is also available on the official ICOS [YouTube channel](#).



Figure 18.3. ICOS-Spain Atmospheric Station. Upper panel: IZO. Mid panel: IZO instrument terrace. Lower panel: working in the laboratory. Image credit: [ExploreICOS - The station above the clouds](#).

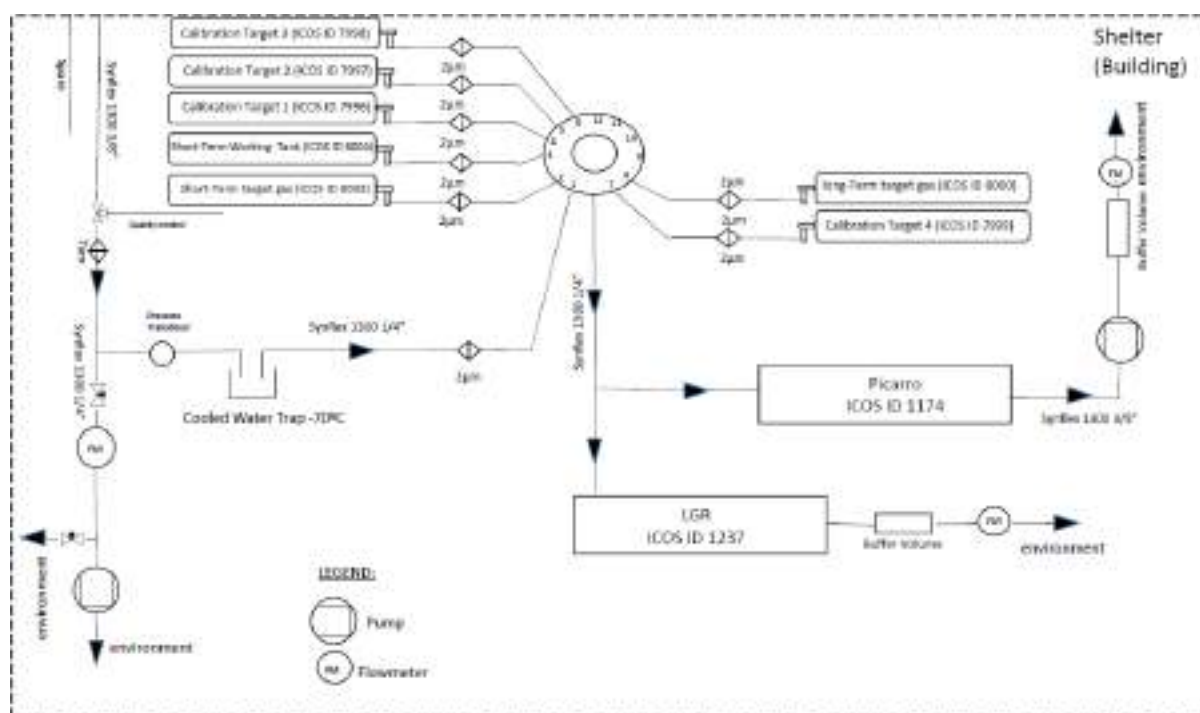


Figure 18.4. a) Schematic diagram of the instrument setup used to deliver ambient air and calibration gases to the analyzers in a controlled, sequential manner, enabling periodic calibration and verification of the measurements. b) Photographs showing main components of the installation. From left to right: (1) air inlet that directs ambient air to both analyzers, (2) flow controllers that measure intake flow, (3) the analyzers themselves (Picarro G2401 and LGR 907 0015) along with their corresponding workstations and displays, and (4) gas cylinders used for calibration and measurement verification.

The ICOS IZO Atmospheric station includes an automated sequencer that controls the flow of air into the instruments according to a predefined schedule. It alternates between ambient air and pressurized reference gases stored in cylinders.

These cylinders contain air with known concentrations of trace gases. Some are designated for calibration (performed every 14 days and 23 hours), while others serve as working tanks, used to verify the consistency and stability of the measurements. This configuration ensures traceability, internal quality checks, and compliance with ICOS calibration protocols. Figure 18.4a presents a schematic of the instrumental setup, while Figure 18.4b shows photographs of the main components of the installation.

The measurements collected by both instruments, along with diagnostic and meteorological data from the station, are automatically sent to the Atmosphere Thematic Centre (ATC) on a daily basis using custom Python scripts, which were recently updated (June 2025) to enhance robustness against potential upload errors. These data are first

automatically processed and quality-controlled through the ATC's automated processing pipeline. Then, they must undergo manual quality control by the station research staff, using a visualization tool developed by the ATC. All data are openly accessible via the ICOS Carbon Portal, including Level 1 data (automatically processed) and Level 2 data (processed and manually validated).

Figure 18.5 shows the hourly-averaged time series for all gas species measured by ICOS IZO Atmospheric station from its operational start on 2 November 2022 through to 31 December 2024. Data flagged as invalid or non-representative of background conditions after the manual quality control were excluded. The time series show strong agreement with measurements from the co-located WMO GAW station (see section 4), as expected given that both stations operate at the same site and use comparable instrumentation. This co-location enables direct intercomparison of GHGs measurements from both programmes, facilitating the identification of systematic discrepancies and supporting robust quality assurance.

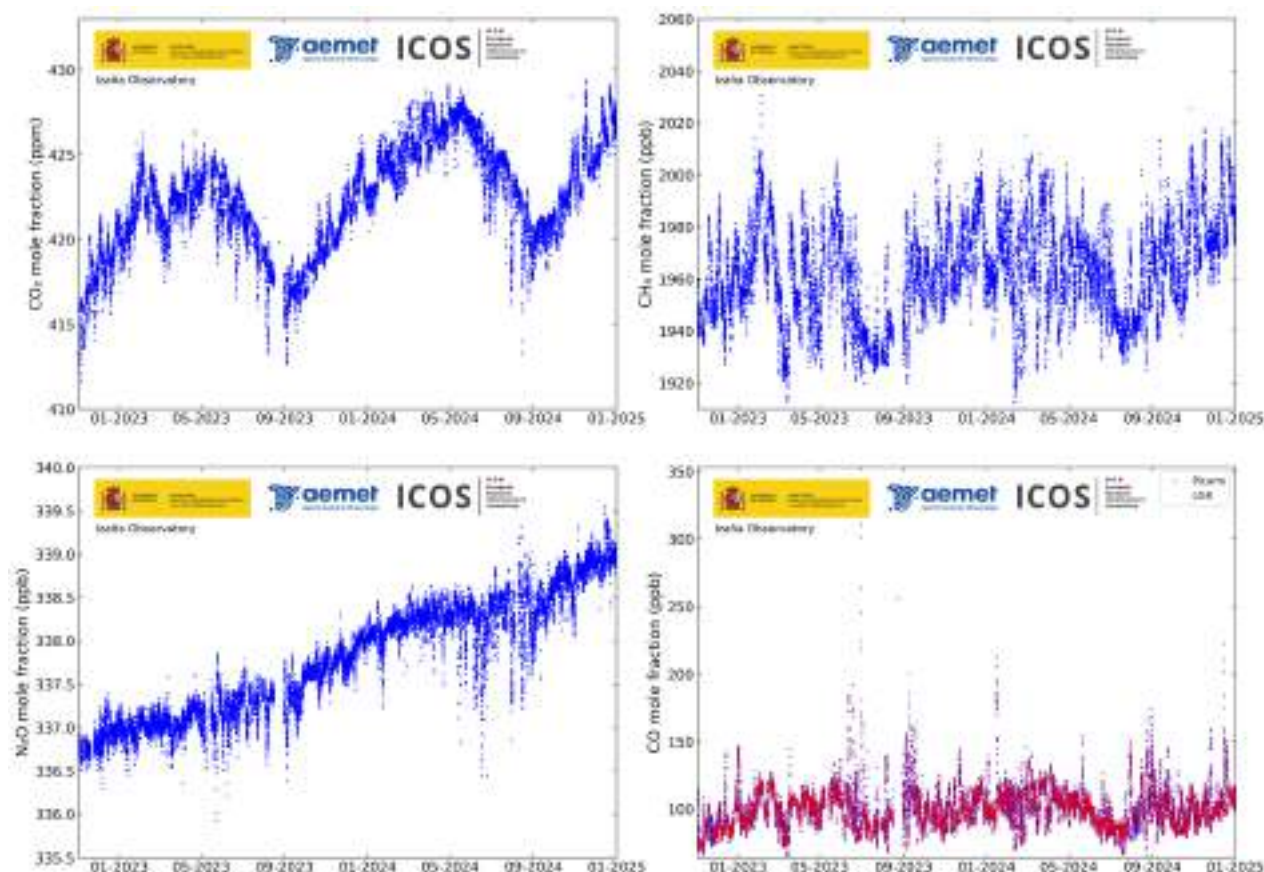


Figure 18.5. Hourly-averaged time series of atmospheric in situ mole fraction of gas species measured at the ICOS Izaña Atmospheric Station from 2 November 2022 to 31 December 2024, excluding non-valid and non-background data. For carbon monoxide, both instruments (Picarro G2401 and LGR 907-0015) provide measurements; therefore, both are shown in the corresponding plot.

In addition to the ICOS Science Conferences, there are Monitoring Station Assemblies where the ATC and station researchers meet to discuss, among other things, the status of the station network and the evaluation of their instruments. The atmospheric Monitoring Station Assembly was held in Brussels (Belgium) from 15–17 May 2023. Pedro Pablo Rivas and Sergio León attended as representatives of the ICOS IZO Atmospheric station (Figure 18.6).



Figure 18.6. Participants in the atmospheric Monitoring Station Assembly (MSA) held in Brussels (Belgium) from 15–17 May 2023. Image credit: ICOS-ERIC.

18.3 New project to develop science-based climate services in Africa: KADI

ICOS has over 180 measurement stations on the European continent and on the adjacent oceans. On the African continent, however, there is currently no stable infrastructure to standardize the operation of the existing stations, and to harmonize the data into one portal. Moreover, the current global models and observational instructions have been developed mainly in non-tropical regions, meaning that they need to be fitted to the African environment.

To start addressing these issues, ICOS-ERIC leads a EU HORIZON-INFRA project called Knowledge and Climate Services from an African Observation and Data Research Infrastructure (**KADI**). KADI aims to improve knowledge about climate change in Africa and develop tools to combat its negative consequences. The project will investigate what kind of climate services are needed in the African continent to tackle the climate crisis. The aim is to design a pan-African climate observation research infrastructure. IARC scientists participate as team members in this project.

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18.5 Staff

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- Carlos Torres (from September 2023 – National Network Focal Point; Director of IARC)
- Pedro Pablo Rivas Soriano (AEMET; Head of programme)
- Dr Sergio Fabián León Luis (until February 2025 - TRAGSATEC; Research Scientist)
- Dr Ayoze Álvarez Hernández (from May 2025 - TRAGSATEC; Research Scientist)
- Ramón Ramos (AEMET; Head of Infrastructure and instrumentation)
- Enrique Reyes (AEMET; Software and data processing)
- Dr Omaira García (AEMET; Research Scientist)
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19 WMO Measurement Lead Centre for Aerosols and Water Vapour Remote Sensing Instruments

The mission of the Commission for Instruments and Methods of Observations (CIMO) was to promote and facilitate international standardization and compatibility of instruments and methods of observations used by Members, in particular within the WMO Global Observing System, to improve quality of products and services delivered to/by Members and to meet their requirements. CIMO XVI nominated IZO as WMO Testbed for Aerosols and Water Vapour Remote Sensing Instruments.

Following approval of the WMO Reform package by the Eighteenth World Meteorological Congress in June 2019, a Joint Session of the new Technical Commissions and Research Board agreed on working structures in May 2020. As a result of the WMO reform of the constituent bodies, CIMO was dissolved and its activities were included in the activities of the Commission for Observation, Infrastructure and Information Systems (INFCOM). In 2021, INFCOM decided to replace the existing concepts of WMO Testbeds and Lead Centres with the single concept of WMO Measurement Lead Centres (MLC) (for more information see [here](#)).

The main ongoing activities of the WMO Measurement Lead Centre for Aerosols and Water Vapour Remote Sensing Instruments at IZO are related to instrument validation, development of new methodologies and devices for aerosol and water vapour observations.

19.1 The Langley ratio method, a new approach for transferring photometer calibration from direct sun measurements

The article published by Almansa et al. (2024) introduces a novel method for transferring calibration from a reference sun photometer—referred to as the "master"—to a secondary or "field" sun photometer using a synergistic approach, even when the two instruments operate with different spectral bands. The methodology was initially applied between a Precision Filter Radiometer (PFR) from the World Optical Depth Research and Calibration Center (WORCC), recognized by the WMO as a standard reference, and a CE318-TS (Cimel) photometer, the instrument commonly used within AERONET. These instruments differ significantly in terms of optics, sun-tracking systems, and spectral characteristics.

The calibration transfer relied on the Langley Ratio (LR) technique, which was applied to 1-minute synchronized measurements for solar air masses ranging from 2 to 5, and its performance was compared to the traditional Langley calibration method. The evaluation was conducted at two locations (IZO and Valladolid) over a six-month period, capturing diverse aerosol conditions. At IZO, calibration constants transferred from the PFR to the Cimel showed minimal relative differences and standard deviations (as low as 0.29% and 0.46%, respectively), after accounting for instrumental factors such as differing fields of view and potential calibration anomalies. In contrast, larger discrepancies were observed in Valladolid (up to 1.04%) and in the shorter-wavelength bands (reaching 0.78% in IZO and 1.61% in Valladolid).

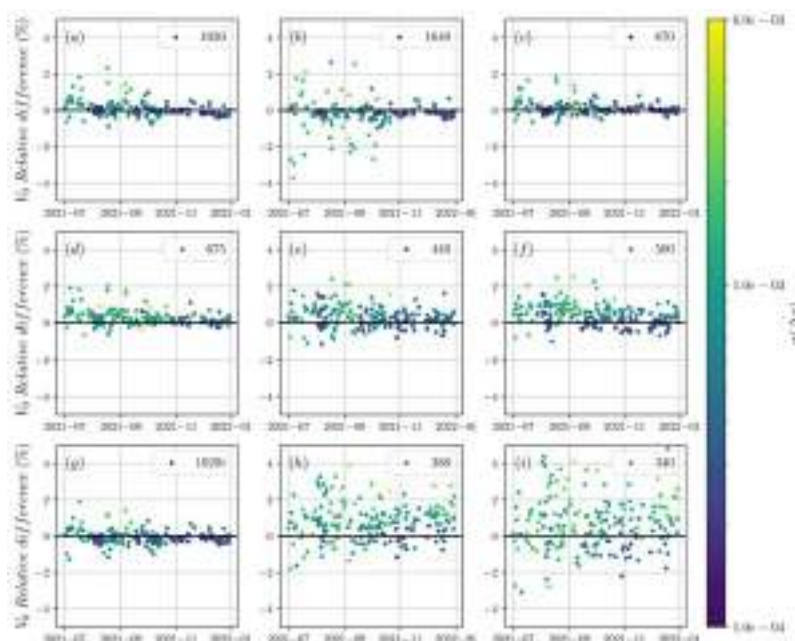


Figure 19.1. Daily $V_{0,\lambda}$ relative differences (in %) between the calibration constant obtained by applying the standard Langley calibration ($V_{0,\lambda SL}$) to the CE318-TS instrument no. 1089 at IZO and the calibration constant transferred to the Cimel from the PFR by applying the LR method ($V_{0,\lambda LR}$) to daily observations at IZO. Reprinted from Almansa et al. (2024).

Moreover, the LR method proved effective in transferring calibration between different CE318-T models, achieving high accuracy (with deviations between 0.17% and 0.69% in morning observations), despite differences in their central wavelengths of up to 91 nm. The study also highlighted the method's potential for diagnosing and correcting instrument-related issues. This was demonstrated through the detection of temperature sensitivity in the UV bands (380 nm and 340 nm) of the Cimel photometers, with temperature-induced signal variations quantified and used to implement the first operational temperature correction for these spectral bands.

19.2 Aerosol properties derived from ground-based Fourier transform spectra within COCCON

Fourier Transform Infrared spectroscopy plays a crucial role in climate research due to its ability to capture detailed absorption features of trace gases as well as broad continuum signals related to aerosols and water vapour across the infrared spectrum. A study by Álvarez et al. (2023) evaluated the performance of the compact and portable EM27/SUN spectrometer, utilized within the COCCON research infrastructure, for retrieving aerosol spectral properties from low-resolution solar absorption FTIR spectra (0.5 cm^{-1} resolution).

The focus was on deriving AOD and its spectral variation in the 873–2314 nm range using COCCON measurements conducted at IZO. These observations coincided with AERONET sun photometer data over a three-year period (December 2019 to September 2022). A cross-validation between the AERONET and COCCON datasets in their overlapping spectral range (870–1640 nm) revealed strong agreement, with average AOD differences around 0.005, standard deviations reaching up to 0.021, and Pearson correlation coefficients as high as 0.97.

These results confirmed that, when supported by a robust calibration approach—such as Langley plot or absolute calibration methods to correct for system degradation (approximately 0.72% per month)—the low-resolution COCCON spectrometers are capable of accurately capturing the broadband aerosol signal in addition to trace gas measurements (for more details see section 7).

19.3 Calitoo sun-photometer studies

19.3.1 Aerosol retrievals derived from a low-cost Calitoo sun-photometer on board a research vessel

The study published by García et al. (2024) offers a detailed assessment of AOD and Ångström Exponent data collected over a five-year period (March 2018–September 2023) using a hand-held Calitoo sun photometer aboard the

research vessel Ángeles Alvariño. Measurements were conducted across key maritime regions, including the Canary Islands, North African coasts, the Mediterranean, Portugal, the Cantabrian Sea, and the Bay of Biscay (Figure 19.2). The Calitoo instrument records solar irradiance at three specific wavelengths (465, 540, and 619 nm). A Monte Carlo-based uncertainty analysis for the AOD retrievals indicated expanded uncertainties ranging from 0.008 to 0.050, with an average uncertainty of 0.032 ± 0.008 across the measured wavelengths. The device also exhibited notable calibration stability over the five-year period, with a variation of just 2.6%.

The Calitoo AOD measurements were validated against reference AOD data from AERONET stations in SCO, El Arenosillo (Huelva), and Palma de Mallorca. These comparisons showed strong agreement, with correlation coefficients ranging from 0.727 to 0.917 and mean biases between -0.030 and -0.001 . Additional comparisons with satellite-derived and modelled aerosol products from MODIS and CAMS-ECMWF respectively revealed that Calitoo AOD values tended to be lower, with negative mean biases of -0.063 and -0.024 , respectively.

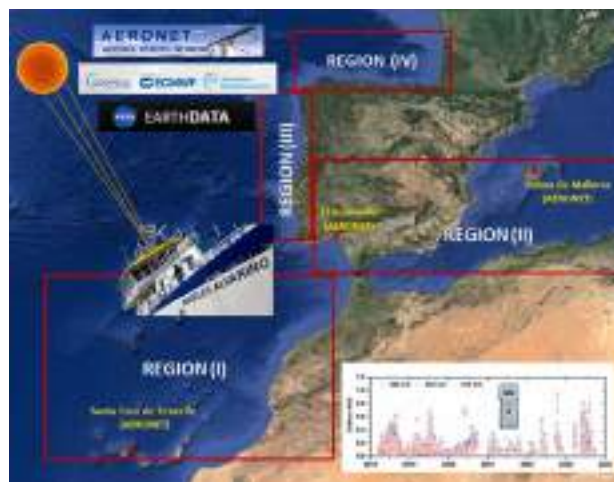


Figure 19.2. Main regions and databases used in the paper published by García et al. (2024)

Analysis of AE versus AOD patterns across the three maritime zones demonstrated consistency with aerosol characterizations derived from AERONET-Cimel data collected under similar conditions. These results affirm the Calitoo's potential as a reliable and cost-effective tool for aerosol monitoring in areas lacking fixed observation networks. Its affordability and portability make it well-suited for deployment on commercial or passenger ships and in remote or under-observed regions, offering valuable real-time AOD/AE data for aerosol process studies, model validation, and satellite product verification.

19.3.2 Calibration of Calitoo sun-photometers

Fifty Calitoo sun-photometers were calibrated at IZO as part of the WMO Measurement Lead Centre for Aerosols and

Water Vapour Remote Sensing Instruments programme, from 7–15 May 2024 (Figure 19.3).

Calitoo sun-photometers are involved in the Global Learning and Observations to Benefit the Environment (GLOBE) programme, a worldwide hands-on science and education initiative for primary and secondary schools.

Following their manufacturing, sun photometers must be periodically calibrated to provide measurements of AOD. The optimal calibration conditions at IZON have enabled the calibration of these Calitoo sun photometers for the fourth time (in 2014, 2015, 2017, and 2024).



Figure 19.3. TENUM Calitoo activities at IZO: preparations and measurements for Langley calibration performed by Frederic Bouchar and Stéphane Villeneuve, 7–15 May 2024

19.4 LIME: Lunar Irradiance Model of ESA

19.4.1 LIME: A new tool for absolute radiometric calibration using the Moon

Absolute calibration of Earth observation (EO) sensors is essential to ensure long-term stability and cross-mission interoperability, both of which are crucial for maintaining reliable global climate records and generating accurate forecasts. The Moon serves as an ideal calibration source due to its photometric stability, radiance levels comparable to Earth observations, and freedom from atmospheric interference. However, to use it effectively, it is necessary to model how its disk-integrated irradiance varies with changes in the Sun–Earth–Moon geometry.

In this context, the European Space Agency (ESA) has developed LIME (Lunar Irradiance Model of the European Space Agency), a new lunar irradiance model derived from ground-based measurements using a dedicated lunar radiometer installed at IZO. Top-of-Atmosphere lunar irradiance is determined using the Langley plot method, with full traceability to the International System of Units (SI) through calibrations performed at the UK National Physical Laboratory (NPL), (Toledano et al., 2024). At the time of the study, approximately 590 lunar observations collected between March 2018 and December 2022 have contributed to the model, which builds on the analytical

framework of the widely adopted ROLO (Robotic Lunar Observatory) model.

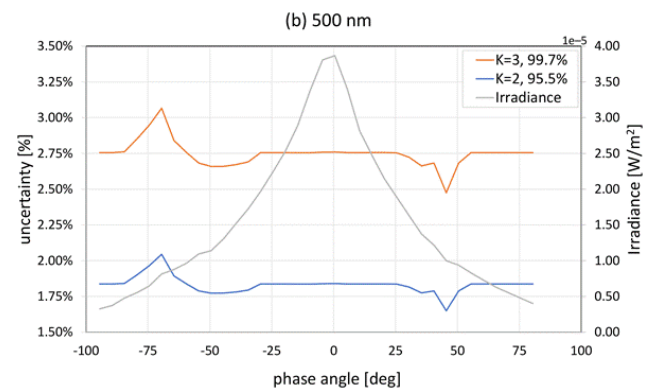


Figure 19.4. Uncertainty levels determined by Toledano et al. (2024) for the Cimel photometer spectral bands

Toledano et al. (2024) presents the methodology used to develop LIME, including the radiometer characterization, the derivation of nightly ToA irradiance, and the fitting of model parameters, along with a rigorous metrological uncertainty assessment. The model output has been compared with data from EO satellites such as PROBA-V, Pléiades, and Sentinel-3B, as well as with the ROLO model as implemented by VITO. Preliminary results indicate that LIME predicts 3% to 5% higher disk-integrated irradiance than ROLO in the visible and near-infrared spectral bands. The model's expanded radiometric uncertainty ($k=2$) is around 2% for the wavelengths observed by the lunar radiometer. Continued observations are expected to further refine the model parameters in future updates.

19.4.2 Extension of the ESA-LIME Project

This new phase of the ESA Project focuses on enhancing the LIME model previously developed. The core objectives of this initiative include:

- Creating a dedicated website for LIME.
- Ensuring continued support and updates for the LIME toolbox (TBX) and its accompanying documentation.
- Validating the LIME-TBX outputs by comparison with hyperspectral lunar datasets.

Model improvements will involve:

- Processing and modelling the lunar degree of linear polarization and integrating these models into the LIME-TBX.
- Incorporating a new spectral channel near 2 microns to extend the LIME measurement capabilities.
- Refining the spectral interpolation methods used in the LIME reflectance outputs.

19.5 Optical properties of North Atlantic aerosols from compact dual-wavelength depolarization Lidar observations

González et al. (2024) presented a characterization of the optical properties of various aerosol types based on observations made with a compact dual-wavelength depolarization elastic lidar (CIMEL CE376) operating at 532 and 808 nm. This study focuses on the vertical distribution and temporal evolution of aerosols observed in the subtropical North Atlantic region between August 2021 and August 2023, including Saharan dust outbreaks, volcanic aerosols, and fresh and aged wildfire smoke. A modified two-wavelength Klett inversion algorithm was applied to derive aerosol backscatter and extinction coefficients from CE376 lidar data.

The performance of the CE376 lidar was evaluated during an intercomparison campaign with an MPL-4B lidar (part of MPLNET), while both instruments were co-located at IZO).

Both systems provided consistent vertical aerosol profiles, with discrepancies primarily due to differences in overlap function determination, depolarization calibration, and increased sensitivity of the CE376 system to solar background noise during daytime. Absolute differences in

volume depolarization ratio (δv) were 0.3%, reduced to 0.2% when considering only nighttime measurements.

Key aerosol parameters derived from the dual-channel CE376 measurements included the particle linear depolarization ratio (δP), the extinction Ångström exponent (EAE, 532/808 nm), and the Attenuated Color Ratio (ACR, 808–532 nm). These allowed detailed insight into aerosol size and composition. Fresh Saharan dust exhibited the largest, most non-spherical particles and travelled in well-mixed layers, showing low EAE (532/808), high ACR (808–532), and δP (532) > 0.15 . In contrast, finer particles with nearly homogeneous morphology were linked to sulfate aerosols from the early stages of the Cumbre Vieja volcanic eruption and aged smoke from Canadian wildfires transported across the Atlantic, characterized by $\delta P < 0.08$ and EAE (532/808) > 1 . Intermediate values of these indicators were associated with heterogeneous mixtures of ash, soot, and charred material from local fresh wildfires.

Overall, the retrieved properties confirm the strong performance of the CE376 micro-lidar for continuous monitoring and detailed characterization of the vertical and temporal distribution of atmospheric aerosols.

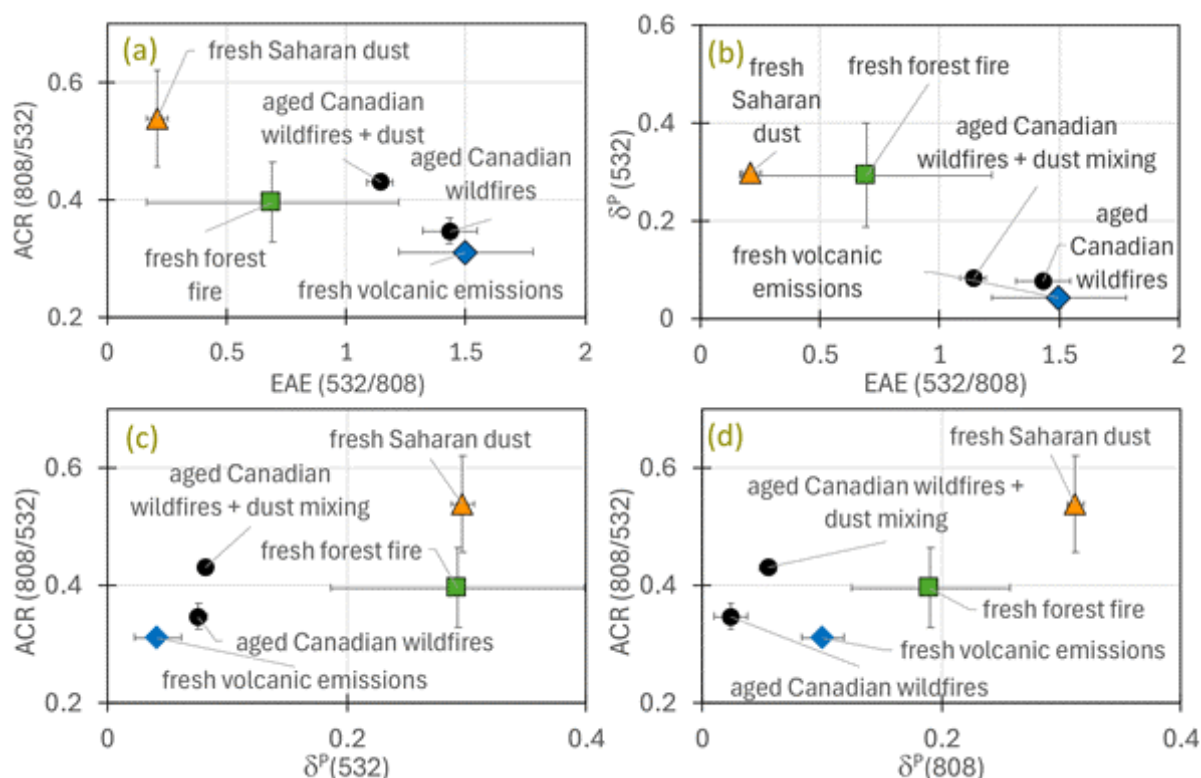


Figure 19.5. Variability of δP (532, 808), ACR (808-532) and EAE (532/808) observed across the different aerosol types studied in this work: 1) fresh Saharan dust particles (orange triangle), 2) fresh emission of volcanic sulphate aerosols (blue rhomboid), 3) aged smoke from Canadian wildfires (black dots) and 4) fresh emissions from local forest fires (green square). Figures a) through d) illustrate the following relationships: a) EAE (532/808) vs. ACR (808-532), b) EAE (532/808) vs. δP (532), c) δP (532) vs. ACR (808-532), and d) δP (808) vs. ACR (808-532). Reprinted from González et al. (2024).

19.6 COSMO Site and Design Advancement (COSADA)

COSMO is envisioned as an observatory that will host the Large Coronagraph, featuring a 1.5-metre aperture designed to investigate the Sun's coronal magnetic field. A global site assessment is currently underway to identify locations with optimal atmospheric and climatic conditions to enable accurate solar observations. This phase of the evaluation emphasizes two key meteorological factors: local wind characteristics and aerosol concentration.

To compare solar observation conditions across candidate sites, parameters such as wind speed and AOD are being analysed. Of the six potential locations under review, five have already had their atmospheric data processed. The final location pending analysis is IZO. The same Langley Method employed at the other sites will be applied to IZO's data once access is secured.

Because the method for extracting AOD from direct-sun radiometer data has already proven effective for the other five sites, it is anticipated that IZO's analysis will be completed within the expected timeline, assuming there are no data access delays. At this stage of the site survey, no instrumentation or on-site setup is required at Izaña.

19.7 NASA PACE project

The NASA Plankton, Aerosol, Cloud, ocean Ecosystem mission (PACE) mission is equipped with three dedicated instruments aimed at characterizing components of the Earth system and enhancing our understanding of their interrelated physical dynamics. The Ocean Color Instrument (OCI), a hyperspectral sensor with low spectral resolution, is designed to measure radiance reflected from the Earth's surface within the 340–890 nm range, using 5 nm intervals.

This project outlines a strategy to gather key data supporting the validation of atmospheric products derived from PACE-OCI, specifically the ultraviolet aerosol index (UVAI) and single scattering albedo (SSA) at 380 nm. Given that AERONET already provides routine measurements of AOD across multiple wavelengths (including 380 nm), no additional data collection efforts are planned for that parameter.

To meet the validation objectives, modified versions of the Multi-Filter Rotating Shadowband Radiometer (MFRSR) have been developed. These instruments will be deployed at selected AERONET sites located in low- and mid-latitude regions across both hemispheres during a series of field campaigns over a three-year period. One such instrument is currently operational at SCO (Figure 19.6).



Figure 19.6. UV-MFRSR582 sunphotometer installed at Santa Cruz Observatory (Tenerife)

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20 WMO Dust Regional Centers

In 2007, the WMO GAW Programme, launched the research initiative on sand and dust storms, the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS, for more details see WMO, 2020, 2023). It seeks to strengthen operational forecasting and warning services for various regions of the world in a globally coordinated manner to reduce the impacts on the environment, health, and economies.

The SDS-WAS mission is to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations, information, and knowledge to users through an international partnership of research and operational communities.

SDS-WAS currently operates through four regional nodes:

- 1) [WMO SDS-WAS Regional Node for Northern Africa, Middle East and Europe](#) (NA-ME-E), coordinated by a Regional Center in Barcelona, Spain, hosted by AEMET and the Barcelona Supercomputing Centre (BSC).
- 2) [WMO SDS-WAS Regional Node for Asia](#), coordinated by a Regional Center in Beijing, China, that is hosted by the China Meteorological Administration (CMA).
- 3) [WMO SDS-WAS Pan-American Regional Node](#), coordinated by a Regional Center in Bridgetown, Barbados, hosted by the Caribbean Institute for Meteorology and Hydrology (CIMH).
- 4) [WMO SDS-WAS Regional Node for Gulf Cooperation Council countries](#), coordinated by a Regional Center in Jeddah, Kingdom of Saudi Arabia, hosted by National Center for Meteorology (NCM).

20.1 WMO SDS-WAS Regional Center for Northern Africa, Middle East and Europe: Barcelona Dust Regional Center

The WMO Barcelona Dust Regional Center was established in 2007 to coordinate WMO GAW SDS-WAS activities within Northern Africa, the Middle East and Europe. In May 2013, in view of the demand of many national meteorological services and the good results obtained by the Regional Center related to operationalization, the 65th Session of the WMO Executive Council designated this Regional Center in Barcelona (managed by the consortium formed by AEMET and BSC) as the first WMO Regional Specialized Meteorological Centre with activity specialization in Atmospheric Sand and Dust Forecast (RSMC-ASDF).

The WMO Barcelona Dust Regional Center operationally distributes dust predictions for Northern Africa (north of the

Equator), Middle East and Europe from more than more than 15 regional and global forecast systems contribute to this regional model intercomparison. The forecast systems that are currently participating in the model intercomparison are listed [here](#). Among the participating forecast systems, the Multiscale Online Nonhydrostatic Atmosphere Chemistry (MONARCH) forecast system (operated by AEMET and BSC) is the reference dust forecasts within the mandatory functions of the RSMC-ASDF (for more details see Werner et al., 2024, 2025).

The WMO Barcelona Dust Regional Center [website](#) Figure is a place where visitors can find the latest dust-related observations and the most up-to-date experimental dust forecasts.

A global observational network is crucial to any forecast and early warning system for real-time monitoring, validation, and evaluation of forecast products, as well as for data assimilation. The main data sources are in situ aerosol measurements performed at air quality monitoring stations, indirect observations (visibility and present weather) from meteorological stations, sun photometric measurements (e.g. AERONET network), lidar, ceilometers and satellite products.

The exchange of forecast products is a core part of the WMO GAW SDS-WAS initiative and the basis for the joint visualization and evaluation initiative. The web portal offers dust forecasts (dust surface concentration and Dust Optical Depth (DOD) at 550 nm) generated by various global and regional modelling systems as well as the multi-model median.

An important element of any forecasting system is the evaluation of the products. The main goal of this process is to assess whether the modelling systems successfully simulate the evolution of dust-related parameters. In addition, the evaluation improves the understanding of the model capabilities, limitations, and appropriateness for the purpose for which they were designed. The evaluation is performed by comparing the model forecasts with observational data. The individual models and multi-model median forecasts of DOD at 550 nm are compared with AERONET observations of AOD for 40 selected dust-prone stations. In addition to this near-real-time evaluation, a system to assess quantitatively the performance of the different models has been implemented. It yields evaluation scores computed from the comparison of the simulated DOD with the AERONET retrievals of AOD.

The WMO Barcelona Dust Regional Center works toward strengthening the capacity of countries to use the observational and forecast products distributed in the framework of the WMO SDS-WAS initiative in partnership with National Meteorological and Hydrological Services (NMHSs) in the region and other relevant organizations.

20.2 Contribution of the WMO Barcelona Dust Regional Center to international aerosol dust-related infrastructures and networks

20.2.1 Development of a dust storm warning system for West Africa: MAC-CLIMA and CREWS

In 2018, a warning advisory system for sand and dust storm was launched for the 13 administrative regions of Burkina Faso (Terradellas et al., 2018). This system has been designed and is operated by AEMET and BSC in collaboration with the Burkina Faso National Meteorological Agency. Daily dust warnings are released through the WMO Barcelona Dust Regional Center. This was a pilot project funded by the CREWS initiative.

Inspired by the Burkina Faso pilot project, the WMO Barcelona Dust Regional Center has participated in two projects, MAC-CLIMA and CREWS with complementary strategies.

The **MAC-CLIMA** project aims were to generate a meteorological and ocean observation system and use these observations to promote resilience and adaptation to climate change. The cooperation area consisted of Madeira, Azores and the Canary Islands and three geographically close countries that accepted to participate in the programme: Cabo Verde, Senegal and Mauritania.

The closing event of the MAC-CLIMA project was held on 13 December 2023 in Las Palmas de Gran Canaria. This event was aimed at technical staff, professionals, and specialists related to climatology, forest management, water and energy resource management, public administrations, and related fields (Figure 20.1).



Figure 20.1. Gerardo García-Castrillo during the MAC-CLIMA final meeting in Las Palmas de Gran Canaria (13 December 2023)

The Climate Risk and Early Warning Systems (**CREWS**) initiative is a financial mechanism which funds projects in the Least Developed Countries (LDCs) and Small Island Developing States (SIDS) to establish risk-informed early warning services. CREWS works directly with countries to increase the availability of, and access to, early warning systems.

Country and regional projects are implemented by the countries with the support of three Implementing Partners: the United Nations Office for Disaster Risk Reduction (UNDRR), the World Bank Global Facility for Disaster Reduction and Recovery (GFDRR) and WMO.

The collaboration of the WMO Barcelona Dust Regional Center in CREWS currently covers the following countries: Senegal, Mauritania, Cabo Verde, Mali, Niger and Chad. As an example, the forecast of dust storms is shown for the different provinces with a 4-colour code map, for 4 February 2024 (Figure 20.2).



Figure 20.2. Warning Advisory product forecasted alert level for 4 February 2024. Source: WMO Barcelona Dust Regional Center (<https://dust.aemet.es/>)

In the framework of the MAC-CLIMA and CREWS projects, new and improved Particulate Matter – Low-Cost Sensors (PM-LCS) were designed with the aim of providing PM information at MAC-CLIMA and CREWS countries.

These sensors, named DUST sensors, were validated against reference grade monitors (Figure 20.3). Hand-held Calitoo sun photometers were expected to be installed again in CREWS countries, as done in MAC-CLIMA. Online workshops on installation, management, and operation of instrumentation, as well as on interpretation of the Warning Advisory System and its implementation in the daily work routine have been organized for Mauritania, Cabo Verde and Chad (see section 25 on capacity-building).



Figure 20.3. PM-LCS installation at IARC (CREWS DUST sensors)

The comparison analysis of different PM-LCS was performed in Santa Cruz between 22 December 2022 to 4 March 2023 (Figure 20.4). The reference measurements were obtained from the Canary Islands AQMN. Hourly PM measurements were conducted using a Beta Attenuation Monitor (Met One Instruments-BAM 1020).



Figure 20.4. Testing of new PM-LCS (four sensors) in Santa Cruz de Tenerife for the CREWS project

The primary objective of this intercomparison analysis was to identify the low-cost sensor that exhibited superior performance in detecting PM_{10} and $PM_{2.5}$ for the CREWS project among the three different models used: Sensirion SPS30, Nova SDS011 and Plantower PMS5003. Correction factors were applied to each PM-LCS. This analysis showed how the NOVA SDS011 was the best performing low-cost PM sensor to be utilized in the CREWS project with a close agreement with reference data, with a RMSE of $30 \mu\text{g}/\text{m}^3$ in PM_{10} .

20.2.2 Observing mineral dust in Northern Africa, the Middle East, and Europe: Current capabilities and challenges ahead for the development of dust services

A research article has been prepared within the framework of the WMO Barcelona Dust Regional Center and the COST Action inDust by Mona et al. (2023) to enhance the understanding of these effects and ultimately strengthen the resilience of impacted countries. Achieving this goal relies on a robust, extensive, and varied set of dust observations

(Figure 20.5), which are essential for developing and delivering accurate dust forecast products tailored to specific needs. Over the past decade, there has been significant progress in dust observation capabilities, including improvements in the range of parameters measured, the geographical scope, delivery speed, and the generation of products targeted at both scientific audiences and operational end-users.

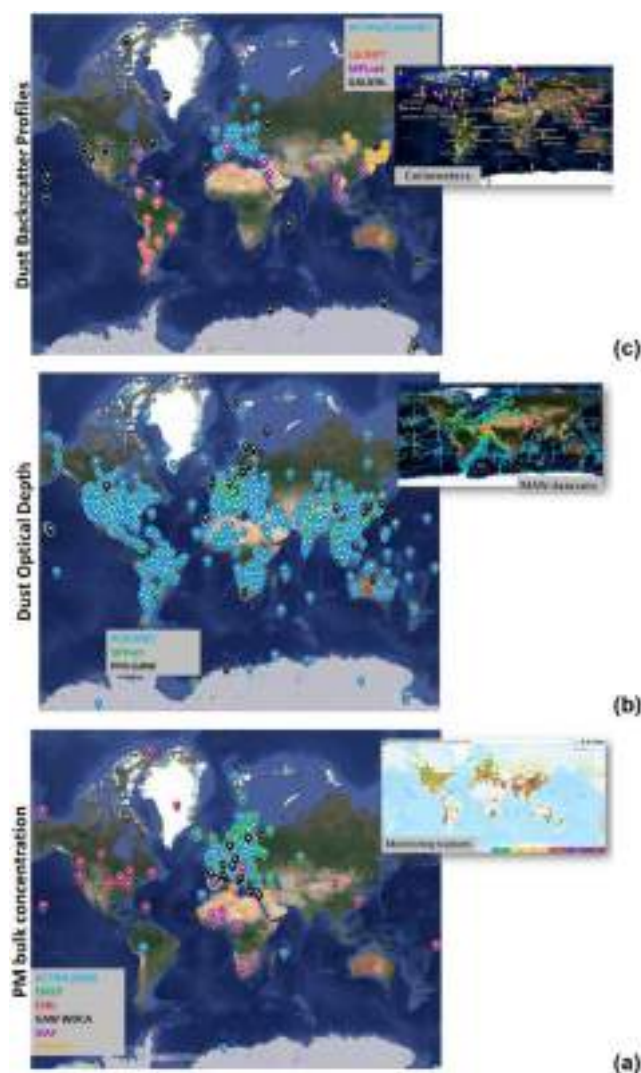


Figure 20.5. Geographical coverage of the networks of interest for mineral dust observations: (a) in situ near-surface, (b) photometer, and (c) lidar networks. Reprinted from Mona et al. (2023)

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21 WMO GAW Tamanrasset twinning programme

In 2006, the “WMO GAW-Twinning” between IZO and WMO GAW Tamanrasset stations was initiated with the Saharan Air Layer Air Mass characterization (SALAM) project. This was part of a cooperation programme between the l’Office Nationale de la Météorologie (ONM, Algeria) and AEMET. In September 2006, the AERONET Tamanrasset-AEMET Cimel station was installed (Figure 21.1). The instruments of the WMO GAW Tamanrasset twinning programme are located on the roof of the Regional Meteorological Center (southern regional meteorological department, ONM, Algeria) in Tamanrasset. This area, free of industrial activities, is in the highlands of the Algerian Sahara. Tamanrasset-Assekrem is a WMO GAW global station.



Figure 21.1. The AERONET Cimel photometer (upper image) at Tamanrasset on the terrace of the Regional Meteorological Centre (lower image)

21.1 Column aerosols

This station now has a long-term time series of AERONET AOD data, covering the period 2006–2024 (Figure 21.2), despite the enormous environmental and logistical difficulties to keep it in operation, thanks to the effort and great collaboration of the team in charge of the GAW Tamanrasset-Assekrem facilities.

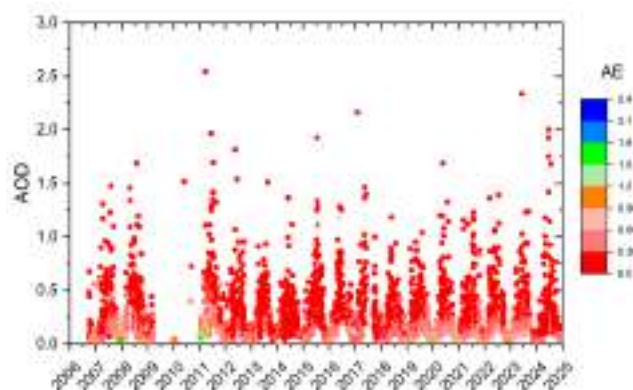


Figure 21.2. The Tamanrasset AERONET AOD data series (2006–2024)

The GAW station Tamanrasset is in the south of Algeria, in the heart of the Sahara, and it provides unique and precious data in an extensive region near important dust sources. Tamanrasset station is the only permanent AERONET observation site in the heart of the Sahara region (Figure 21.3a). This station is strategic not only for the characterization of atmospheric composition over the Sahara Desert in the frame of the GAW Programme, but also to evaluate atmospheric models and validate satellite data. The Tamanrasset station has been regularly used to evaluate satellite-derived products, such as the IASI aerosols product including desert mineral dust (e.g. Callewaert et al., 2019). In fact, it is a key station to assess the performance of mineral dust prediction models in a challenging region where there are numerous nearby dust sources.

Tamanrasset is a singular station of special attention for the WMO Barcelona Dust Regional Center for forecast evaluation (e.g. Terradellas et al., 2016) (see section 20 for more details). This AERONET photometer is calibrated by the IARC on an approximately annual basis.

An automatic comparison of 12 model forecasts of Dust Optical Depth (DOD) at 550 nm versus AERONET AOD data for February–March 2024 at Tamanrasset is shown in Figure 21.3. This comparison is available at the WMO Barcelona Dust Regional Center [website](#).

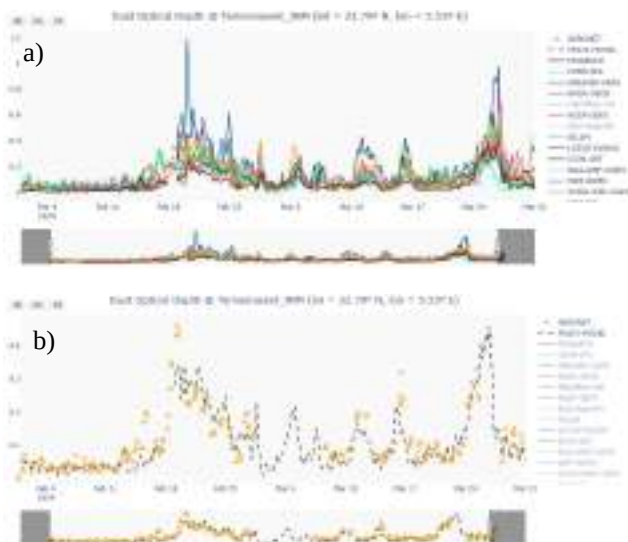


Figure 21.3. Dust AOD (DOD) comparison at Tamanrasset in February–March 2024: a) 14 forecast systems and b) WMO Dust multi-model product and AERONET

Source: WMO Barcelona Dust Regional Center

Since March 2017, a Calitoo hand-held sun photometer has been operating at Tamanrasset. During this time, the performance of the Calitoo under the challenging conditions in a desert area have been tested with very good results (Figure 21.4).

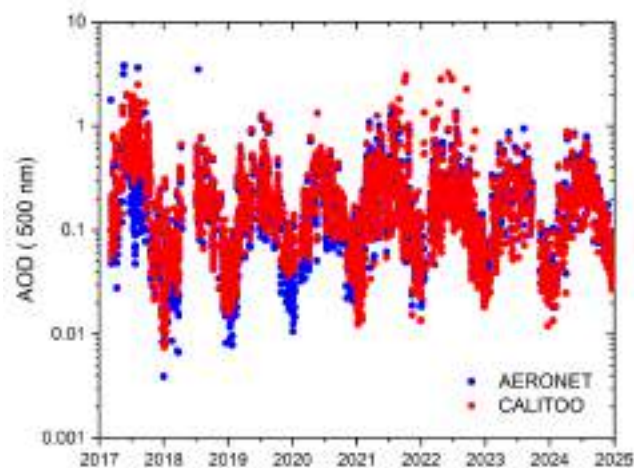


Figure 21.4. AERONET AOD 500 nm from Cimel photometer versus AOD 540 nm from Calitoo hand-held photometer at Tamanrasset (2017–2024)

21.2 Total ozone column and UV

The twinning was completed with the installation at Tamanrasset of a double Brewer Spectrophotometer #201 (MARK-III) in October 2011 (Figure 21.5), thanks to the

project entitled “Global Atmosphere Watch in the Maghreb-Sahara Region” (GAW-Sahara) financed by the Spanish Agency for International Development Cooperation (AECID).



Figure 21.5. Brewer#201 at Tamanrasset on the terrace of the Regional Meteorological Centre. On the left, the AERONET Cimel photometer

An operational Dobson (#11; WMO station code 002) spectrophotometer has been operated at Tamanrasset since April 1994. This station is one of the few sites in the world where permanent and long-term intercomparison between the Dobson, the Brewer and the present and future satellite-based sensors could be performed on a routine basis. This initiative has been strongly recommended by the WMO GAW Programme and represents a unique contribution to the total ozone global network Quality Assurance. In addition, the Brewer instrument provides spectral ultraviolet radiation data.

Tamanrasset, with the Brewer Spectrophotometer #201, plays an important role in the context of other global observation networks, e.g. in the EUBREWNET network (Figure 21.6) (see section 6 for more details) providing near-real-time data of column ozone, spectral radiation and AOD in the UV range (see López-Solano et al., 2018).

As an example, Figure 21.6 shows two of the many products that EUBREWNET provides. The total ozone data on 16 June 2024 is shown in Figure 21.6b. During this day there were clear conditions that allowed more than 100 direct sun measurements, with a very low ozone content of 251 DU and quite stable values, making it a day that can be used for Langley calibration. In Figure 21.6c, the diurnal cycle of the UV-index at Tamanrasset on 16 June 2024 is shown.

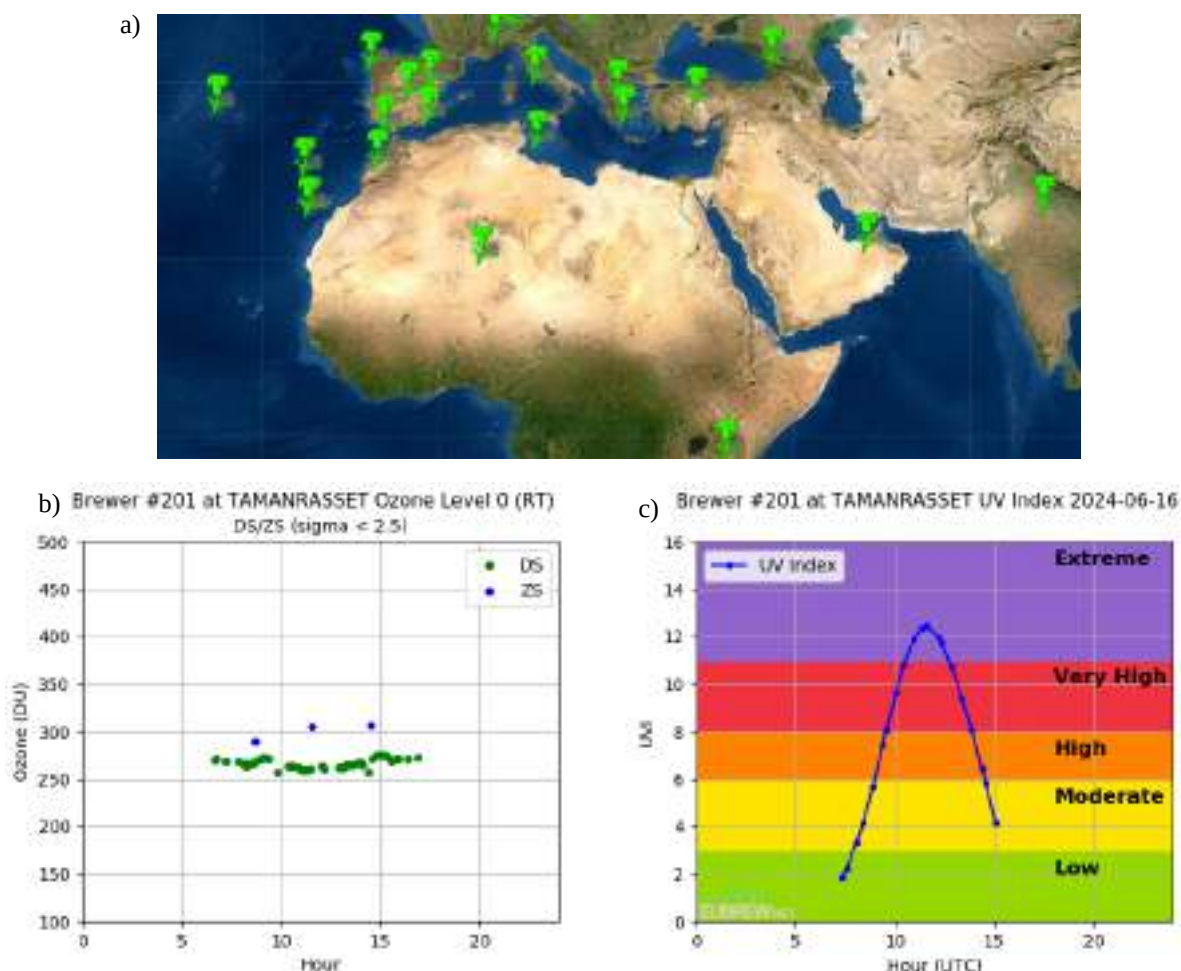


Figure 21.6. a) The Brewer spectrophotometer of Tamanrasset as part of the EUBREWNET network. Data from Brewer #201 at Tamanrasset on 16 June 2024; b) example of total ozone data display and c) example of UV index diurnal cycle. Clear conditions allow for more than 100 direct sun measurements.

The Brewer #201 is periodically calibrated by the Regional Brewer Calibration Center for Europe hosted by IARC taking advantage of the biannual intercomparisons that are held at the INTA station at El Arenosillo-Huelva (Southern Spain).



Figure 21.7. Sida Lamine Baika, Brewer operator at Tamanrasset with the Brewer #201

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21.4 Staff

Dr Emilio Cuevas (AEMET, PI of the Tamanrasset-Izaña twinning, until August 2023)

Dr África Barreto (AEMET, PI of the Tamanrasset-Izaña twinning, from September 2023)

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Virgilio Carreño (AEMET; Meteorological Observer)

Local contributors:

Mr Sidi Lamine Baika (Tamanrasset-Assekrem GAW station, Head)

Mr Abdessadek Saanouni and Mr Abdelhadi Belmiloud (Technical staff).

22 Activities in collaboration with national institutes

22.1 Activities in collaboration with IAC

IARC, within the framework of the Specific Collaboration Agreement between AEMET and the Instituto de Astrofísica de Canarias (IAC) (Institute of Astrophysics of the Canary Islands), provide information and data to IAC. In particular, IARC provides data that allows IAC to characterize and monitor parameters that determine the astronomical quality of their observatories on the Canary Islands: 1) Teide Observatory (TO), in Tenerife, approximately 1km away from the Izaña Observatory (IZO) and 2) Roque de los Muchachos Observatory (RMO) on the island of La Palma.

IARC provides measurements of AOD in different channels, aerosol optical properties and water vapour in the atmospheric column, to IAC, both for TO and RMO, from measurements obtained by sunphotometers enrolled in AERONET installed at IZO and RMO, respectively (Figure 22.1).



Figure 22.1. The AERONET sunphotometer at Roque de los Muchachos Observatory (RMO), La Palma

Near-real-time information on column water vapour (precipitable water) is provided from a high-precision GNSS receiver installed at IZO. Real-time PM₁₀ particulate matter data are provided from the PM TEOM analyzer installed at IZO, for operational purposes (Figure 22.2). This information allows decisions to be made about the operability of the telescopes based on aerosols surface concentration; as above at relatively low threshold, aerosols, and specifically mineral dust, can cause damage to the optics and other mechanical elements of the telescopes.



Figure 22.2. Upper panel: Internal web page detailing the different information provided by IARC to IAC. Lower panel: PM₁₀ real-time information from the TEOM analyzer at IZO (1-12/8/2024).

In addition, data from the radiosondes launched daily at 00 and 12 UTC from the AEMET Güímar (Tenerife) automatic radiosonde station (WMO GRUAN station, #60018) (Figure 22.3) are provided to the IAC for both operational and scientific purposes.



Figure 22.3. Image of the AEMET GRUAN automatic radiosonde station in Güímar (Tenerife)

IAC also has real-time access to the images obtained with all-sky and regular cameras installed at IZO, which show the state of the sky every five minutes. Meteorological information from the automatic meteorological stations installed at IZO and RMO is also provided.

In addition to meteorological and atmospheric observations, AEMET provides specific meteorological forecasts at the two sites (TO and RMO), of geopotential height, temperature, relative humidity, wind, precipitation, cloud cover and mineral dust from the Sahara, which allows IAC to carry out a flexible scheduling of telescope operation. Much of this information is very useful for short- and medium-term planning of observations.

22.2 Research activities in collaboration with UAH

22.2.1 Creation of the Izaña Cosmic Ray Observatory (ICaRO)

The Izaña Cosmic Ray Observatory (ICaRO) was installed in late February 2023 at IZO (Figure 22.4) in the framework of the research collaboration between AEMET and the University of Alcalá (UAH) (Blanco et al., 2021; 2023; 2024). ICaRO is the second of its kind to be installed in Spain; the first one is located at the Spanish Antarctic Base Juan Carlos I. It is dedicated to observing secondary cosmic rays, particularly neutrons and muons, and in the case of the latter, also their direction of incidence.



Figure 22.4. ICaRO Installation with the University of Alcalá and IARC Team

Cosmic rays are highly energetic particles that originate from outer space and constantly penetrate interplanetary space and the Earth's atmosphere. Fortunately for life on Earth, not all cosmic rays reach the Earth's surface; the magnetosphere and the Earth's atmosphere act as a natural protective layer against them. Magnetic rigidity is the physical magnitude that determines the threshold at which a cosmic ray can produce secondary particles that may reach the Earth's surface. In turn, the minimum magnetic rigidity that a charged particle must have in order to penetrate the magnetosphere and the Earth's atmosphere, and produce particles capable of reaching Earth's surface from outer space, is known as the vertical rigidity threshold.

Due to its geographical location and altitude of 2373 m a.s.l., IZO has a calculated vertical rigidity threshold of 11.5 GV. This means that only those particles exceeding this rigidity level will be able to reach the detector.

Having measurements from different stations with distinct vertical cutoff rigidities is a powerful tool for various scientific investigations. This makes the global coverage of comparable detectors desirable, to ensure detection at different energy thresholds and to cover different regions of the sky. The [Neutron Monitor Database \(NMDB\)](#), which provides access to neutron monitor measurements from stations around the world, is an example of this, Figure 22.5 depicts the position of many of the neutron monitors around the world. ICaRO's elevation above sea level and cutoff rigidity position it as an exceptional detector, filling a gap in the NMDB. Moreover, it enables the observation of neutrons generated during highly energetic solar events, facilitates solar activity monitoring, and enables the study of interactions between cosmic rays and solar energetic particles within the atmosphere.

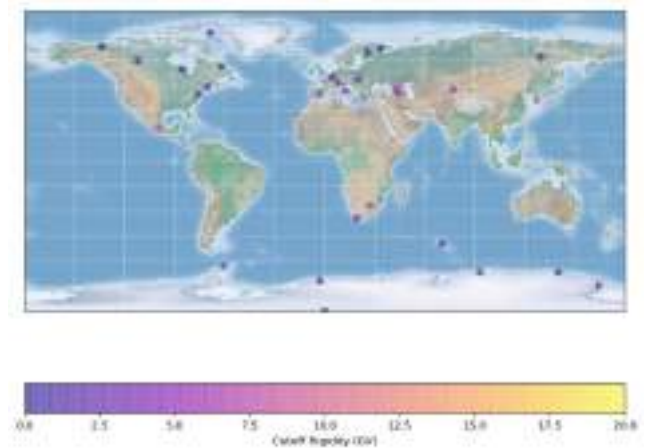


Figure 22.5. Neutron monitor global distribution. Colour bar shows vertical cutoff rigidity range. Reprinted from Blanco et al. (2021).

While ICaRO is still in the process of being commissioned, it has been consistently generating stable data since its installation. Once its implementation is complete, this observatory will provide the unique capability to observe both galactic neutrons and muons as well as those emerging during solar events, enabling continuous monitoring of solar activity. Moreover, it enables the investigation of the intricate interactions between cosmic rays and energetic particles originating from the Sun within the atmospheric environment. These investigations yield significant insights in the context of space weather and its ramifications.

22.2.2 Installation of a portable neutron monitor in Tenerife at different altitudes

The flux of secondary cosmic rays is highly influenced by atmospheric pressure at the observation site. Since pressure decreases with increasing altitude, conducting

measurements at various elevations using mobile instruments is essential for understanding how the atmosphere affects secondary cosmic ray production. These measurements also serve to validate models that describe the interactions between cosmic rays and atmospheric atoms. Since October 2023, a monitoring campaign has been underway on Tenerife using a portable neutron monitor. Four locations have been selected for measurements at altitudes of 20 m a.s.l. (SCO, Figure 22.6), 868 m a.s.l. (Güímar), 2373 m a.s.l. (IZO), and 3355 m a.s.l. (TPO). The site at IZO serves as a reference point, where a standard 3NM64 neutron monitor has been operating since early 2023 (see 22.2.1).



Figure 22.6. Portable neutron monitor at SCO with the University of Alcalá and IARC Team

22.3 References

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23 Ocean Colour System Vicarious Calibration (OC-SVC)

The European Commission, via its Copernicus programme, invests in operational Earth Observation from space. As part of this programme, Ocean Colour (OC) instruments onboard the Sentinel-3 missions, as well as Sentinel-2, have become an essential source of data at global and regional scales for continuous monitoring, forecasting and alerting on ocean biogeochemistry and the state of marine ecosystems.

Through the Copernicus Marine Environment Monitoring Service (CMEMS), these data are supporting the implementation of European marine and environmental policies, contribute to climate studies, and empower economic activities. These activities include fisheries, aquaculture, shipping, water supply, tourism, offshore operations, and mitigation of health and economic risks associated with poor water quality.

Achieving the Copernicus objectives requires climate-quality ocean colour data with emphasis on accuracy and stability, both for long-term and cross-mission time series. The main challenge resides in the necessary stringent calibration and characterization of the sensors, because the marine signal is only a small fraction of the radiometry acquired by the satellite at the top of atmosphere.

Limiting the uncertainty of water-leaving radiance to below 5%, as required by the Sentinel-3 Mission Requirement Document and Global Climate Observing System, cannot be achieved today with pre-launch and onboard instrument calibrations alone. Ocean Colour instruments require a complementary System Vicarious Calibration (SVC), i.e. an indirect calibration of the sensor and the processing algorithm through highly accurate and long-term sea-truth measurements (see Figure 23.1).

EUMETSAT has been planning the development of the OC-SVC infrastructure in coordination with the EC Copernicus Programme, ESA and the EC's Joint Research Centre. The roadmap for the development of the OC-SVC infrastructure is composed of six phases. The first three phases have now been completed. More information about the Copernicus OC-SVC study can be found [here](https://www.eumetsat.int/OC-SVC).

Phase 3 concerned the infrastructure placement and in 2021, EUMETSAT conducted a study to investigate five candidate locations across European sea waters to select the optimal placement for the potential Copernicus OC-SVC infrastructure. One of the marine sites under consideration in this study is off the island of El Hierro, the furthest south-west island of the Canary Islands (Figures 23.2 and 23.3).

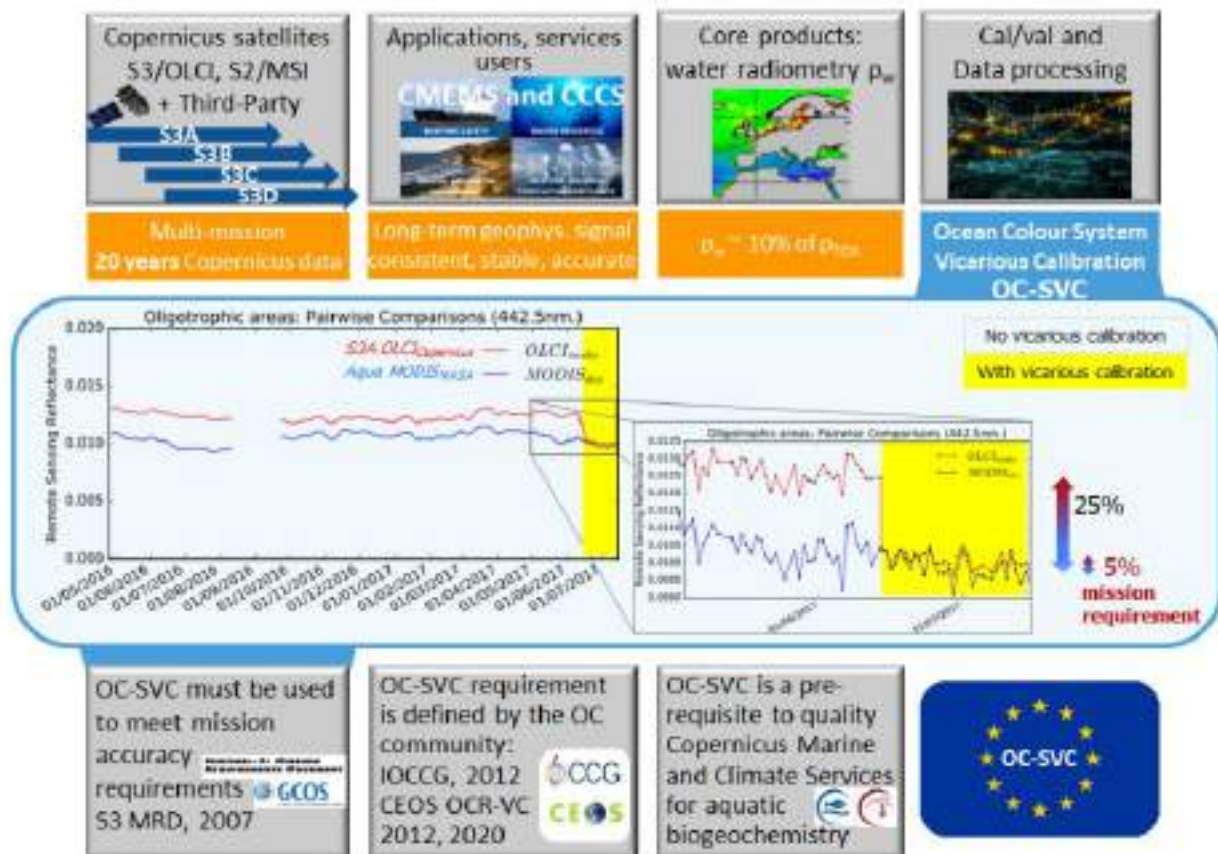


Figure 23.1. Requirements for Copernicus Ocean Colour System Vicarious Calibration Infrastructure. Credit <https://www.eumetsat.int/OC-SVC>.

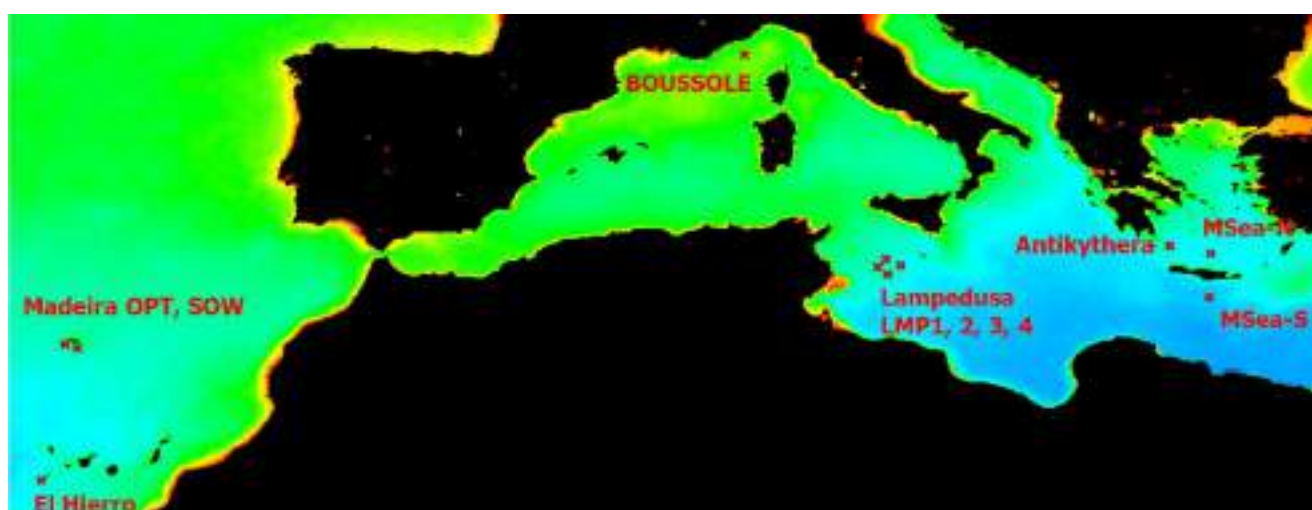


Figure 23.2. Copernicus OC-SVC infrastructure candidate locations considered in Phase 3. Credit <https://www.eumetsat.int/OC-SVC-locations>.

A climatological characterization of the El Hierro candidate site, presenting key atmospheric, oceanographic and environmental features was conducted in conjunction with the Spanish Institute of Oceanography (IEO) (see Fraile-Nuez et al., 2021). More information about the Copernicus OC-SVC El Hierro candidate location can be found [here](#).

An international Expert Review Board conducted a review of the Candidate Locations for Copernicus OC-SVC Infrastructure (see EUMETSAT, 2022) and recommended to move to the next phases of the OC-SVC infrastructure roadmap with two candidate OC-SVC locations: El Hierro (Spain) and MSEA-S (Crete, Greece).

On 8 November 2023, EUMETSAT hosted a “Copernicus OC-SVC Information Day” at its headquarters in Darmstadt, Germany (Figure 23.5). The aims of the OC-SVC information day included the following:

- To provide information on EUMETSAT’s plans for the next Copernicus OC-SVC phases: Phase 4: Engineering design; Phase 5: Development, testing, and demonstration; Phase 6: Operations
- To present the two candidates for Copernicus OC-SVC locations: El Hierro and South of Crete, and their plans for site development and future operations.

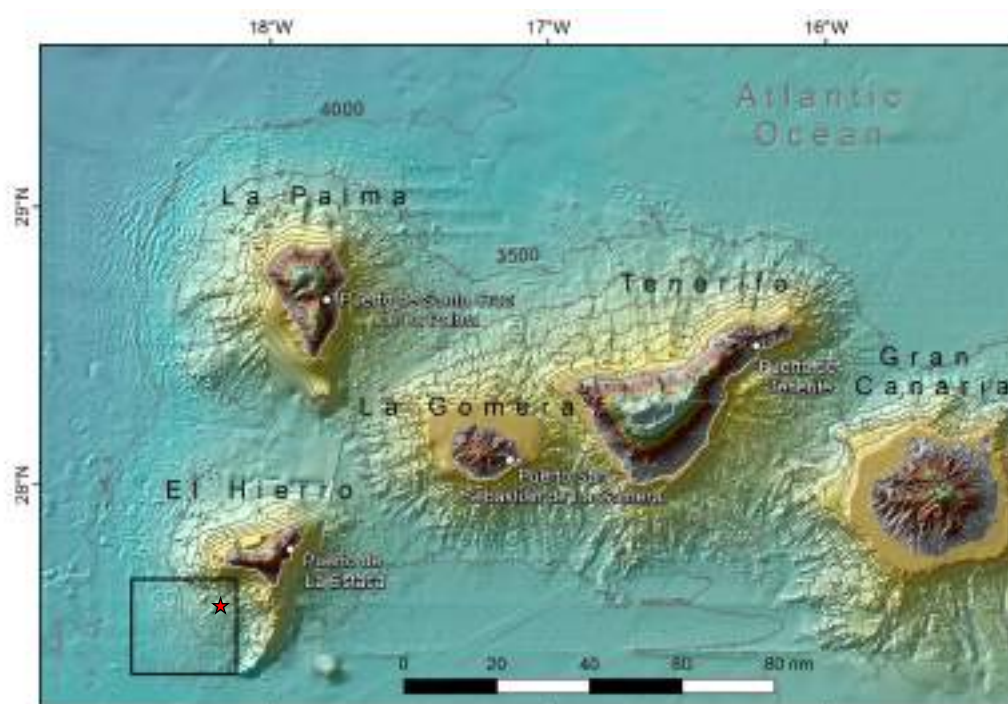


Figure 23.3. Location of the El Hierro - Mar de Las Calmas OC-SVC candidate site. Reprinted from Fraile-Nuez, et al. (2021).



Figure 23.4. Copernicus OC-SVC infrastructure roadmap. Reprinted from EUMETSAT (2022).

23.1 References

The El Hierro - Mar de Las Calmas (Spain) candidacy to host the European Commission Copernicus OC-SVC infrastructure was presented in the XX Congreso Nacional de Teledetección in Cádiz, 3–6 June 2024 (Fraile-Nuez et al., 2024b) and in the conference, Ocean Optics XXVI, Las Palmas de Gran Canaria, 6–11 October 2024 (Fraile-Nuez et al., 2024a).

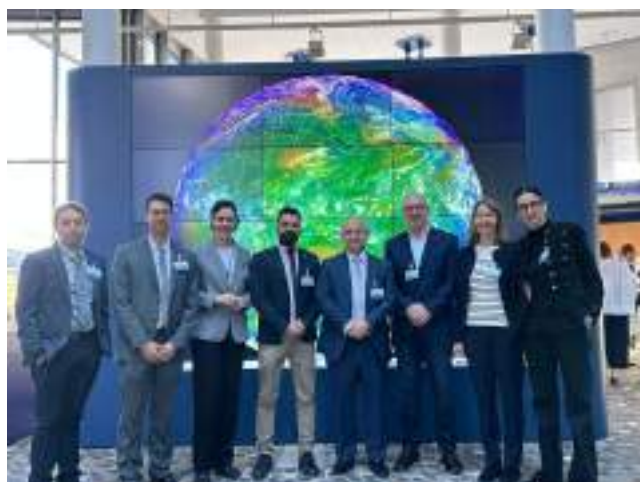


Figure 23.5. Copernicus OC-SVC Information Day at EUMETSAT headquarters in Darmstadt, Germany, 8 November 2023. Presentation of the El Hierro - Mar de Las Calmas (Spain) candidacy to host the Copernicus OC-SVC infrastructure (IEO and AEMET).

The European Commission via EUMETSAT initiated an Invitation To Tender (ITT) in September 2024 for the Detailed Design, Development, and Demonstration of operations of the Copernicus OC-SVC infrastructure, covering Phases 4 and 5.

EUMETSAT, Conclusions of the Review of Candidate Locations for Copernicus Ocean Colour System Vicarious Calibration Infrastructure (EUMETSAT study report, EUMETSAT, Darmstadt, Germany), EUM/RSP/REP/22/1303790, v5D, 27 July 2022. <https://www.eumetsat.int/media/49961>

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24 Impact of the August 2023 wildfire

On 15 August 2023, one of the most devastating wildfires (Category 6) in recent memory in Tenerife began in the higher ground of the Arafo municipality. Despite immediate efforts to control it, the fire rapidly spread both northward into the La Orotava Valley and southward into the Güimar Valley, affecting 12 municipalities and over 12,000 hectares of land. On 20 August, the fire even reached the Izaña mountain, home to IZO (Figure 24.1).

Thanks to the swift action of firefighting resources, the observatory's infrastructure was spared, and the fire was ultimately brought under control in the following days. Despite the severity of the fire in the observatory's vicinity, most of the measurement programmes remained operational. However, the fire's impact was evident in anomalies recorded in several of the measurement programmes, including greenhouse gases, reactive gases, in situ aerosols, column aerosols and radiation.

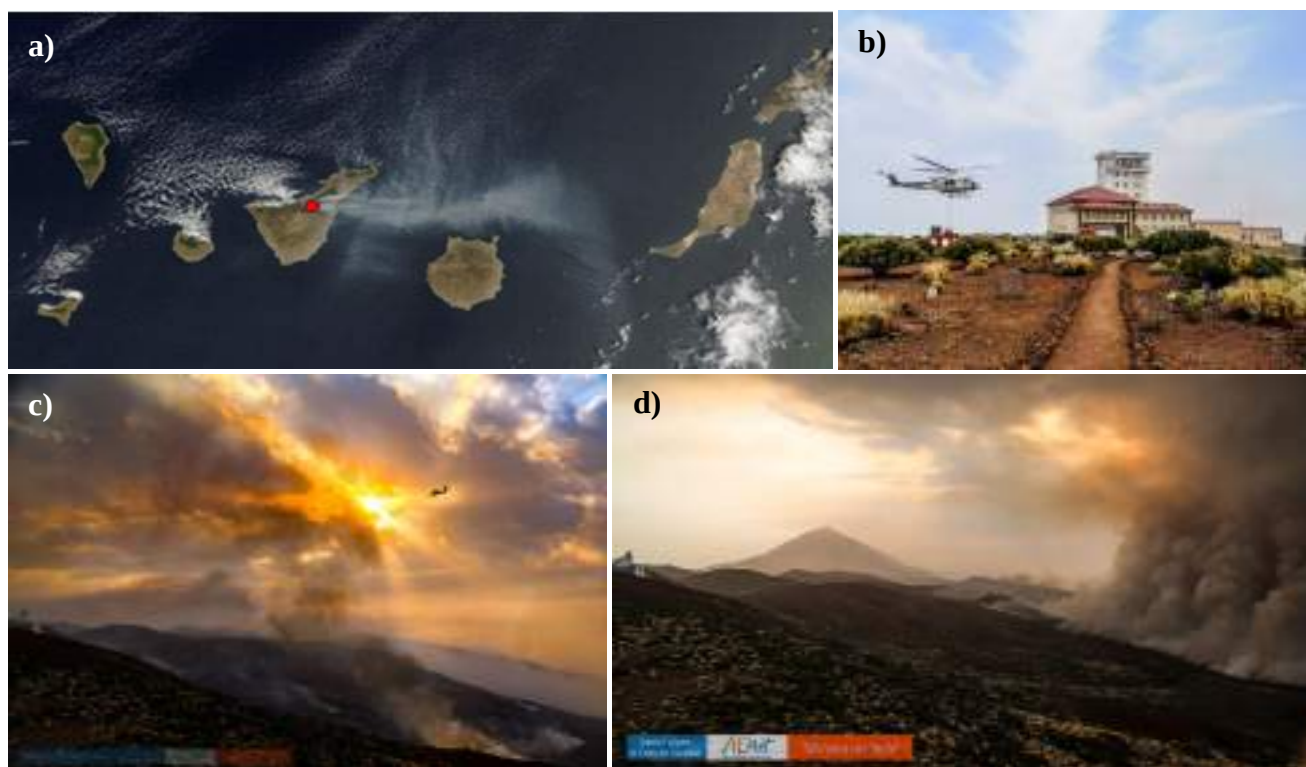


Figure 24.1. Figure 1. a) Image captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard NASA's Terra satellite on 18 August 2023 (Image: NASA Worldview; <https://worldview.earthdata.nasa.gov/>). The red dot marks the location of Izaña Observatory. b) Image of firefighting service in action at IZO on 22 August 2023. c) and d) Images of Teide National Park taken from IZO (Teide Clouds Laboratory, TeideLab).

In the context of GHG, the maximum recorded CO_2 value exceeded 500 ppm on 17 August 2023 (normal values measured at IZO range between 410 to 430 ppm) (Figure 24.2a). Additionally, on 19 August 2023, the maximum recorded values of CH_4 and CO were greater than 2800 and likely over 10 000 ppb, respectively (Figure 24.2b, c) (normal values for CH_4 range between 1 800 to 2 100 ppb, while CO values range between 50 to 200 ppb at IZO).

Measurements taken during the wildfire by in situ aerosol instruments reached maximum values much higher than typical values usually recorded at IZO, as shown in Figures 24.2 and 24.3.

During the wildfire, the values of the scattering coefficient (Figure 24.2e) and the values of black carbon content (Figure 24.2f) reached the highest levels recorded at the IZO since records began in 2012.

Figure 24.3 illustrates the temporal evolution of AOD at 500 nm and the Ångström Exponent parameter measured at IZO. The maximum values of AOD at 500 nm were 3.63 and 4.16 recorded on 17 and 20 August 2023, respectively. These values represent the highest AOD values ever recorded at IZO since it joined AERONET in 2005. The maximum values of AE on the same days (17 and 20 August 2023) were 2.14 and 1.71, respectively.

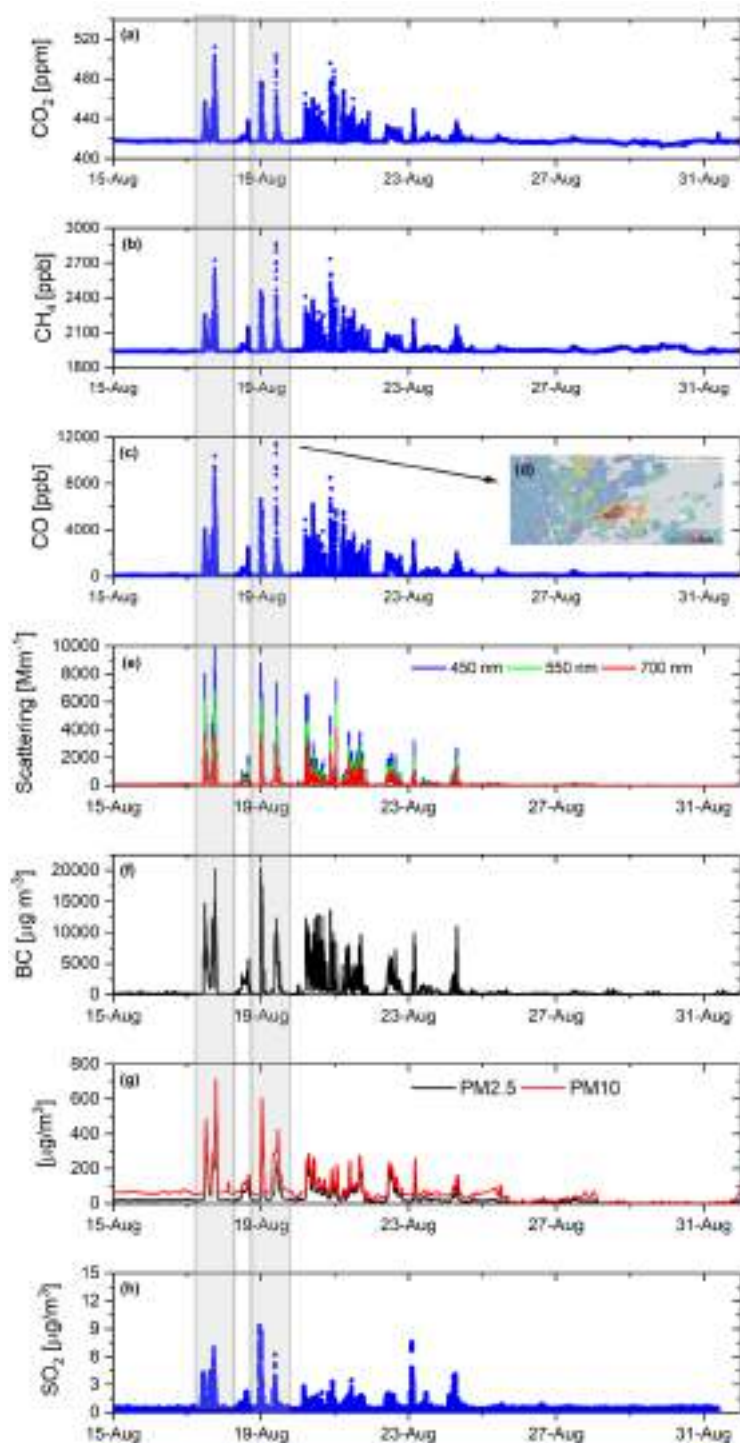


Figure 24.2. Time series of surface mole fractions of (a) CO₂ (ppm), (b) CH₄ (ppb), (c) CO (ppb), (d) CO map taken by the TROPOMI satellite between 17 and 18 August 2023, (e) Scattering coefficient measured with the nephelometer in Mm⁻¹, (f) Black carbon content in µg m⁻³ measured with the MAAP, (g) PM_{2.5} and PM₁₀ concentration in µg m⁻³ measured with the TEOM and (h) surface SO₂ concentration (µg m⁻³) measured at IZO, 15–31 August 2023.

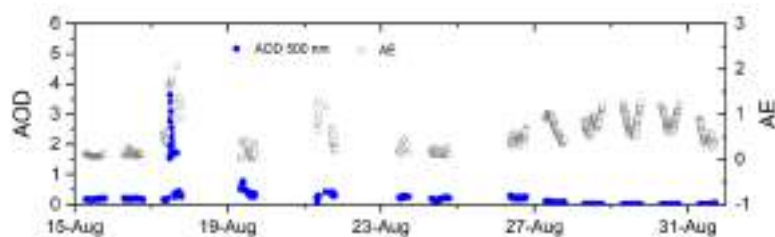


Figure 24.3. Time series of AOD at 500 nm and AE measured at IZO, 15–31 August 2023

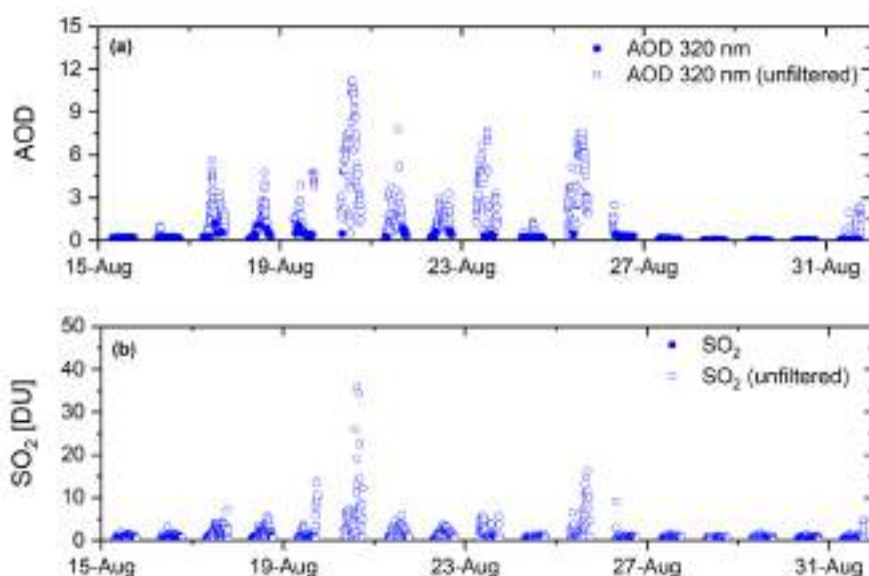


Figure 24.4. Time series of (a) AOD at 320 nm and (b) Total SO₂ column (DU) obtained from measurements with the Brewer spectroradiometer at IZO, 15–31 August 2023

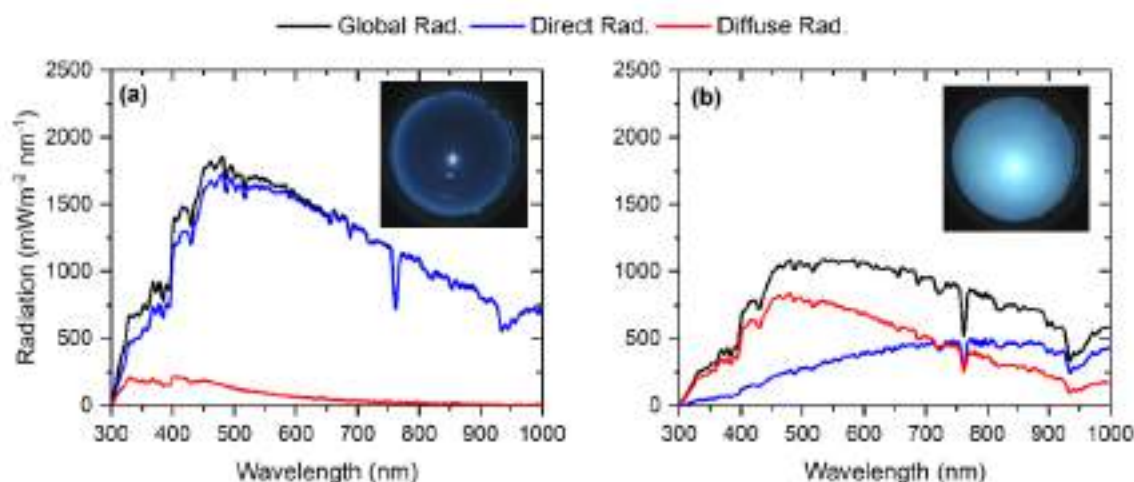


Figure 24.5. Spectral radiation (global, direct, and diffuse) measured between 300 and 1100 nm with the EKO-RSB spectroradiometer at IZO on (a) 6 August 2023 at 13:00 UTC, under clean conditions, and (b) 17 August 2023 at 13:00 UTC, under conditions affected by the wildfire. The small, inserted images were taken by the SONA camera (Automatic Cloud Observation System).

The temporal evolution of AOD at 320 nm and the total SO₂ column determined from measurements with the Brewer spectrophotometer #183 at IZO are shown in Figure 24.4. The figure also includes data flagged for quality control and requiring further evaluation.

Radiation measurements were also significantly affected during the wildfire. Figure 24.5 shows spectral global, direct, and diffuse radiation measurements made with the EKO-RSB spectroradiometer at IZO. The differences between measurements under clean atmospheric conditions (6 August 2023; Figure 24.5a) and those affected by the wildfire on 17 August 2023 (Figure 5b) are clearly shown.

Following maintenance and cleaning of all observatory instrumentation, normal operations were restored at the end of August. Furthermore, all the measurements taken during this period are invaluable to improve understanding of how wildfires affect the composition of the atmosphere.

In addition, from IARC we would like to give, once again, our most sincere thanks to all the emergency services that participated in the control and extinguishment of the fire, which allowed us to keep safe not only all personnel but also all the infrastructures that are part of this centennial Observatory and the highly sensitive scientific instrumentation that is installed in it.

25 Capacity-building activities

During 2023–2024 IARC participated in various capacity-building activities, some of which are described here. For further details of these activities, see individual sections or the IARC [webpage](#).

25.1 WMO GAW workshop for Cabo Verde: (online) 3 February 2023

As part of the MAC-CLIMA Interreg project, AEMET held an online workshop on 3 February 2023, focused on mineral dust forecasting and related observational products. The event was specifically designed for meteorologists and technical staff from the Instituto Nacional de Meteorología e Geofísica (INMG) of Cabo Verde (Figure 25.1).

This initiative represented an initial step in the development of a warning system for sand and dust storms intended for countries across western and northern Africa. The system built upon the experience of a pilot warning advisory service that has been successfully operating in Burkina Faso since October 2018.



Figure 25.1. Some of the participants of the SDS-WAS Workshop for Cabo Verde, held online, 3 February 2023

The initial segment of the workshop was focused on forecast products and the Warning Advisory System developed by the WMO Barcelona Dust Regional Center for Cabo Verde and other African nations. Participants learnt how to integrate these tools into the daily operational activities of meteorological forecasting teams. The second part of the workshop, given by IARC staff, concentrated on the instruments supplied through the project, specifically a hand-held photometer and a PM sensor, which have already been installed at the INMG facilities.

25.2 WMO training school for operators of sun-photometers and Brewer calibration in North Africa: 30 Oct– November 2023

A training course funded by WMO GAW and coordinated by IARC and University of Valladolid was held in Izaña on 30 October – 3 November 2023. Operators from Spain, Morocco, Saudi Arabia and Algeria joined the training course (Figure 25.2).



Figure 25.2. Participants in the WMO GAW training school held at Izaña Observatory, 30 October–3 November 2023

The training focused on developing the skills of personnel from various remote stations in North Africa in operation of Cimel CE318 sun photometers that participate in AERONET. Various training activities related to the installation, uninstallation, monitoring and maintenance of the CE318 were carried out, as well as practical experiences to solve common problems related to the operation of this type of instrumentation. The purpose is to guarantee the quality of the data supplied by these stations, which play a key role in modelling of aerosol.

25.3 International University of Andalucía summer school: 22 July 2024

Dr Omaira García participated in the International University of Andalucía, summer school “Con Ciencia Renovable/With Renewable Science”, with a presentation titled “Greenhouse Gases, Climate Change and the Future” on 22 July 2024 (Figure 25.3).



Figure 25.3. Dr Omaira García, International University of Andalucía summer school, Huelva, 22 July 2024

25.4 SDS-WAS workshop for Chad: (online) 16 October 2024

As part of the CREWS initiative, AEMET organized an online workshop on 16 October 2024, focused on mineral dust forecasting and related observational tools. The workshop was directed at meteorologists and technical staff from Mali, Niger, and Chad (Figure 25.4).

As for the workshop for Cabo Verde, this training was focused on forecast products and warning system, given by the WMO Barcelona Dust Forecast Center staff, while the second part, focused on instrumentation, was given by IARC staff.



Figure 25.4. Some of the participants of the SDS-WAS Workshop for Chad, held on-line, 16 October 2024

25.5 Integrating low-cost sensor (LCS) systems and networks to enhance air quality applications

IARC staff participated in the GAW Report No. 293, published in June 2024 (Malings et al., 2024). This report was produced by WMO GAW in collaboration with the United Nations Environment Programme (UNEP), International Global Atmospheric Chemistry project (IGAC) and international experts on technical and application areas. It discusses LCS use in networks and alongside other data sources for comprehensive air quality applications, complementing other WMO publications on Low-Cost sensors Systems (LCS) operating principles, calibration, performance assessment, and data communication. These are the key findings of the report:

- LCS can fill gaps in existing networks.
- Low and middle income countries can benefit from LCS use.
- LCS are an important additional tool which can be harnessed at the community level.
- Data-driven policy supports action towards combating air pollution.
- The effects of air pollution lead to an estimated 7 million deaths every year

25.6 References

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26 Scientific communication and outreach

The main tool of scientific communication of the IARC is its webpage (<http://izana.aemet.es>). Scientific information and articles are regularly posted there. In this section, we give details of some of the science communication and outreach activities during the 2023–2024 period.

26.1 Habla Canarias, Puerto de La Cruz: March 2023

Dr Omaira García took part in a debate about the Climate Crisis: "Alerta roja. Debate sobre crisis climática", organized by Habla Canarias, Puerto de La Cruz, on 27 March 2023. A link to the event can be found [here](#).



Figure 26.1. Dr Omaira García during a debate about the Climate Crisis, Puerto de La Cruz, Tenerife, 25 March 2023. Photo credit: D. Crespo.

26.2 Manchester University visit: March 2023

Students of Earth Sciences at the University of Manchester (UK) took part in a guided visit to Izaña Observatory on 27 March 2023.



Figure 26.2. Participants during the University of Manchester visit to Izaña Observatory, 27 March 2023

26.3 Tribute to Dr Emilio Cuevas: June 2023

A tribute to Dr Emilio Cuevas Agulló, by the Government of the Canary Islands, recognizing his outstanding professional, scientific and civil service career, took place in the auditorium of the Presidency of the Canary Islands Government on 8 June 2023.



Figure 26.3. Tribute to Dr Emilio Cuevas Agulló by the Government of the Canary Islands, Presidency of the Canary Islands Government, 8 June 2023

26.4 Spanish Meteorological Association (AME): June 2023

Alberto Redondas gave a presentation online titled: "El agujero de ozono y el cambio climático", (The ozone hole and climate change), Aula Francisco Morán, Asociación Meteorológica Española (AME), on 15 June 2023. A recording of the presentation can be found [here](#).



Figure 26.4. Alberto Redondas gave a presentation online to the Asociación Meteorológica Española (AME) (Spanish Meteorological Association) on 15 June 2023

26.5 Educational visit: September 2023

Dr Omaira García gave a presentation to students at the secondary school, IES José María Pérez Pulido, entitled: “El presente de la investigación atmosférica en Canarias y la visibilización de la mujer en las ciencias actuales” on 25 September 2023.



Figure 26.5. Dr Omaira García gave a presentation to students at the secondary school, IES José María Pérez Pulido, 25 September 2023

26.6 Spanish Meteorological Association: November 2023

Dr Omaira García gave a presentation online titled: “COCCON-España: Hacia un Sistema Integrado de Observación de Gases de Efecto Invernadero en España”, (COCCON-Spain: Towards an Integrated Greenhouse Gas Observation System in Spain), Aula Francisco Morán, AME, on 23 November 2023. A recording of the presentation can be found [here](#).



Figure 26.6. Dr Omaira García gave a presentation online to the Asociación Meteorológica Española (Spanish Meteorological Association) on 23 November 2023

26.7 Spanish Meteorological Association: January 2024

Dr África Barreto gave a presentation online titled: “Los aerosoles y el clima: el papel del Observatorio Atmosférico de Izaña”, (Aerosols and climate: the role of the Izaña Atmospheric Observatory), Aula Francisco Morán, AME, on 9 January 2024. A recording of the presentation can be found [here](#).



Figure 26.7. Dr África Barreto gave a presentation online to the Asociación Meteorológica Española (Spanish Meteorological Association) on 9 January 2024

26.8 La Laguna University visit: February 2024

Students of Environmental Chemistry at the University of La Laguna visited Izaña Observatory on 8 February 2024.



Figure 26.8. Participants during the University of La Laguna visit to Izaña Observatory, 8 February 2024

26.9 Manchester University visit: March 2024

Students of Earth Sciences at the University of Manchester (UK) visited Izaña Observatory on 18 March 2024.



Figure 26.9. Participants during the University of Manchester visit to Izaña Observatory, 18 March 2024.

26.10 World Meteorological Day: March 2024

A celebration of the World Meteorological Day (23 March 2024), was held in Izaña Observatory on 20 March 2024, organized jointly by the Delegation of AEMET in the Canary Islands and IARC. Various presentations were given on the subject of “Observation, Prediction, and Mitigation of Adverse Meteorological Phenomena in the Canary Islands”.



Figure 26.10. World Meteorological Day 2024 visit to Izaña Observatory, 20 March 2024

26.11 Izaña Observatory visit: April 2024

The Official College of Doctors and Graduates in Philosophy, Arts and Sciences of Santa Cruz de Tenerife, visited the Izaña Observatory on 12 April 2024, exchanging reflections on science and society.



Figure 26.11. Participants during the College of Doctors and Graduates in Philosophy, Arts and Sciences of Santa Cruz de Tenerife visit to Izaña Observatory, 12 April 2024

26.12 Climate Fair: June 2024

IARC participated with a stand in the “Feria del Clima”/Climate Fair, Puerto de la Cruz, Tenerife on 28 June 2024 providing information about the installations and activities of IARC.



Figure 26.12. IARC stand during the Feria del Clima/Climate Fair, Puerto de la Cruz, Tenerife, 28 June 2024

26.13 Science conducted in Teide National Park 2019–2023: November 2024

Dr Natalia Prats presented an invited talk titled “Air Quality: Pollutants and Calimas”, at the 2-day workshop “Science conducted in Teide National Park 2019–2023”, on 27–28 November 2024 at the Teide National Park visitor centre, La Orotava, Tenerife. A video summary of the workshop can be found [here](#).



Figure 26.13. Dr Natalia Prats gave a presentation in the “Science conducted in Teide National Park 2019–2023” 2-day workshop, La Orotava, Tenerife, 27–28 November 2024

26.14 Doctoral thesis: December 2024

Dr David Suárez Molina (Delegate of AEMET in the Canary Islands) gave a presentation of his doctoral thesis: “Prediction of Adverse Weather Phenomena Using High-Resolution Models and Early Warning Systems” at the Izaña Observatory on 11 December 2024.



Figure 26.14. Presentation of doctoral thesis of Dr David Suárez Molina at the Izaña Observatory on 11 December 2024

26.15 TeideLab images: 2023–2024

TeideLab is an initiative created between the Teide Cable Car Company and various other institutions, including IARC, to produce high quality content that advances and disseminates knowledge about the natural, scientific, cultural and recreational values of Teide National Park. It seeks to facilitate collaboration between different institutions, both those with a direct presence in Teide National Park, as well as those that are particularly relevant to the interests of the park.



Figure 26.15. Photographic images taken during the “Teide Clouds Laboratory” project from Izaña Observatory by Daniel López

The “Teide Clouds Laboratory” project, which started in December 2015, is one of four projects within TeideLab. The project is the result of a collaboration between the IARC, the Teide Cable Car Company, and the renowned Astrophotographer Daniel López, with the main aim of registering meteorological phenomena in Teide National Park using high quality photographic images and high temporal resolution “time-lapse” videos. Cameras are placed within the main technical tower at IZO and in a “Cloud Tower” outside the observatory to allow diurnal and nocturnal photographic images to be captured remotely (Figure 26.15). A video presentation of the “Teide Clouds Laboratory” project can be found [here](#). Examples of the daily sunrise and sunset images of Teide National Park collected in the TeideLab project are shown in Figure 26.16.



Figure 26.16 Sunrise and sunset images from Izaña Observatory “Teide Clouds Laboratory” project by Daniel López

27 Publications

27.1 List of peer-reviewed papers

2024

- Almansa, A. F., Barreto, Á., Kouremeti, N., González, R., Masoom, A., Toledano, C., Gröbner, J., García, R. D., González, Y., Kazadzis, S., Victori, S., Álvarez, Ó., Maupin, F., Carreño, V., Cachorro, V. E., and Cuevas, E.: The Langley ratio method, a new approach for transferring photometer calibration from direct sun measurements, *Atmos. Meas. Tech.*, 17, 659–675, <https://doi.org/10.5194/amt-17-659-2024>, 2024.
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28 List of scientific projects

Table 28.1. List of scientific projects at IARC during 2023-2024.

Project title	Duration	Funding agency	Project website	Principal Investigator/ Contact
Validation of Sentinel-4 and Sentinel-5 Total Ozone using Brewer, Dobson and UV-visible/SAOZ networks (VALTOZ-S45)	2024-	European Space Agency (ESA)		PI: AUTH Dr Katerina Garane PI (IARC-AEMET): Alberto Redondas Franciso Parra
Validation of the Sentinel 5 Level 2 surface UV radiation product	2024-	European Space Agency (ESA)		PI: FMI Kaisa Lakala PI (IARC-AEMET): Alberto Redondas
Pervasive gas spectroscopy using optical fibres, as part of the communication network of the future (GASPOF)	2024-2028	European Commission HORIZON-CL4-2024-DIGITAL-EMERGING-01 (No 10118965)	https://gaspof.eu/	PI (CY.R.I.C) PI (IARC-AEMET): Dr Omaira García
Ultraviolet Aerosol Index (UVAI) and 380 nm Aerosol Absorption Optical Depth: PACE-OCI Validation Plan	2023-2027	NASA/GSFC		PI (NASA): Omar Torres PI (IARC-AEMET): Dr África Barreto
Aerosol, Clouds and Trace gases Research InfraStructure (ACTRIS)	2020-2027	European Commission H2020-INFRADEV, Grant agreement ID: 871115	https://www.actris.eu/	PI (FMI): Dr Eija Juurola PI (IARC-AEMET): Dr África Barreto
Red Española de Participantes en ACTRIS (Spanish network of participants in ACTRIS)	2023-2026	Spanish Ministry of Science and Innovation Grant RED2024-153891-E funded by MICIU/AEI/10.13039/501100011033	https://actris.es/en/	PI (ACTRIS Spain): Lucas Alados PI (AEMET): Dr África Barreto
high-Resolution air Emissions Systems to support modelling and monitoring Efforts (RESPIRE)	2023-2026	European Commission – NextGenerationEU Recovery, Transformation and Resilience Plan	https://respire.bsc.es/	PI (Barcelona Supercomputer Center): Marc Guevara PI (AEMET): Yolanda Luna
RED NACIONAL COCCON-ESPAÑA PARA LA OBSERVACIÓN DE GASES DE EFECTO INVERNADERO (COCCON-Spain)	2023-2026	European Commission – NextGenerationEU Recovery, Transformation and Resilience Plan		PI (IARC-AEMET): Dr Omaira García
International network for harmonization of atmospheric aerosol retrievals from ground-based photometers (HARMONIA)	2022-2026	European Commission COST Action CA21119	https://harmonia-cost.eu/	PI: Stelios Kazadzis (PMOD) PI (IARC-AEMET): Dr África Barreto

Brewer Error Budget in Eubrewnet (BREWET)	2020-2026	European Space Agency (ESA) 4000117151/16/I-LG KNMI-2020/658	http://www.tropomi.eu/data-products/mission-performance-centre	PI (ESA): Dr Angelika Dehn PI (IARC-AEMET): Alberto Redondas
Knowledge and climate services from an African observation and Data research Infrastructure (KADI)	2022-2025	European Commission HORIZON-INFRA-2021-DEV-01	https://kadi-project.eu/	PI: ICOS ERIC PI (IARC-AEMET): Dr África Barreto – Dr Omaira García
Solutions for Sustainable Access to Atmospheric Research Facilities (ATMO-ACCESS)	2021-2025	European Commission H2020-INFRAIA-2018-2020 (H2020)	https://izana.aemet.es/atmo-access-isaf/#home	PI (CNRS): Prof Paolo Laj PI (IARC-AEMET): Dr Natalia Prats
Climate Risk and Early Warning System (CREWS)	2021-2025	WMO		PI: WMO PI (AEMET): Ernest Werner
Towards the Next Generation of Sensors for Surveying the Atmospheric Carbon Cycle (CarbonSurvey)	2022-2024	Spanish Ministry of Science and Innovation		PI (UC3M): Dr Marta Ruiz Llata PI (IARC-AEMET): Dr Omaira García
Metrology for aerosol optical properties (MAPP)	2020-2023	EURAMET: European Association of National Metrology Institutes	https://www.pmdwrc.ch/en/MAPP/	PI (SFI Davos): Dr Julian Gröbner PI (IARC-AEMET): Dr África Barreto
Mac-Clima	2019-2023	MAC2/3.5b/254, Inter-Reg	https://mac-clima.energiagrancanaria.com	Consortium
S5P Nitrogen Dioxide and Formaldehyde Validation using NDACC and complementary FTIR and UV-Vis DOAS ground-based remote sensing data (NIDFORVal)	2016-2023	European Space Agency (ESA) ID28607		PI (BIRA-IASB): Dr Corinne Vigouroux Dr Gai Pinardi PI (IARC-AEMET): Dr Omaira García
Validation of S5P Methane and Carbon Monoxide with TCCON Data (TCCON4S5P)	2016-2023	European Space Agency (ESA)		PI (BIRA-IASB): Dr Filip Desmet PI (IARC-AEMET): Dr Omaira García

For a definition of the acronyms used in the above table, see section 32.

29 List of major national and international networks, programmes and initiatives

The Izaña Atmospheric Research Center participates in the following national and international networks, programmes and initiatives:

ACTRIS	Aerosols, Clouds, and Trace gases Research InfraStructure
AERONET	AErosol RObotic NETwork
ALC	Automatic Ceilometer and Lidars Network
BSRN	Baseline Surface Radiation Network
CarbonTracker	CO ₂ measurement and modelling system developed by NOAA to keep track of sources and sinks of carbon dioxide around the world

[CarbonTracker Europe](#)

CARS	ACTRIS Centre for Aerosol Remote Sensing
CCRES	ACTRIS Centre for Cloud Remote Sensing
COCCON	Collaborative Carbon Column Observing Network
EAN	European Aeroallergen Network
EARLINET	European Aerosol Research Lidar Network
E-GVAP	EUMETNET GNSS Water Vapour Programme
E-PROFILE	EUMETNET Profiling Programme
EPN	EUREF Permanent Network
EUBREWNET	European Brewer Network
EUMETNET	European Meteorological Network
GAW	WMO Global Atmosphere Watch Programme
GCOS	Global Climate Observing System
GEOMON	Global Earth Observation and Monitoring of the Atmosphere

[GLOBALVIEW-CO₂](#)

[GLOBALVIEW-CH₄](#)

[GLOBALVIEW-CO](#)

[GLOBALVIEW-CO₂C₁₃](#)

GURME	WMO GAW Urban Research Meteorology and Environment project
ICOS	Integrated Carbon Observation System
LOTUS	Long-term Ozone Trends and Uncertainties in the Stratosphere
MPLNet	Micro-Pulse Lidar NETwork
NDACC	Network for the Detection of Atmospheric Composition Change

[NOAA/ESRL/GMD CCGG Cooperative Air Sampling Network](#)

[Pandonia Global Network](#)

PHOTONS	PHOTométrie pour le Traitement Opérationnel de Normalisation Satellitaire
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RBCC-E	Regional Brewer Calibration Center for Europe
REA	Red Española de Aerobiología
REDMAAS	Red Española de DMAs Ambientales
SDS-WAS	WMO Sand and Dust Storm Warning, Advisory and Assessment System
SPALINET	Spanish and Portuguese Aerosol Lidar Network
SPARC	Stratosphere-troposphere Processes And their Role in Climate
TCCON	Total Carbon Column Observing Network
TOAR	Tropospheric Ozone Assessment Report
WCCAP	World Calibration Centre for Aerosol Physics
WDCGG	World Data Centre for Greenhouse Gases
WDCRG	World Data Center for Reactive Gases
WOUDC	World Ozone and Ultraviolet Data Center
WRC-WORCC	World Radiation Centre-World Optical Depth Research and Calibration Center
WRC-WCC-UV	World Radiation Centre-World Calibration Center-Ultraviolet Section
WRDC	World Radiation Data Centre

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31 List of acronyms

ACE-FTS - Atmospheric Chemistry Experiment - Fourier Transform Spectrometry	CESAR - Cabauw Experimental Site for Atmospheric Research
ACR - Attenuated Color Ratio	CIMH - Caribbean Institute for Meteorology and Hydrology
ACSO - Absorption Cross Sections of Ozone	CIMO - Commission for Instruments and Methods of Observations
ACTRIS - Aerosol, Clouds and Trace Gases Research Infrastructure	CINDI - Cabauw Intercomparison campaign Nitrogen Dioxide measuring Instrument
ADF - aerosol radiative forcing	CINDI-3 Third Cabauw Intercomparison of UV-Vis DOAS Instruments
AE - Angstrom Exponent	CMA - China Meteorological Administration
AECID - Agencia Española de Cooperación Internacional para el Desarrollo (Spanish Agency for International Development Cooperation)	CNR - Consiglio Nazionale delle Ricerche (National Research Council of Italy)
AEMET - Agencia Estatal de Meteorología (State Meteorological Agency)	CNRS - Centre National de la Recherche Scientifique (French National Centre for Scientific Research)
AEROCOM - Aerosol Comparisons between Observations and Models	COALITION - Characterization Of Aerosols In The subtropical North Atlantic
AERONET - Aerosol Robotic Network	COCCON - Collaborative Carbon Column Observing Network
AF - Radiative Forcing	CoSQM - Color Sky Quality Meter
AI - Artificial Intelligence	COST - European Cooperation in Science and Technology
ALC - Automatic Ceilometer and Lidars Network	CPCs - Condensation Particle Counter
AMISOC - Atmospheric Minor Species relevant to the Ozone Chemistry at both sides of the Subtropical jet	CRDS - Cavity Ring-Down Spectroscopy
ANN - Artificial Neural Network	CREWS - Climate Risk and Early Warning System
AOD - Aerosol Optical Depth	CRR - Convective Rainfall Rate
APS - Aerodynamic Particle Sizer	CSIC - Consejo Superior de Investigaciones Científicas (Spanish National Research Council)
AQMN - Air Quality Monitoring Network	DNI - Direct Normal Irradiance
ARTI - African Residence Time Index	DOAS - Differential Optical Absorption Spectroscopy
ATC - Atmospheric Thematic Center (ICOS)	DOD - Dust Optical Depth
BC - Black Carbon	DQO - Data Quality Objective
BDCN - Banco Nacional de Datos Climatológicos (National Climatological Database)	DREAM - Dust Regional Atmospheric Model
BDRC - Barcelona Dust Regional Centre	DS - Direct Sun
BIRA-IASB - Royal Belgian Institute for Space Aeronomy	DSCR - Digital Sky Colour Radiometer
BSC-CNS - Barcelona Supercomputing Centre – National Supercomputing Centre	DU - Dobson Unit
BSRN - Baseline Surface Radiation Network	DVB - Digital Video Broadcast
BTO - Botanic Observatory	DWD - Deutscher Wetterdienst (German National Meteorological Service)
CAIS - Centre for Aerosol In Situ (ACTRIS)	EAN - European Aeroallergen Network
CAMS - Copernicus Atmosphere Monitoring Service	ECC - Electrochemical concentration cell
CARS - Centre for Aerosol Remote Sensing (ACTRIS)	ECCC - Environment and Climate Change Canada
CARSNET - China Aerosol Remote Sensing Network	ECD - Electron Capture Detector
CBL - Convective Boundary Layer	ECMWF - European Centre for Medium-Range Weather Forecasts
CCD - Charge-coupled device	ECMWF-IFS - European Centre for Medium-Range Weather Forecasts - Integrated Forecasting System
CCGG - Carbon Cycle Greenhouse Gases group	ECN - Energy research Centre of the Netherlands
CCI - Climate Change Initiative	ECV - Essential Climate Variable
CCLs - Central Calibration Laboratories	EGVAP - EUMETNET GPS Water Vapour Programme
CCN - Cloud Condensation Nuclei	
CEAM - Centro de Estudios Ambientales del Mediterráneo (Mediterranean Center for Environmental Studies)	
CEOS - Committee on Earth Observation Satellites	

EMPA - Eidgenössische Materialprüfungs- und Forschungsanstalt (Swiss Federal Laboratories for Materials Science and Technology)

EMPIR - European Metrology Programme for Innovation and Research

EMRP - European Metrology Research Programme

Eolo-PAT EOLO-Predicción Aerobiológica para Tenerife

EPS - Ensemble Prediction System

ERA4CS - European Research Area for Climate Services

ERA-Interim – ECMWF global atmospheric reanalysis from 1979

ERIC - European Research Infrastructure Consortium

ESA - European Space Agency

ESA-CALVAL – European Space Agency Calibration and Validation project

ESFRI - European Strategy Forum on Research Infrastructures

ESRL - Earth System Research Laboratory

ESTOC - Estación de Series Temporales en el Océano de las Islas Canarias

ET-ACMQ - Expert Team -Atmospheric Composition Measurement Quality

ETC - Extraterrestrial constant

EUBREWNET - European Brewer Network

EU COST - European Cooperation in Science and Technology

EUDAT - European Data Infrastructure

EUMETNET - European Meteorological Network

EUMETSAT - European Organisation for the Exploitation of Meteorological Satellites

EURAMET - European Association of National Metrology Institutes

EVDC - ESA Validation Data Center

EVOLUTION - EVALuation of aerOsol LUNar measuremets at the saTellite cOMmunication chaNNels

FCS - Fraction Clear Sky

FETCH4 - Fate, Emissions, and Transport of CH₄

FID - Flame Ionization Detector

FLC - Ferroelectric Liquid Crystal

FLEXTRA - FLEXible TRAjectories

FMI - Finnish Meteorological Institute

FNL - Final Analysis Data

FOV - Field Of View

FRC-V Fifth Filter Radiometer Comparison

FRM - Fiducial Reference Measurements

FRM4DOAS - FRM for DOAS

FT - Free Troposphere

FTIR - Fourier transform infrared spectroscopy

FTS - Fourier Transform Spectrometry

FW2 - Fitting Window 2

FW5 - Fitting Window 5

FWHM - Full Width at Half Maximum

GAW - Global Atmosphere Watch

GAWSIS - GAW Station Information System

GCOS - Global Climate Observing System

GC-RGD - Gas Chromatography Reduction Gas Analyser

GDAS - Global Data Assimilation System

GEO – Geostationary Orbit

GEOS-5 -Goddard Earth Observing System model

GFDRR - World Bank Global Facility for Disaster Reduction and Recovery

GFS - Global Forecast System

GHG - Greenhouse Gas

GLOBE - Global Learning and Observations to Benefit the Environment

GLONASS - Global Navigation Satellite System

GMD - Global Monitoring Division

GMES - Global Monitoring for Environment and Security

GNSS - Global Navigation Satellite System

GOA - Atmospheric Optics Group

GOA-UVA - University of Valladolid Atmospheric Optics Group

GOME - Global Ozone Monitoring Experiment

GOSAT - Greenhouse gases Observing SATellite

GPS - Global Positioning System

GRASP - Generalized Retrieval of Aerosol and Surface Properties

GRUAN - Global Climate Observing System Reference Upper-Air Network

GSFC - Goddard Space Flight Center (NASA)

GSR - Global Solar Radiation

HEGIFTOM - Harmonization and Evaluation of Ground-based Instruments for Free Tropospheric Ozone Measurements

H2020 - Horizon 2020

HIRLAM - High Resolution Limited Area Model

HYSPLIT - Hybrid Single Particle Lagrangian Integrated Trajectory Model

IAC - Instituto de Astrofísica de Canarias (Institute of Astrophysics of the Canary Islands)

IAGOS - In-Service Aircraft for a Global Observing System

IARC - Izaña Atmospheric Research Center

IASI -Infrared Atmospheric Sounding Interferometer

ICaRO - Izaña Cosmic Ray Observatory

ICOS - Integrated Carbon Observation System

ICP-AES - Inductively Coupled Plasma Atomic Emission Spectroscopy

ICP-MS - Inductively Coupled Plasma Mass Spectroscopy

IDAEA - Instituto de Diagnóstico Ambiental y Estudios del Agua (Institute of Environmental Assessment and Water Research)

IEO - Instituto Español de Oceanografía (Spanish Institute of Oceanography)

IES - Instituto de Educación Secundaria (Institute of Secondary Education)	LIME - Lunar Irradiance Model ESA
IGAC - International Global Atmospheric Chemistry Project	LOA - Laboratoire d'Optique Atmosphérique (Atmospheric Optics Laboratory)
IGACO - Integrated Global Atmospheric Observations	LR - Lidar Ratio
IGN - Instituto Geográfico Nacional de España (Spanish National Geographic Institute)	LOTUS - Long-term Ozone Trends and Uncertainties in the Stratosphere
IG3IS - Integrated Global Greenhouse Gas Information System	MAAP - Multi Angle Absorption Photometer
ILAS - Improved Limb Atmospheric Spectrometer	MAPP - Metrology for Aerosol Optical Properties
IMAA - Institute of Methodologies for Environmental Analysis	MARS - Meteorological Archival and Retrieval System
IMAP - Inverse Multi-Angle Polarimeter	MAXDOAS - Multi Axis Differential Optical Absorption Spectroscopy
IMK-ASF - Institut für Meteorologie und Klimaforschung - Atmosphärische Spurengase und Fernerkundung (Institute of Meteorology and Climate Research - Atmospheric Trace Gases and Remote Sensing)	MBL - Marine Boundary Layer
IN - Ice Nuclei	McIDAS - Man Computer Interactive Data Access System
INAR - Institute for Atmospheric and Earth System Research	MetUN - Met Office Unified Model
INM - Institut National de la Météorologie	MEE - Mass Extinction Efficiency
INMG - Instituto Nacional de Meteorologia e Geofísica (Cabo Verde)	MERRA-2 Modern-Era Retrospective Analysis for Research and Applications, version 2
INPE - Instituto Nacional de Pesquisas Espaciais (Brazil)	MFRSR - Multi Filter Rotating Shadow-Band Radiometer
INSTAAR - Institute of Arctic and Alpine Research	MGA - Modified Geometrical Approach
INTA - Instituto Nacional de Técnica Aeroespacial (Spanish National Institute for Aerospace Technology)	MIPAS - Michelson Interferometer for Passive Atmospheric Sounding
INTERCOONECTA - Knowledge Transfer, Exchange and Management Plan for the Development of Spanish Cooperation in Latin America and the Caribbean	MIR - Middle Infrared
IOS - International Ozone Services	MISR - Multi-angle Imaging SpectroRadiometer
IO3C - International Ozone Commission	MITECO - Ministerio para la Transición Ecológica y el Reto Demográfico (Spanish Ministry for the Ecological Transition and the Demographic Challenge)
IPCC - Intergovernmental Panel on Climate Change	MLC - Measurement Lead Centre (WMO)
IPMA - Instituto Português do Mar e da Atmosfera (Portuguese Institute for Sea and Atmosphere)	MLO - Mauna Loa Observatory
IR – Infrared	MM5 - Mesoscale Model
ISAF - Izaña Subtropical Access Facility	MOCAGE - Modèle de Chimie Atmosphérique de Grande Echelle
ISAMO - Iron Salt Atmospheric Methane Oxidation in Sahara Dust Mixed with Sea Spray Aerosol	MODIS - Moderate Resolution Imaging Spectroradiometer
IUP - Institut für Umweltphysik (Institute of Environmental Physics)	MOL-RAO - Meteorologisches Observatorium Lindenberg - Richard Aßmann-Observatorium
IZO - Izaña Observatory	MONARCH - Multiscale Online Nonhydrostatic Atmosphere Chemistry model
JMA - Japan Meteorological Agency	MOSAIC - Multidisciplinary drifting Observatory for the Study of Arctic Climate
JRC - Joint Research Centre	MPA - Moon phase angle
KADI - Knowledge and climate services from an African observation and Data research Infrastructure	MPL - Micro Pulse Lidar
KIT - Karlsruhe Institute of Technology	MSG - Meteosat Second Generation
LAP - Laboratori d'Anàlisi Palinològiques (Laboratory of Palynological Analysis)	MUSICA - Multi-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water
LDCs - Least Developed Countries	NAIS-PSM Neutral cluster and Air Ion Spectrometer - Particle size magnifier
LEO - Low Earth Orbit	NA-ME-E - The Regional Center for Northern Africa, Middle East and Europe
LHR - Laser Heterodyne Radiometry	NAO - North Atlantic Oscillation
LIDAR - Laser Imaging Detection and Ranging	NAS - Network-Attached Storage
	NASA - National Aeronautics and Space Administration
	NASA MPLNET - The NASA Micro Pulse Lidar Network

NCEP - National Centers for Environmental Prediction	QASUME - Quality Assurance of Spectral Ultraviolet Measurements
NDACC - Network for the Detection of Atmospheric Composition Change	QA4EO - Quality Assured Data for Earth Observation communities
NDIR - Non Dispersive Infrared	QC - Quality Control
NEMS - NOAA Environmental Modeling System	QUIMA - Institute of Oceanography and Climate Change
NGAC - NEMS GFS Aerosol Component	RA - Row Anomaly
NIDFORVal - NItrogen Dioxide and FORmaldehyde Validation	R&D - Research and Development
NIES - National Institute for Environmental Studies	R+D+I – Research, Development & Innovation
NILU - Norwegian Institute for Air Research	RBCC-E - Regional Brewer Calibration Center for Europe
NIPR - National Institute of Polar Research of Japan	RCF - RIMO Correction Factor
NIR - Near Infrared	REA - Red Española de Aerobiología (Spanish Aerobiology Network)
NIST - National Institute for Standards and Technology	REDMAAS - Red Española de DMAs Ambientales (Spanish Network of Environmental DMAs)
NMDB - Neutron Monitor Database	RGB - composite - Red Green Blue composite
NMHSS - National Meteorological and Hydrological Services	RH - Relative Humidity
NMMB - Nonhydrostatic Multiscale Model on the B-grid	RIMO - ROLO Implementation for Moon-photometry Observation
NMME - North American Multi-Model Ensemble	RMSE - Root Mean Square Error
NOA - National Observatory of Athens	RMTC - WMO Regional Meteorological Training Centre
NOAA - National Oceanic and Atmospheric Administration	ROLO - Robotic Lunar Observatory model
NPF - New Particle Formation	RSMC-ASDF - Regional Specialized Meteorological Centre with activity specialization on Atmospheric Sand and Dust Forecast
NRT - Near Real Time	RTM - Radiative Transfer Model
OCI - Ocean Color Instrument	SAF - Satellite Application Facilities
OCO-2 - Orbiting Carbon Observatory-2	SAG - Scientific Advisory Group
OC-SVC - Ocean Colour System Vicarious Calibration	SAL - Saharan Air Layer
ODSs - Ozone Depleting Substances	SALAM - Air Layer Air Mass characterization
OMI - Ozone Monitoring Instrument	SAO - Smithsonian Astrophysical Observatory
ONM - Office National de la Météorologie	SBSTA - Subsidiary Body on Scientific and Technical Advice
OLI - Operational Land Imager	SCIAMACHY - Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
OSC - ozone slant column	SC-MINT - Standing Committee on Measurement, Instrumentation and Traceability
O3S-DQA Ozonesonde Data Quality Assessment	SCO - Santa Cruz Observatory
OT - Ozone Tropopause	SD - Sunshine Duration
PACE - Plankton, Aerosol, Cloud, ocean Ecosystem	SDM - Standard Delivery Mode
PAR - Photosynthetically Active Radiation	SDR - Shortwave downward radiation
PBS - Polarizer Beam Splitter	SDS - Sand and Dust Storm
PFR - Precision Filter Radiometer	SDS-WAS - Sand and Dust Storm Warning Advisory and Assessment System
PI - Principal Investigator	SEAIC - Sociedad Española de Aerobiología e Inmunología Clínica (Spanish Society of Aerobiology and Clinical Immunology)
PLOCAN - Oceanic Platform of the Canary Islands	SeaWIFS - Sea-Viewing Wide Field-of-View Sensor
PM - Particle Matter	SEM - Standard Error of the Mean
PM-LCS - Particle Matter – Low Cost Sensors	SHL - Saharan Heat Low
PMOD - Physikalisches-Meteorologisches Observatorium Davos	SI - International System of Units
PRTR - Recovery, Transformation, and Resilience Plan	SIDS - Small Island Developing States
PSR - Precision Solar Spectroradiometer	
PTB - Physikalisches-Technische Bundesanstalt (National Metrology Institute of Germany)	
PV - Potential Vorticity	
PWV - Precipitable Water Vapour	
QA - Quality Assurance	

SMN - Argentinian Meteorological Service	WDCA - World Data Centre for Aerosols
SMPS - Scanning Mobility Particle Sizer	WDCGG - World Data Centre for Greenhouse Gases
SONA - Sistema de Observación de Nubes Automático (Automatic cloud observation system)	WDCRG - World Data Center for Reactive Gases
SOP - Standard Operating Procedure	WIGOS – WMO Integrated Global Observing System
SPARC - Stratosphere-troposphere Processes And their Role in Climate	WMO - World Meteorological Organization
SPC - Science Pump Corporation	WORCC - World Optical Depth Research and Calibration Center
SSDM - Server Meteorological Data System	WOUDC - World Ozone and Ultraviolet Data Center
STJ - Subtropical Jet Stream	WRC - World Radiation Center
STS - Sky Temperature Sensor	WS-CRDS - Wavelength-Scanned Cavity Ring-Down Spectroscopy
STT - Stratosphere-to-troposphere	WWRP - World Weather Research Programme
SWIR - short-wave infrared	XS - Cross Section
SYNERA - SYNERgies for assessing short- and long-term variations of Aerosols properties in the subtropical North Atlantic	ZHD - Zenith Hydrostatic Delay
SYNOP - Surface Synoptic Observation	ZSR - Zenith Sky Radiance
SZA - Solar Zenith Angle	ZTD - Zenith Total Delay
TNA - Trans National Access	
ToA - Top-of-Atmosphere	
TOAR-II - Tropospheric Ozone Assessment Report, phase II	
TOC - Total Ozone Column	
TPO - Teide Peak Observatory	
TROPOMI - TROPOspheric Monitoring Instrument	
TSP - Total Suspended Particles	
UAB - Universidad Autónoma de Barcelona (Autonomous University of Barcelona)	
UFPs - Ultrafine Particles	
UFMS - Federal University of Santa Maria (Brazil)	
ULL - University of La Laguna	
ULPGC - University of Las Palmas de Gran Canaria	
UNAM - National Autonomous University of Mexico	
UNDRR - United Nations Office for Disaster Risk Reduction	
UNEP - United Nations Environment Programme	
UNFCCC - United Nations Framework Convention on Climate Change	
UPC - Universitat Politècnica de Catalunya	
UT – Upper Troposphere	
UTC - Coordinated Universal Time	
UTLS - Upper Troposphere Lower Stratosphere	
UV - Ultraviolet	
UVA - University of Valladolid	
VIS - Visible	
VMR - Volume Mixing Ratio	
VOS - Volunteer Observing Ship	
WBT - World Brewer Triad	
WCC - World Calibration Center	
WCCAP - World Calibration Centre for Aerosols Physics	
WCRP - World Climate Research Programme	

32 Acknowledgements

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Back cover photograph: Izaña Observatory (Photo: Fernando Rey Daluz)



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