Internal consistency of the IAGOS ozone and carbon monoxide measurements for the last 25 years.

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Abstract.

The In-service Aircraft for a Global Observing System is a European research infrastructure that equips Airbus A340/330 with a system for monitoring atmospheric composition. The IAGOS instruments have three different configurations: IAGOS-CORE, IAGOS-MOZAIC and IAGOS-CARIBIC. Since 1994, there have been a total of 17 aircraft equipped. In this study, we
5 perform an inter-comparison of about 8000 landing and take-off profiles to compare the O3 and CO measurements performed from these different configurations. The collocated profiles used in the study met various selection criteria. The first was a maximal 1 hour time difference between an ascent or descent by two different aircraft at the same airport and the second was a selection based on the similarity of air masses based on the meteorological data acquired by the aircraft. We provide here an evaluation of the internal consistency of the O3 and CO measurements since 1994. For both O3 and CO, we find no drift in the
10 bias amongst the different instrument units (6 O_3 and 6 CO IAGOS-MOZAIC instruments, 9 IAGOS-CORE Package 1 and the 2 instruments used in the IAGOS-CARIBIC aircraft). This results gives us confidence that the entire IAGOS data base can be treated as one continuous program, and is therefore appropriate for studies of long-term trends.

1 Introduction

The In-service Aircraft for a Global Observing System (IAGOS, https://www.iagos.org) is a European research infrastructure
15 (Petzold et al., 2015) that was officially launched in 2011 to equip Airbus A340/330 long-haul passenger aircraft with a newly designed system (named IAGOS-CORE) for collecting data on gases, aerosol and trace species throughout the tropopshere and lower stratosphere, and by maintaining the fleet of the former projects Measurement of OZone and water vapor by Airbus In-service AirCraft (MOZAIC now IAGOS-MOZAIC; Marenco et al. (1998)) and the Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container (CARIBIC I & II now IAGOS-CARIBIC; Brenninkmeijer et al. (1999,
20 2007), https://www.caribic-atmospheric.com).
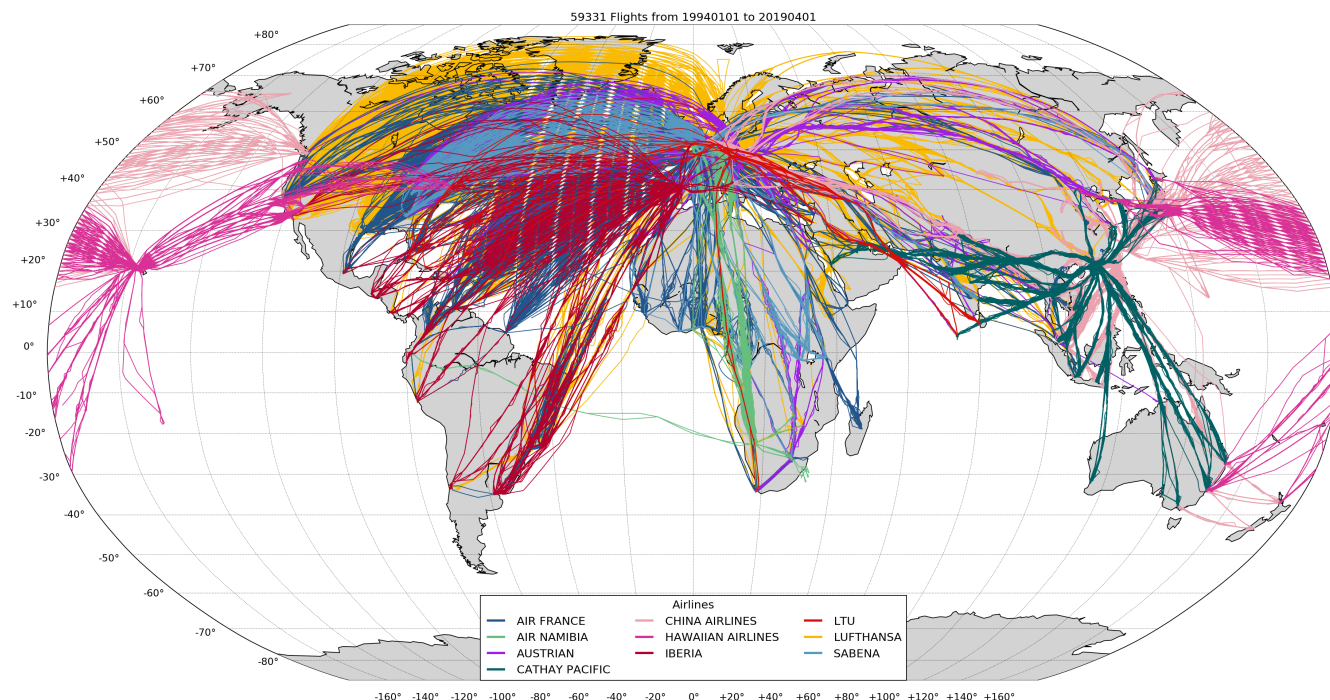
Figure 1. IAGOS aircraft fleet routes per airlines since 1994.

The IAGOS program was inspired by the The Global Atmospheric Sampling Program (GASP) started by the National Aeronautics and Space Administration (NASA) in 1975 (Perkins and Papathakos, 1977; Falconer et al., 1978; Falconer and Pratt, 1979) that showed that civil aircraft can serve as a new kind of observing platform for the atmosphere and can provide high temporal and spatial resolution for a relatively low cost compared with dedicated research aircraft field campaigns (Eyres and Reid, 2014). In the 1990s, the European aircraft manufacturer Airbus, concerned by the probable growing impact of the aeronautical industry on climate, has supported the Centre National de la Recherche Scientifique (CNRS) to develop the program MOZAIC with 5 long-range Airbus A340s permanently equipped with sensors to sample O_3 (Thouret et al., 1998), water vapor (Helten et al., 1999; Smit et al., 2014), CO (since 2001; Nedelec et al. (2003)) and NOy (2000-2005; Volz-Thomas et al. (2005)). At about the same time, the program CARIBIC was launched in Germany with a different but complementary approach compared with MOZAIC. In MOZAIC, measurements of few key atmospheric components are taken on every flight made by the aircraft. In CARIBIC, every month, a one-ton-capacity aircraft freight container is loaded onto an aircraft to sample a large number of atmospheric species (up to 100 species). Originally planned for few years of operation, strong long term support from the French and German ministries of research, the European union (UE Framework Program fundings) and the participating airlines (Air France, Lufthansa, Iberia, Cathay Pacific, China Airlines, Hawaiian Airlines, Austrian Airlines, Air Namibia, Sabena) has allowed IAGOS to equip 17 Aircraft in 25 years (9 retired), delivering an impressive amount of measurements, both at cruising altitude (about 180 hpa) and during landings and take-offs over cities. It represents more than

60000 flights of 6 to 8h duration in average and around 120000 profiles over 338 cities. In total, it is about 3.5M points of observation spread around the world (see Figure 1). A more detailed overview of the IAGOS program and instruments can be found in Petzold et al. (2015).

40   Here we focus on the O_3 and CO data measured within the IAGOS program. These two atmospheric components have been identified as Essential Climate Variables (GCOS, 2010) for which long-term monitoring is a key requirements for climate change projections. O_3 is the third most effective climate forcer in the Upper Troposphere/Lower Stratosphere (UTLS) after CO2 and CH4 (IPCC, 2013) and it has a detrimental impact on the human health. CO leads the production of O_3 by oxidation by the hydroxyl radicals (OH) and, at the same time, affects the oxidation potential of the troposphere (CO can act to both

45   create and destroy OH) (Feilberg et al., 2002). CO, as primary pollutant formed by combustion processes is also a good proxy to track troposphere-stratosphere vertical transport and transcontinental transport pathways of plumes due to its relative long life time.

Until the 1990s, ozonesondes (i.e. the World Ozone and Ultraviolet Radiation Data Centre (WOUDC)) used to be the primary source of information on long-term changes of tropospheric O_3 (Tanimoto et al., 2015) besides the monitoring ground stations

50   (i.e. the World Data Centre for Greenhouse Gases (WDCGG)) for the lower troposphere. For CO, the global sustainable observations for the troposphere came in 1999 with the satellite MOPITT (Measurements of Pollution in the Troposphere), also supported for validation by ground stations and research aircraft campaigns. O_3 and CO measurements have been part of the MOZAIC system since 1994 and 2001, respectively, with a large spatial and temporal coverage over different regions. Compared with other platforms, the IAGOS measurements are in-situ and the sampling techniques and the calibration strategies

55   have remained the same since the beginning of the program (Nédélec et al., 2015). The avionic setup and the certification processes have evolved to comply with current aeronautical civil safety regulations. Because of this long-term continuity, the IAGOS dataset is particularly adapted to studies of decadal trends and climatologies (Thouret et al., 2006; Zbinden et al., 2006; Hess and Zbinden, 2013; Zhang et al., 2016; Petetin et al., 2016b,a, 2018b; Gaudel et al., 2018; Cohen et al., 2018) and also air quality studies in and around urban agglomerations in the lower troposphere (Petetin et al., 2018a) thanks to the many

60   international airports that serve big cities.

Supported by the European project IGAS (see Petzold et al. (2015) and http://www.igas-project.org/) launched in 2013, great efforts have been made to document standard operating procedures and to implement robust Quality Assurance and Quality Control (QA/QC) procedures for each measured atmospheric component. As a long term monitoring program and planned to last as long as it gets support from the aeronautical industry and public research entities, it is of primary importance to

65   guarantee the traceability of the data and to regularly track the performances of the instruments in order to ensure a consistent time-series. In this paper, we present results which are part of the procedures for the QA/QC routinely performed within the IAGOS program. We investigate the internal consistency of the IAGOS dataset over the period 1994-2020, for O_3 and CO, by inter-comparing colocated IAGOS measurements obtained from the different aircraft of the fleet.

This study is organized as follows: section 2 describes the the instrumentation. The focus here is not to provide details on the

70   IAGOS-MOZAIC, IAGOS-CORE and IAGOS-CARIBIC aeronautical system setup since all the descriptions can already be found in their associated publications Marenco et al. (1998), Nédélec et al. (2015) and Brenninkmeijer et al. (2007). Similarly,

description of the corresponding instruments measuring O_3 and CO can also be found in Thouret et al. (1998), Nedelec et al. (2003), Nédélec et al. (2015), Zahn et al. (2012) and Scharffe et al. (2012). However, for a smooth reading of the paper, some key details of the project concepts are provided. Each sub program will hereafter be referred to as MOZAIC, IAGOS

75 and CARIBIC (all being part of the IAGOS infrastructure). In the section 3, we will briefly describe the Quality Assurance (QA) part of the Standard Operation Procedures (SOPs) that each O_3 and CO sampling units undergoes before, during and after installation on the different IAGOS aircraft. In the two last sections, the methodology used to evaluate long-term internal consistency IAGOS O_3 and CO and then the global results since 1994 are presented.

2 Instrumentation

80 ### 2.1 Concept overview

Equipping passenger aircraft with scientific instrumentation for atmospheric observations requires a unique and original approach in order to match scientific needs with the safety rules in the airline industry. Airborne observation programs using civil aircraft as a measurement platform share the same core characteristics. First, in-flight operations (system powering, measurements, calibration, data acquisition and safety checks) must be completely automatic with no attention required by the flight

85 crew. Secondly, system maintenance should never interfere with the aircraft schedules. Finally, and maybe the most challenging, all equipment and structural modifications added to the aircraft (support racks, inlets, etc ...) must meet the requirements of either European Aviation Safety Agency (EASA), Federal Aviation Administration (FAA) or any other legal airworthiness institution. This is covered by the deliverance of a supplemental type certificate (STC). All measuring, controlling and safety systems, are powered by the aircraft facilities. Besides the deployment of dedicated scientific instruments, flight navigation and

90 meteorological (see Table 1) data made by the aircraft system itself are collected using the Aeronautical Radio (ARINC) Inc. protocol.

2.2 Fleet

Table 2 presents the list of aircraft that have been equipped with the MOZAIC, the IAGOS and CARIBIC systems. Since 1994, 9 international airlines, with in total 17 aircraft, with their home bases in various airports, have joined the programs. For

95 MOZAIC, 5 Airbus A340 were equipped before delivery during the aircraft manufacturing at the Airbus facilities in Toulouse. This process was not applied for the IAGOS system. It can be noted that aircraft with Manufacturer Serial Number (MSN) lower than 100 carried the MOZAIC measuring system for over 10 to 20 years until the last aircraft retired in 2014. The CARIBIC cargo container first flew on a Boeing 767 from LTU between 1997 and 2002 before an A340 (D-AIHE) from Lufthansa (DLH). First the DLH IAGOS aircraft, the A340 MSN 304 D-AIGT, joined the fleet in 2011. During the following 6

100 years, 9 additional A340s or A330s were equipped with the system. For IAGOS, the aircraft modification is performed during the long maintenance lay-overs which occur roughly every 5 to 10 years of aircraft lifetime. Some IAGOS equipped aircraft are retired earlier than others depending on the requirements of the airline. Between 2011 and 2014, 4 IAGOS, 1 CARIBIC aircraft

Table 1. Parameters provided by the A340/A330 aircraft system.

Name	Unit
Baro altitude	m
Radio altitude	m
GPS altitude	m
Latitude/Longitude	degrees
Meridional wind speed	ms^{-1}
Zonal wind speed	ms^{-1}
vertical wind speed	ms^{-1}
Altitude rate	ms^{-1}
Wind speed	ms^{-1}
Wind direction	°
Aircraft ground speed	ms^{-1}
Aircraft air speed	ms^{-1}
Mach number	
Total air pressure	hPa
Left Static Pressure	hPa
Right Static Pressure	hPa
Total air temperature	° Celsius
Static air temperature	° Celsius
Track angle	degrees
Roll angle	degrees
Pitch angle	degrees
True heading	degrees
Track angle	degrees

Table 2. List of the aircraft Manufacturer Serial Number (MSN) equipped with the IAGOS-MOZAIC, IAGOS-CORE and IAGOS-CARIBIC system since 1994.

Project	n°	Airline	Type	MSN	Tail Sign	Installed in :	Based in :	Dates
IAGOS-MOZAIC	1	Air France (AFR)	A340	49	retired	Airbus Toulouse	Paris	1994 to 2004
	2	Multiple Airlines [a]	A340	51	retired	Airbus Toulouse	Paris/Frankfurt Bruxelles/Windhoek	1994 to 2013
	3	Lufthansa (DLH)	A340	35	retired	Airbus Toulouse	Frankfurt	1994 to 2014
	4	Lufthansa (DLH)	A340	53	retired	Airbus Toulouse	Frankfurt	1994 to 2014
	5	Austrian (AUS)	A340	75	retired	Airbus Toulouse	Vienna	1995 to 2006
IAGOS-CORE	6	Lufthansa (DLH)	A340	304	D-AIGT	Hamburg/Frankfurt	Frankfurt	2011 to now
	7	China Airlines (CAL)	A340	433	retired	Taipei	Taipei	2012 to 2017
	8	Air France (AFR)	A340	377	retired	Paris	Paris	2013 to 2019
	9	Cathay Pacific (CPA)	A330	421	B-HLR	Xiamen	Hong-Kong	2013 to now
	10	Iberia (IBE)	A340	221	retired	Tel-Aviv/Madrid	Iberia	2014 to 2016
	11	Lufthansa (DLH)	A330	989	D-AIKO	Malta		2015 to now
	12	China Airlines (CAL)	A330	861	B-18317	Taipei	Taipei	2016 to now
	13	Hawaiian Airlines (HAL)	A330	1259	N384HA	Brisbane/Honolulu	Honolulu	2017 to now
	14	Air France (AFR)	A330	657	F-GZCO	Xiamen	Paris	2017 to now
	15	China Airlines (CAL)	A330	838	B-18316	Taipei	Taipei	2017 to now
IAGOS CARIBIC I	1	LTU	Boeing 767	24259	retired	Hamburg	Munich	1997 to 2002
IAGOS CARIBIC II	2	Lufthansa (DLH)	A340	540	D-AIHE	Hamburg	Munich	2004 to 2020

[a] This aircraft was operated first by Air France then Sabena (ex-Sogerma) (SAB) then Lufthansa and finally by Air Namibia (SW)

and 3 MOZAIC A340s were operating. This allow us, later in this study, to compare the performance of the three different systems together.

105 **2.3 System setups**
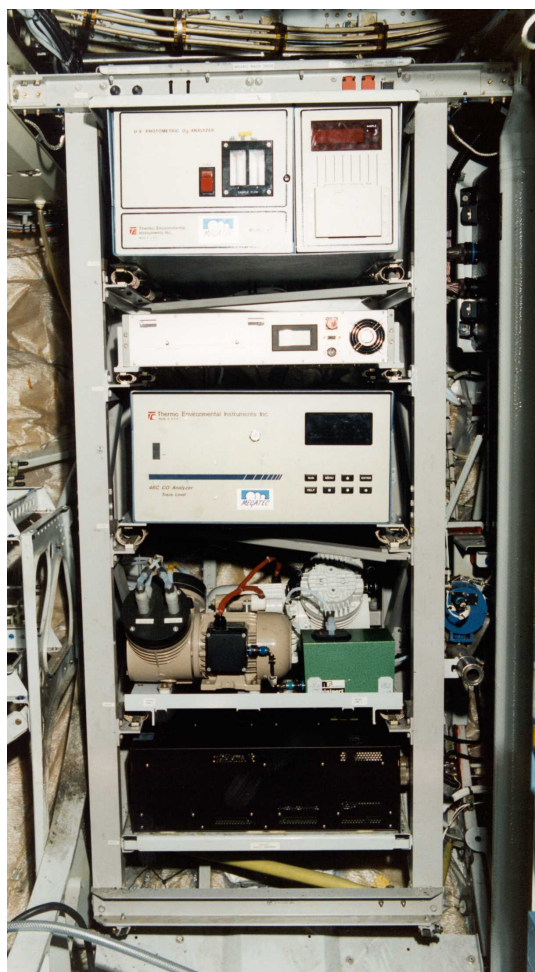
Figure 2. Picture of the MOZAIC system located on a A340 starboard side. See text for a brief description.

Figure 2 shows the MOZAIC system installation inside one of the 5 equipped A340s. All the mechanical parts and other equipments were covered by an Airbus certification. An instrument cabinet rack was located at the starboard side in the avionics bay below the cockpit. The rack was composed of five shelves that received removable/replaceable units. The upper shelf contained a commercial O_3 analyzer (Thermo-scientific, Model 49), the computer that controls the safety of the systems,
110 the system start at takeoff and the stop at landing, the ARINC data acquisition and the data backups. On the third shelf, there was a modified CO instrument (Thermo-scientific, Model 48 CTL, Nedelec et al. (2003)) (this is the configuration post-2001),

(c) IAGOS (since 2011)   (d) CARIBIC II

(a) MOZAIC (1994-2014)   (b) MOZAIC (D-AIGI : 2001-2014)

Figure 3. Pictures of the inlet plates used throughout the various programs. In a), b) and c), air for O_3 and CO measurements is collected through the small facing forward pitot tube. In c), it is done using the lowest small inlet. Other inlets and Rosemount pitots are for water, aerosol or other gases measurements. The inlet shown in b) was installed on 1 MOZAIC aircraft (D-AIGI) with an additional Rosemount inlet for NO_y/NO_x measurements. It is the precursor of the IAGOS inlet.

and below, the pressurization pumps (1 for CO, 1 for O_3) that drive the air from outside the aircraft through an inlet plate (see Figure 3a and 3b) located on the fuselage at the port side. The data were stored on PCMCIA disks replaced roughly every 2 months. In case of O_3 and CO instrument failure, the units could be independently replaced by spares. In total, through

115 the MOZAIC period, from 1994 to 2014, 6 identical O_3 analyzers and 6 identical CO analyzers with the same measurement uncertainties (see Table 3) were dispatched over the 5 MOZAIC aircraft, meaning that during the deployment period, only 1 spare was available at any one time. In the rest of this study, MOZAIC instrument Serial Numbers (SN) are referred to SN_{PM} (ex: 01_{PM}, 02_{PM}, 03_{PM}, etc ...).

In 2009, CNRS and Forschungszentrum Jülich (FZJ) initiated the project to modernize the MOZAIC system to produce a

120 more sustainable concept that would be compliant with the safety regulations of any country. Figure 4 shows a picture of the system inside an A330 aircraft (which shares a similar fuselage to the A340). The setup differs totally from the MOZAIC system. The new cabinet rack is located in the avionics compartment on the aircraft's port side, close to the inlet plate. One of the reasons for changing the position of the cabinet rack from the starboard side to the port side is that on modern aircraft the area that used to house the MOZAIC cabinet is usually occupied by the in-flight entertainment system. The advantage of the

125 new position on the port side, was that it is closer to the inlet plate. The cabinet rack was completely redefined in order to house 3 removable boxes: One for the pressurization pumps, one for O_3 and CO measurements, the so-called "Package 1" (or P1), and a third box for either one of the 2 optional certified "Package 2" (or P2), one for CO2 and CH4 measurements (Filges et al., 2015) and one for NOx measurements (Berkes et al., 2018). Compared with MOZAIC for which O_3 and CO were acquired by 2 separate instruments, the choice for IAGOS was to compact both units into the same box. The measurement characteristics ,

130 however, remain the same (see Table 3). P1 also serves as central data acquisition system that collect the aircraft ARINC data, the IAGOS Capacitive Hygrometer (ICH, Helten et al. (1999)) data, data from the Backscatter Cloud Probe (BCP, (Beswick
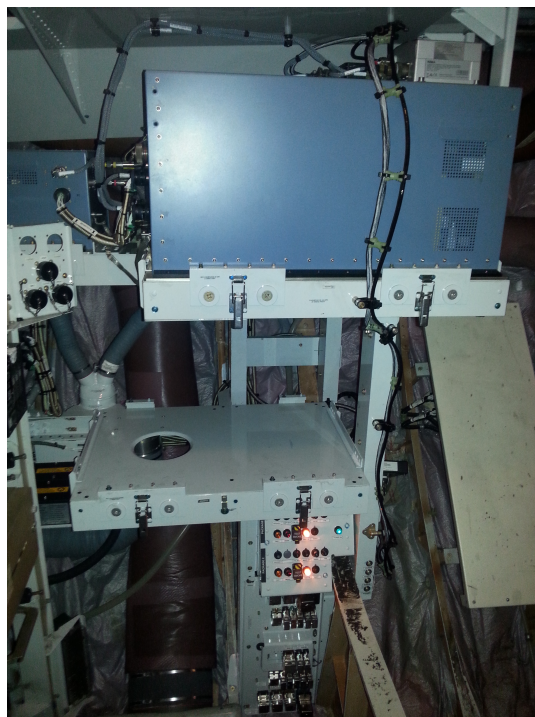
Figure 4. Picture of the IAGOS system setup in avionics bay. The Pump Box (small blue box on the upper corner left) embeds the pressurization pumps that drive the outside air collected through the pitot (see Figure 3c) to the Package 1 (P1, big blue box). The system functioning and safety is done via the control panel and relay panel seen on the lower part of the picture. The empty shelf is available for Package 2 instruments also developed within the IAGOS program.

et al., 2013)), and data from the Package 2 if installed. The data files are transferred to the IAGOS server at CNRS in Toulouse by GSM each time the aircraft cargo door is opened/locked-up on ground and if the modem manages to connect to 2G/3G network for several minutes. In 2020, 14 P1 units were distributed over 7 IAGOS aircraft. Therefore, there was 1 spare unit

135 per aircraft. Each P1 has a serial number from 02 to 16. Serial number 01 was a qualification prototype that has not been used since the operational phase of the program started in 2011, and there is no serial number 13.

Within the CARIBIC I & II programs, CO and O_3 measurements were performed by two separate units embedded into an modified air freight cargo container that additionally contained more than a dozen other instruments with a total weight of about 1.5 tons (Figure 5). The Lufthansa aircraft, which host the CARIBIC container, were modified for the structural addition of an

140 certified inlet system that holds different air intake probes (see Figure 3d) whether for aerosols, trace gases or water sampling. The container is loaded onto the aircraft for sequences of 4 to 6 flights with variable destinations. After take-off, the main power supply is switched on and a master computer (also in the container) takes command of all instrument activations/deactivations in addition to the acquisition of the ARINC parameters (see tables 1) and other data concerning the functional status of the container. In contrast to MOZAIC and IAGOS which start the trace gases measurements during the take-off phase (aircraft
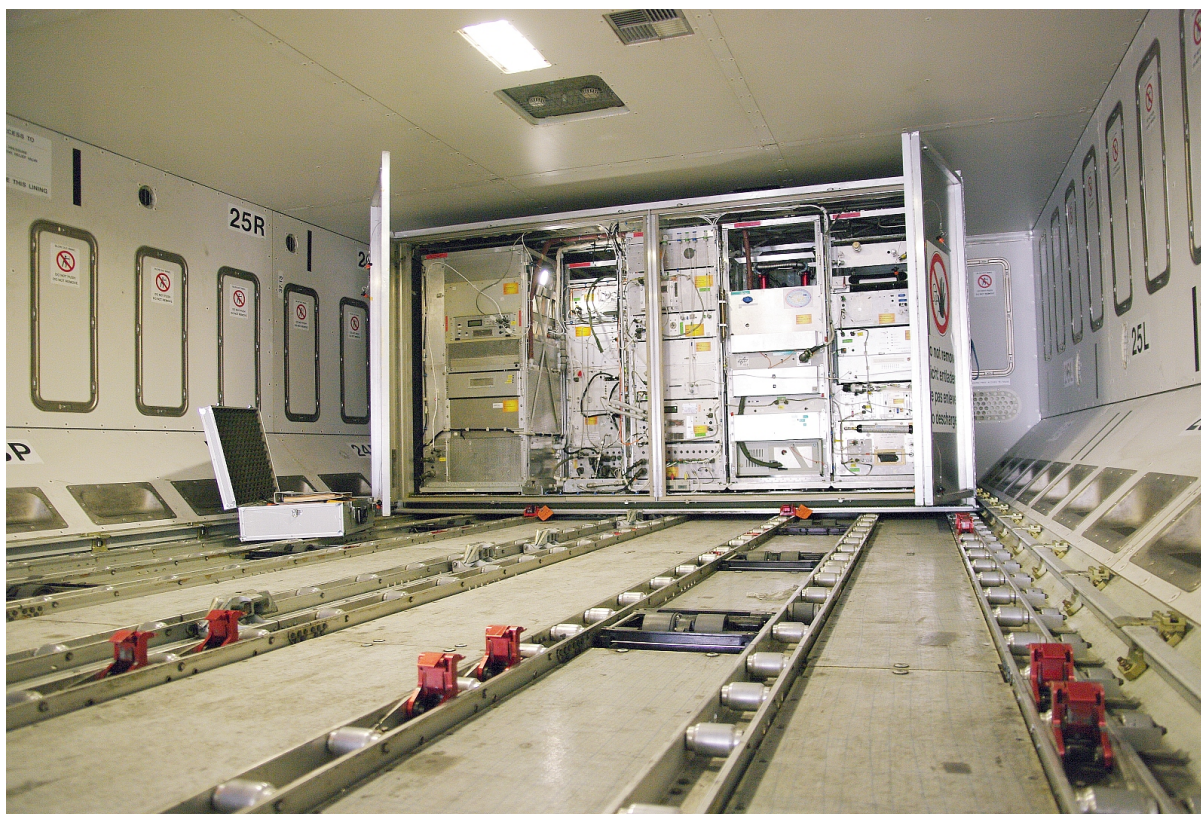
Figure 5. Picture of the CARIBIC laboratory container (1.65 tons, 19 instruments in 2017) inside the aircraft cargo bay.

145 speed $> 25\mathrm{ms}^{-1}$), the master computer starts the measurements at cruise altitude for CARIBIC I and when the baro-altitude is higher than about 2.5km above ground for CARIBIC II. For that reason and because this study will focus only on profiles, the data from CARIBIC I will be discarded. O_3 measurements are performed by an instrument custom-made by Karlsruher Institut für Technologie (KIT) that combines the use of two sampling techniques in one box; the chemiluminescence of a dye in reaction with O_3 and the absorption of the UV light by O_3. CO mixing ratios are provided, in CARIBIC II, by a custom-

150 improved version of the Aero-Laser Model AL 5002 fast-response UV resonance fluorescence instrument. Characteristics, precisions and uncertainties are also summarized in table 3 for both instruments. CARIBIC aircraft flight sequences are roughly every 30 to 60 days (depending on routes, aircraft availability and the availability of the instruments), therefore the need to have several spare units is less crucial compared with IAGOS and MOZAIC. Between each period of operation, all instruments can be maintained and redeployed for the next flight sequences.

Table 3. Summary of the CO and O_3 instrument characteristics. Maximum spatial resolutions are just indicative values and are given for civil aircraft approximated maximum ascent and descent speed of $15\,\text{ms}^{-1}$ and $250\,\text{ms}^{-1}$ during cruise.

Programs	Techniques		Detection limit; Uncertainties (accuracy; precision; integration time or frequency (f))		Maximum spatial resolutions (vertical ; horizontal)	
	O_3	CO	O_3	CO	O_3	CO
IAGOS-MOZAIC & IAGOS-CORE	UV absorption	IR correlation	2 ppbv; ± 2 ppbv; $\pm 2\%$; 4 sec	5 ppbv; ± 5 ppbv ; $\pm 5\%$; 30s	60m ; 1km	450m ; 7.5km
IAGOS-CARIBIC	combination of 2 instruments : dry chemiluminescence + UV absorption	resonance fluorescence in the vacuum UV	2ppbv; ± 2ppbv;$\pm 2\%$; down to 10hz	2ppbv;± 1ppbv for CO below 50ppbv, else $\pm 2\%$.; 1-2s	1.5m; 25m	15m; 250m

3 Standard operation procedures

3.1 MOZAIC and IAGOS

Before deployment, each measuring unit is cleaned and maintained by a subcontractor that holds an EASA Part 145 agreement[1] and according to the corresponding Components Maintenance Manual (CMM), the latter being an official traceable document in regard of the awareness safety rules. All the performed tasks are also traced within an CNRS internal QA/QC document opened for each new maintained unit. After maintenance, O_3 and CO from P1 and the MOZAIC instruments are calibrated in the laboratory in Toulouse by the CNRS. For O_3, it is performed by comparison with a Thermo-Scientific Model 49PS reference instrument at several concentration levels to also check the instrument linearity within 1%. The O_3 reference is sent once a year to the French Laboratoire National d'Essais (LNE) for comparison with a traceable National Institute of Standards and Technology (NIST) instrument. For CO, we use a NIST referenced CO cylinders (CO in N2, 500 ppmv) and a calibrated dilution system. Calibration is performed for several levels of CO to control the linearity of the instrument within 2%. The CO dilution system is also controlled every year by the French LNE for flow calibration. The last important step in the deployment process is the systematic comparison with a MOZAIC measuring system (identical to Figure 2) that was kept in the laboratory to serve as a reference. Comparisons tests are performed, usually at night, using outside ambient atmospheric air, to make sure that the maintained units are robust and that the measurement difference with the reference instrument remained below 2% for O_3 and 5% for CO. After these tests have been made, the units are sent to the airlines for a scheduled installation within standard 6 month of operating time or for an unscheduled replacement if one instrument failed prematurely. The shipping logistics for all IAGOS parts are handled by the IAGOS Maintenance Center (IMC, Enviscope GmbH, http://www.enviscope.de).

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[1]Certification to the European Commission Regulation standards of design, production, maintenance and operation of aircraft components.

The installation date of the unit (P1, PM O3 or PM CO) is reported in the QA/QC document as the start of Flight Period (FP) operation of the unit. The FP ends when the unit is removed from the aircraft. FPs do not depend on whether the instrument is

175 performing measurements successfully and during this period all instrument failures, main aircraft events, maintenance actions by airline staff on the IAGOS system, and any noticeable issues that could impact the O_3 and CO measurements are reported and traced in the QA/QC document within this time. FPs are named using the aircraft MSN, the units SN and the number of the FP (ex: FP0989-10-P1SN04 for operations FP number 10 of P1 serial number 04 on DLH D-AIKO MSN0989). To refer to the aircraft, the SN is used instead of the tail sign since aircraft can be sold to an other airline during its operating life. Also,

180 linked to the FP, instrument functional performances are reported and updated. This is usually done by flagging the functional parameters of the instrument according to previously defined thresholds of normally operating values.

After the six-month deployment on the aircraft, the instruments are returned to CNRS and the O_3 and CO instruments are calibrated and checked for drifts against the laboratory references. This is the last check before applying, if necessary, a correction to the data and to finally deliver the Level 2 (L2) data to the scientific community.

185 ## 3.2 CARIBIC

Because the container is set up aboard the aircraft for only a few flights, the scientific instruments inside undergo less constraints due to the take off and landings. Therefore frequent laboratory-based maintenance are not necessary and these are performed roughly every two months (about 8 flights). The O_3 instrument maintenance is done in KIT and mostly consists in performing leak tests cleaning, pressure tests and the replacement of chemiluminescence sensor disc. All the maintenance tasks are traced

190 filling out a maintenance list and shipping list before reintegration in the container. The functioning of the UV-photometer is controled each 4-6 months by comparison with a KIT custom-made laboratory O_3 instrument (using a Hg lamp as light source) and a long-path UV reference photometer (UMEG, GmbH) crosse-checked by the World Meteorological Organization standard reference photometer n°15 at the Swiss Federal Laboratories for Materials Science and Technology (EMPA) in Switzerland.

For the CO instrument, the main important maintenance corresponds to the change of the MgF_2 CO resonance lamp window

195 every 3 years in order to maintain a high photon transmission statistic. This task was performed for the first time in June 2008. More details can be found in the associated publication Scharffe et al. (2012).

4 The internal consistency of IAGOS measurements

4.1 Background

The strategy of the program is to expand the number of aircraft equipped with the IAGOS system and to get more airlines (ide-

200 ally, a minimum of 2 aircraft per Airline) involved in IAGOS. This has several advantages in addition to feed the atmospheric science community with data with more extensive global coverage. First, as maintenance actions can sometimes take weeks or months to be performed on a single aircraft, multiple aircraft are necessary to ensure the continuity of the time-series, which is particularly important for the studies of trends. Secondly, multiple aircraft offers the possibility to compare the different O_3

	Airports	# Comp.
1	Frankfurt	3068
2	Taipei	340
3	Paris	171
4	Munich	166
5	New York	121
6	Hong Kong	110
7	Atlanta	72
8	Osaka	45
9	Tokyo	29
10	Chicago	18
11	Bogota	14
12	Toronto	13
13	Boston	11
14	Sao Paulo	11
15	Lagos	11

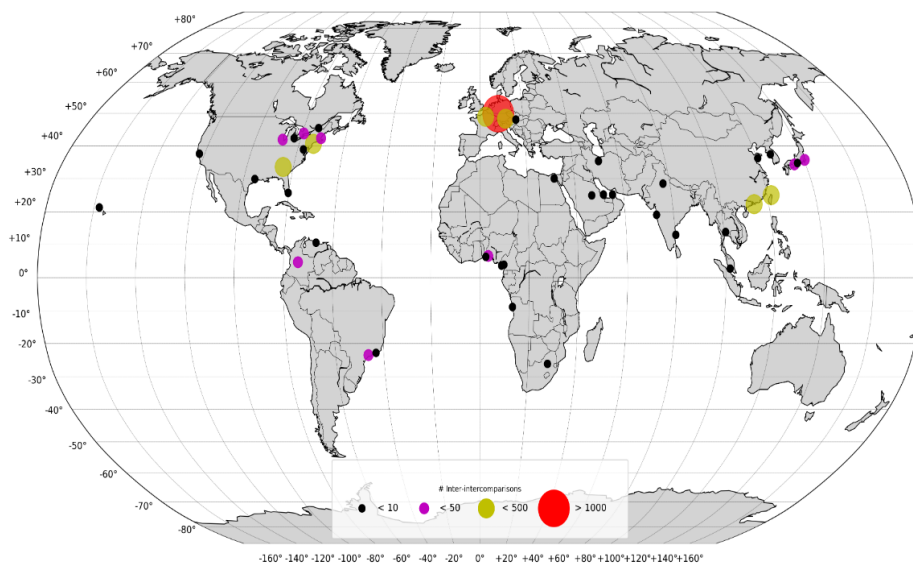



Figure 6. World-map showing the total number of profile flight inter-comparisons observed over airport cities since 1994 for the entire aircraft fleet. The criteria for the maximal time coincidence is 1 hour.

and CO instruments that are installed on each aircraft by looking at trajectory coincidences in time and space. During cruise
205   legs, trajectory coincidences (e.g. at least 2 aircraft that followed a quasi-identical route) are occasionally possible and are very useful in the data validation process. However they do no occur often enough to generate robust statistics. There are however, many more landings or take-offs, which fall within a maximum 1 hour time window and are suitable for inter-comparison (see figure 6). Lufthansa has been deeply involved in IAGOS with several equipped aircraft since the beginning of MOZAIC, and with several aircraft equipped. As such, there are more than 3000 collocated profiles. In Taipei, there are 340 and in Paris 171.
210   Airbus A330/A340 are long-haul aircraft which serve main international airports. The landing and take-off coincidences are not necessarily between aircraft of the same airline and more importantly, the mounted O_3 and CO instruments are dispatched randomly. Consequently, thanks to the large number of daily coincidences, it is possible to perform a quality control on the O_3 and CO measurements getting a fair idea on how each serial number instrument compared with the others according to some limitations inherent to the use of commercial aircraft, which are exposed in the following section.

215   ## 4.2   Methodology

4.2.1   MOZAIC and IAGOS

One of the main obvious limitations with the use of commercial aircraft as a scientific measuring platform is that air routes and departures/arrivals schedules are fixed by the airlines and, of course, strict airworthiness rules must be respected for the safety of the passengers. This implies explicitly that we can not have two aircraft flying too close from each other to perform proper
220   flight inter-comparison exercises as it is often the case for field campaigns using multiple research aircraft. Therefore, even

thought as shown in the section above, there can be several IAGOS aircraft landing or taking off at the same airport within a time difference less than 1 hours (sometimes less than 10 minutes), we can not expect that they follow the same routes and, consequently, that they always fly in the same physically and chemically steady air mass. It is also reasonable to not expect perfect 1:1 regression for the comparisons, however by choosing adequate screening criteria for air masses and flight track coincidences, it is possible to get a good estimate of the internal consistency of the instruments.

225

Figure 7 illustrates the method applied to each flight stored in the database at the CNRS server in Toulouse. We present the steps used for the operational phase of the QC procedure in the IAGOS program. All the data used in the following study are L2 final data provision (see also http://www.iagos-data.fr and Petzold et al. (2015) for details), which are the data that are distributed publicly. For each individual flight, a java script is triggered to look for any other flight in the database that has landed or taken off at the same airport within a time window of maximum 1 hour. Some examples of the testing phase of this procedure were presented in Nédélec et al. (2015). For each individual flight, a java script is triggered to look for any other flight in the database that has landed or taken off from the same airport within a time window of maximum 1 hour. Figure 7 shows an example with one aircraft equipped with the MOZAIC system and an one aircraft equipped with IAGOS system that both took off at Frankfurt airport on 2012/12/17 with only a 13 minutes time difference. As it is often the case, the two aircraft quickly headed to different destinations taking different routes. After only few minutes, the distance between the two tracks can be several hundred kilometers. The profiles of O3 and CO measured by these two aircraft are plotted in Figure 7c. The curves do not refer to the name of the aircraft but to the serial number of the O_3 or CO instrument for MOZAIC or the serial number for package 1 in the case of IAGOS. In this specific example, the MOZAIC aircraft is mounted with the O_3 instrument serial number 03_{PM} and CO instrument serial number 04_{PM} that are compared with the IAGOS package 1 serial number 03. On these two figures, grey horizontal lines indicate where the air masses encountered by the two aircraft present similar characteristics considering the potential temperature (T), the wind direction (WindDir) and the potential vorticity (PV). The wind direction and the temperature are measured directly by the aircraft sensors (see Table 1). The atmospheric pressure and the absolute temperature are also measured directly by the aircraft and are used to derive the potential temperature. The potential vorticity (PV), which is often used to approximate the position of the dynamical tropopause that separates the upper troposphere from the stratosphere (Holton et al., 1995), is taken from the ECMWF operational analyses and evaluated at the aircraft position (Sauvage et al., 2017) by the FLEXible PARTicle dispersion model (FLEXPART, Stohl et al. (2005)). Threshold values for the maximum differences at equal barometric altitude of these screening parameters are summarized in the table Figure 7b. These were found to provide a good compromise compared with very restrictive criteria that would reduce considerably the number of comparable points. To prevent the influence of highly variable mixing ratios due to local sources of pollution within the boundary layer, a lower altitude limit is also set to 2 km.

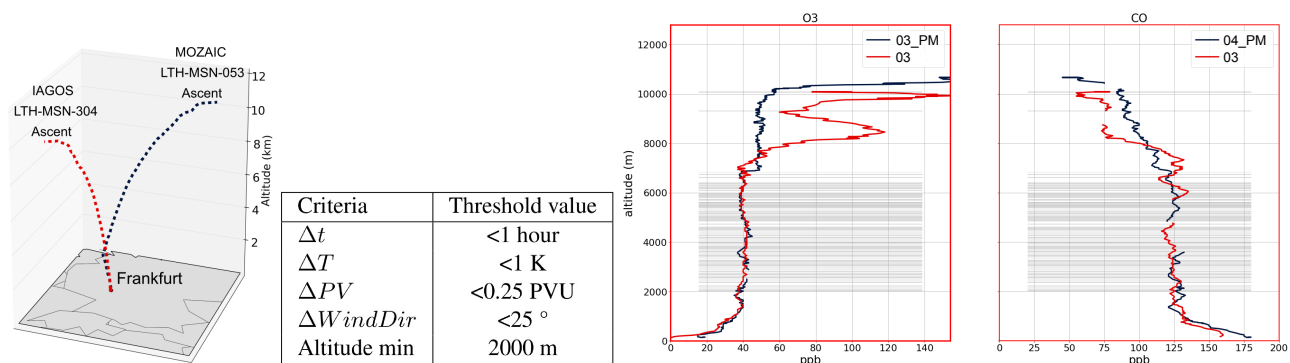
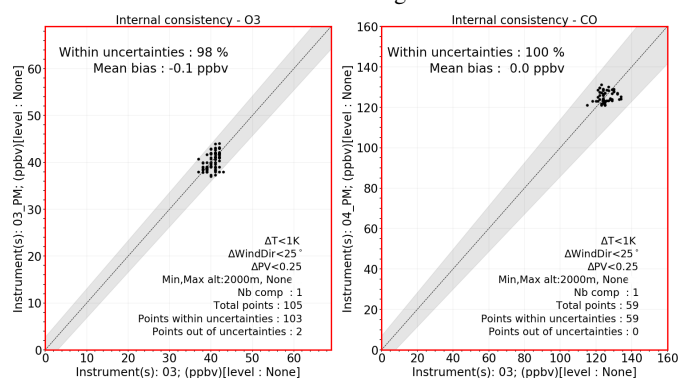
Figure 7d shows the scattergram plot produced with the measurements made from the two aircraft and resulting from the air mass filtering process (the points highlighted by the grey horizontal lines in Figure 7c). The grey area represent the quadratic sum of the total uncertainties for each instruments. Since all O_3 and CO instruments for MOZAIC and IAGOS have the same characteristics, the grey zone, represents the area between $C \pm \sqrt{(2*\Delta C)^2}$ where C is the measured mixing ratio and ΔC is the total uncertainty of the measurements. These scattergram plots are produced routinely for each flight and at each validation

(a) Aircraft ascent tracks. (b) Air mass screening criteria. (c) O$_3$ (left) and CO (right) measurement inter-comparison profiles between the Package MOZAIC (black) and IAGOS Package 1 (red) instruments. Grey lines correspond to the air masses matching according to the criteria in figure 7b. Instrument serial number are indicated in the legend.

(d) O$_3$ (left) and CO (right) scattergram plots comparing measurements from MOZAIC instrument (ordinate) and the IAGOS instrument (Abscissa). Dotted line is the 1:1 line, Grey area displays the total uncertainty for both instruments. Statistic information are also displayed for each components (see text).

Figure 7. O$_3$ and CO profile inter-comparisons on 2012/12/17 between MOZAIC Luthansa msn-053 and IAGOS Luthansa msn-304. Both aircraft ascent from Frankfurt airport within a 13 minutes time interval. The MOZAIC aircraft is equipped with the instrument unit serial number 03_{PM} for O$_3$ and 04_{PM} for CO. The Package 1 mounted on the IAGOS aircraft is serial number 03.

step through the process of data validation. Besides plotting the 1:1 line and the associated uncertainty, 2 main key performance indicators are calculated. The first is the bias between the compared instruments. It is the mean of the distance from the 1:1 line for every points. The second is more an indication of the dispersion by calculating the percent of measurements that remain within the total instrument uncertainties. This is obtained if each compared measurement agrees with :

$$\frac{\mid C_{SN_{abscissa}} - C_{SN_{ordinates}} \mid}{\sqrt{(\Delta C_{SN_{abscissa}})^2 + (\Delta C_{SN_{ordinates}})^2}} \leq 1 \tag{1}$$

As it can be noted, the inter-comparison plots chosen here, in Figure 7, correspond to an ideal case study. For O_3, instrument 03_{PM} measurements do not differ from P1 serial number 03 (mean bias almost zero) and 98% of the points are within measurement uncertainties. For CO, instrument 04_{PM} the result is even better.

However, the information that we really want to reach for the internal consistency is how each instrument performed globally through its entire flight period compared with other instruments flying during coincident periods. For example, CO MOZAIC instrument 04_{PM} of Figure 7 was installed on the Lufthansa A340 SN53 on December 2012 for a flight period that last 448 days in total. It was the thirteenth time (FP n°13) that a CO instrument was operated on this aircraft. During this operating time, 187 flights were found within a 1 hour time window and 12121 points were found to be comparable according to the air mass similarity criteria. Figure 8 shows the scattergram plot that compiles all the available data for this flight period. On the abscissa, the serial numbers of all the CO instruments that were compared to 04_{PM} are highlighted. As it can be noted, the performance indicators present globally a very good score with a bias of -0.7 ppbv and 89% of the points within the total measurements uncertainties. Consequently, it can be stated confidently that the CO measurements of 04_{PM} on Lufthansa Airbus SN53 for FP n°13 present, on average, a negligible bias compared with the other instruments and in regard to the measurement uncertainties.

This methodology is applied to each of the MOZAIC and IAGOS instruments that flew on the IAGOS fleet, for all flight periods since 1994 and for which data were delivered as L2 to the scientific community. The results are gathered in Table 4 and 5 and a summary study is exposed in section 5.

4.2.2 CARIBIC versus MOZAIC/IAGOS

The flight period clustering concept described above can not be applied to evaluate the performance of the CARIBIC measurements compare with those from IAGOS and MOZAIC because CARIBIC operates for only days every couple of months and therefore there are too few flight inter-comparisons per period (maximum 1 or 2 per flight sequences). However, if we apply the method considering the whole CARIBIC operation since 2005 until now, we found 101 and 114 flight inter-comparisons for O_3 and CO, respectively, with, in total, 7254 and 7286 points of comparisons and the vast majority of these profile coincidences where found over Frankfurt airport until 2014, period before DLH moved the aircraft to Dusseldorf as home airport. Frankfurt has remained the home base of all other MOZAIC and IAGOS aircraft. The performances indicators results for CARIBIC are also presented in section 5.

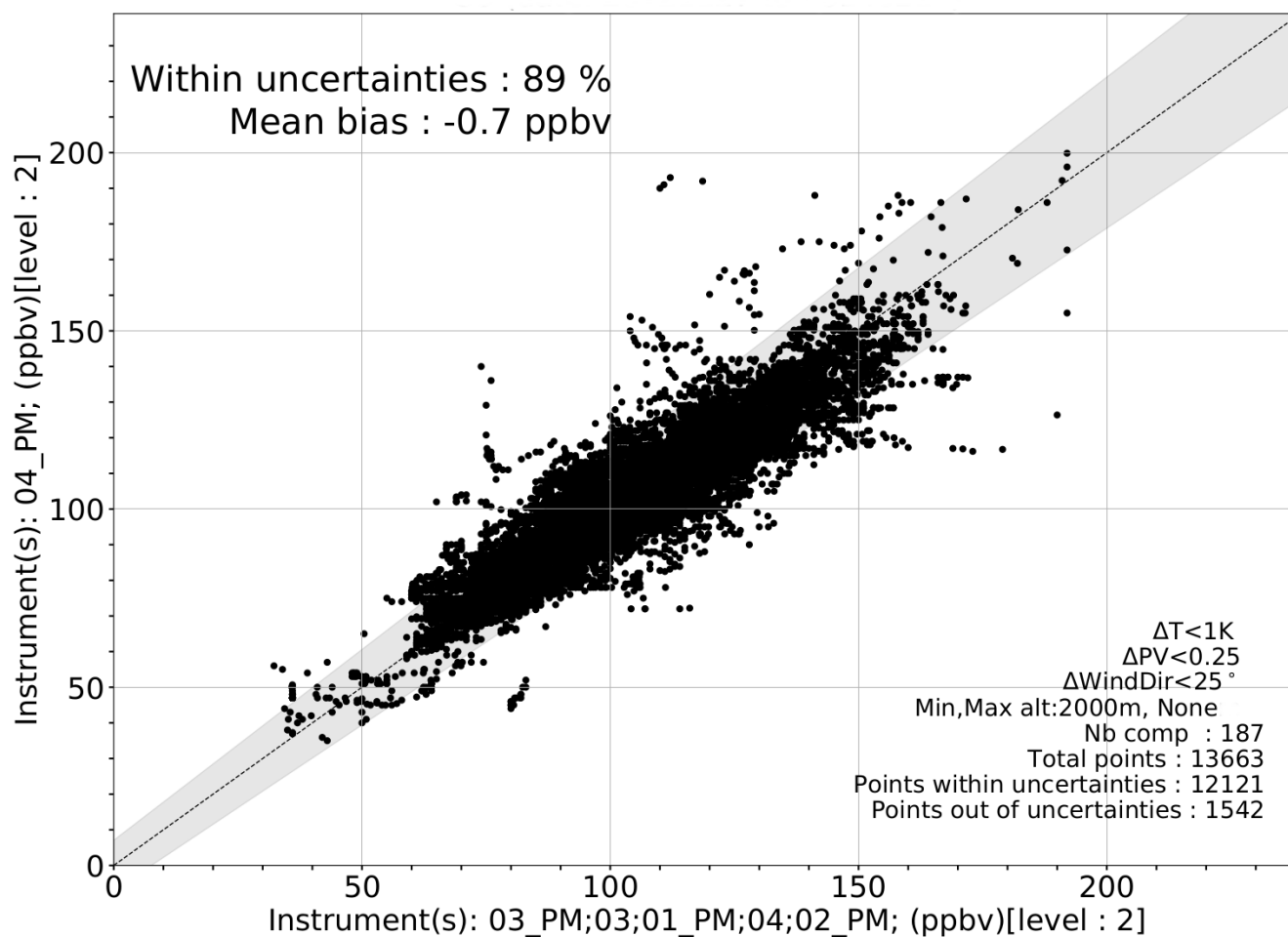



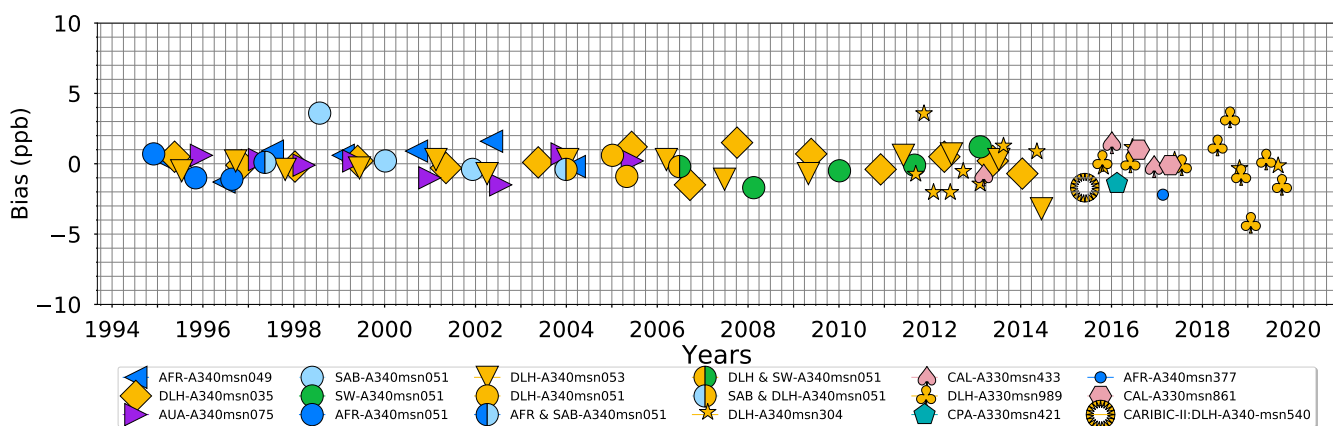
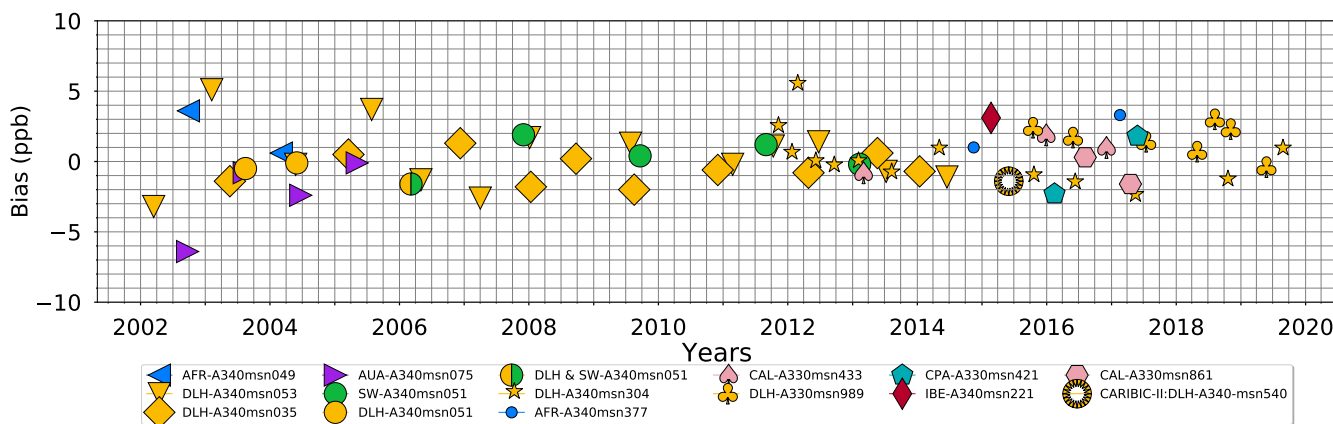
Figure 8. Scattergram plot compiling all the flight-intercomparisons found for CO MOZAIC instrument serial number 04_{PM} for the flight period number 13 on Lufthansa A340 msn53. The grey area represents the total measurement uncertainty. Statistic scores are presented in the figure legend.

(a) O₃

(b) CO

Figure 9. Internal consistency of the long-term O₃ (a) and CO (b) measurement time-series within the IAGOS program. Different symbols are used to differentiate the aircraft and different colors are used for each airline. Symbol positions show the flight inter-comparison measurement mean bias for an intrument FP centered at the middle of the period. For CARIBIC, the symbol is position arbitrarily on the time scale (see text).

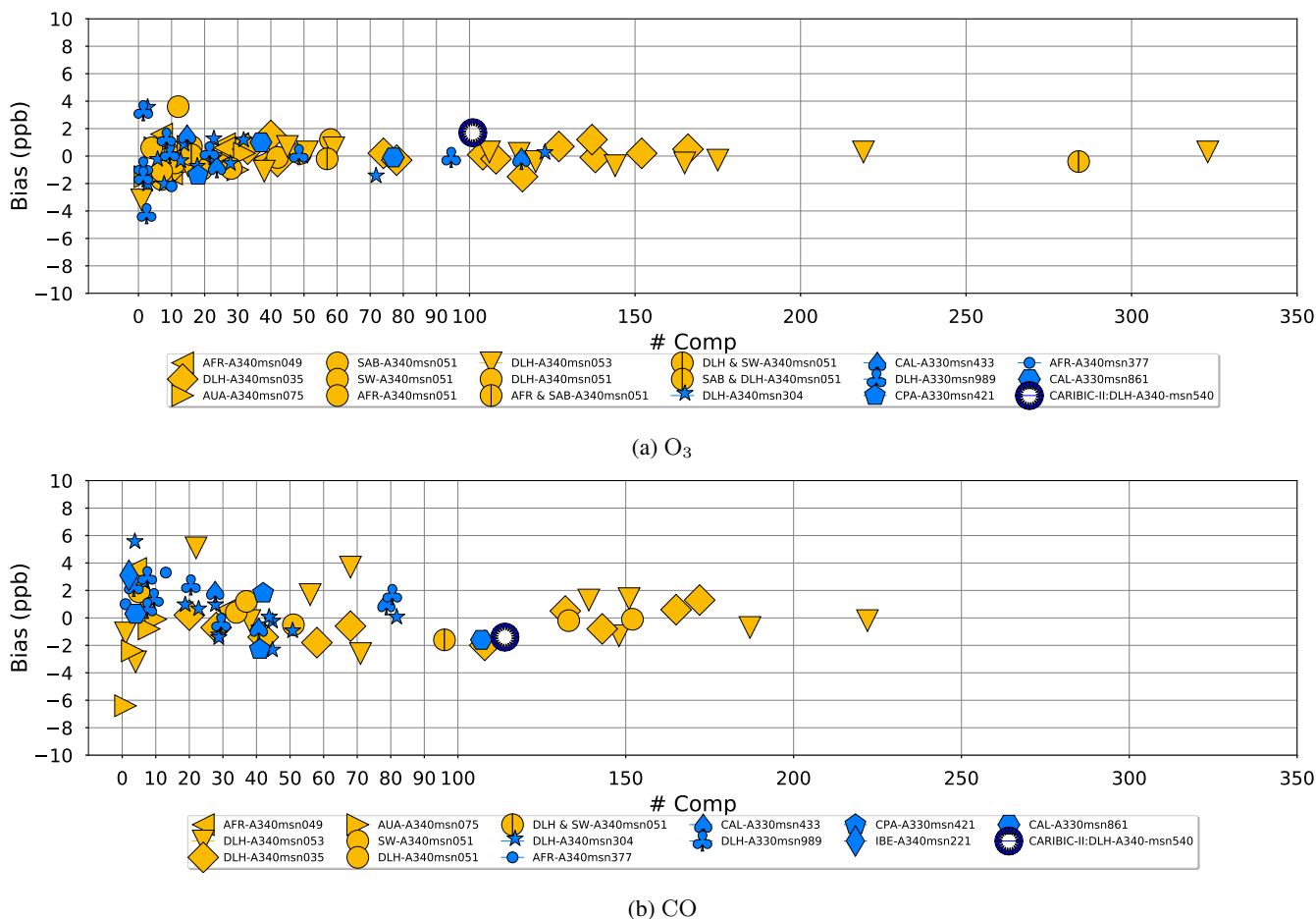



Figure 10. Dependency of the O_3 (a) and CO (b) instrument measurement mean bias for each FP with the number of flight inter-comparison profiles. Different symbols are used for each distinct aircraft (same as Figure 9), the yellow color is for the MOZAIC program and the blue color is for IAGOS and CARIBIC.

5   Results

The results presented in Figure 9 and Figure 10 constitute the milestone of this study and more generally for the QA/QC process within the IAGOS program. It synthesizes the statistics gathered in Tables 4 and 5 and the outcomes of the methodology presented in section 4 applied to every O_3 and CO instrument that flew aboard every MOZAIC, IAGOS and CARIBIC aircraft.

290   Figure 9 presents the time-series of the O_3 and CO mean Bias for all the instrument FPs from 1994 to 2020. For more clarity, the choice was made to cluster the results from each instrument's FP and for each aircraft's MSN. Different symbols are assigned to distinguish different aircraft and a color is assigned for each different airline. Individual symbols represent the mean bias of each instrument compared with the others within their relative FP, excepted for CARIBIC (see section 4.2.2). For O_3, it is easily noticeable on Figure 9 that the large majority of the symbols (including CARIBIC) remain within ± 2 ppbv, which is

295   the accuracy of the O3 Package 1 and Package MOZAIC instruments, and that symbols are homogeneously distributed around
0 ppbv throughout the entire IAGOS time-series since 1994. The same results are evident for CO in Figure 9b with most of
the symbols falling within the accuracy of the CO instruments (i.e. +- 5ppbv), and the symbols are homogeneously distributed
around 0 ppbv. Figure 10 differs from the previous one by showing the mean bias of the O3 and CO instruments according
to the number of profiles that fit the criterium described in section 4.2 for each instrument's FP since 1994. Each symbol
300   is also associated with a distinct aircraft MSN, however only the colours yellow and blue are used in this Figure in order to
differentiate the aircraft equipped with the Package MOZAIC and the IAGOS Package 1 (CARIBIC has its own deep blue round
open circle). Figure 10 highlights that instrument mean bias greater than ± 2 ppbv and ± 5 ppbv for O3 and CO, respectively,
are related to a low number of profiles that fit the criteria for the comparison (less than about 10) per FP. This is due to 3 main
reasons: 1. if an airline has at least 2 of their aircraft equipped with the system, the number of flight coincidences might be
305   reduced if one system isn't working properly for a long period of time. 2. if the equipped aircraft are located in different home
hub. 3. if only one aircraft is equipped by that airline there will be fewer fight coincidences. The coincidences depend on the
aircraft schedules which are not controlled by IAGOS. IAGOS therefore tries to equip more than one aircraft per airline. An
other important result shown by Figure 10 is that the internal consistency of the MOZAIC and IAGOS instruments are similar.
This result offers assurances that despite the differences in instrumentation since IAGOS began in 1994, the database of O3
310   and CO measurements can be considered homogeneous.

6   Conclusions

As pointed out in Tarasick et al. (2019), a lack of information on temporal changes in measurements uncertainties is an area
of concern especially for long-term trend studies of the key compounds which have a direct or indirect impact on climate
change. The IAGOS program (including MOZAIC and CARIBIC) has measured O_3 and CO within troposphere and Lower
315   stratosphere for more than 25 years and represents the longest airborne time-series for these two gases with a large coverage
in time and space, particularly in the northern hemisphere. Since 1994, the aircraft instrument setup has evolved to changing
aeronautical regulations but much care was taken to keep the consistency of the measurement over time. This was achieved by
using the same robust and well-recognized technologies based on UV absorption and IR correlation for O_3 and CO and by
following the the same calibration procedures from the beginning to now.
320   In this study, thanks to many flight profile coincidences to compare the measurements made by different IAGOS aircraft, we
demonstrated that the O_3 and CO data, despite the change of instrument setup over time, present no drifts in bias over time.
The study highlights the needs for the IAGOS program to increase the size of the fleet with at least 2 aircraft per airlines not
only to increase the density of the measurement worldwide but also to be able to monitor closely the performances of each
instrument unit mounted on-board.

325   *Data availability.*   Boulanger, D., Thouret, V., Petzold, A. (2019). IAGOS Data Portal. Aeris. https://doi.org/10.25326/20

Table 4. Table compiling all the MOZAIC and IAGOS flight inter-comparisons O_3 measurement statistics and information for each instrument FPs. The latters are gathered and enumerated per aircraft. "Start date" is the date of the instrument unit installation on the aircraft (start of the flight period). "instr. serial" is the serial number of the instrument unit. "duration" is the lenght of the flight period in days. "mean bias" and "% consistency", see section 4.2 for explanation. "# comparisons" and "# points' are the number of collocated profiles and collocated data points found according to the methodology described in section 4.2.

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MOZAIC Lufthansa A340 MSN-035

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8	FP n°9	FP n°10
start date:	2002/06/04	2004/05/04	2006/02/01	2007/10/18	2008/04/07	2009/03/11	2010/01/24	2011/10/10	2012/11/13	2013/11/26
instr. serial:	02_PM	06_PM	01_PM	02_PM	03_PM	04_PM	03_PM	02_PM	01_PM	02_PM
duration (days):	700	638	624	172	338	319	624	400	378	98
mean bias	-1.4	0.5	1.3	-1.8	0.2	-2.0	-0.6	-0.8	0.6	-0.7
% consistency:	76	79	82	84	87	65	82	82	87	90
# comparisons:	42	132	172	58	20	108	68	143	165	28
# points:	3431	13544	19708	5159	1611	11344	6215	12187	13418	2351

MOZAIC Air France MSN-049

field	FP n°1	FP n°2	FP n°3
start date:	2001/04/30	2002/02/05	2003/05/21
instr. serial:	03_PM	04_PM	01_PM
duration (days):	282	470	578
mean bias		3.6	0.6
% consistency:		67	88
# comparisons:	0	4	31
# points:		152	3655

MOZAIC Multiple MSN-051

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8
start date:	2003/02/10	2003/04/23	2003/12/09	2004/11/22	2007/06/20	2008/05/14	2011/01/26	2012/04/05
instr. serial:	01_PM		05_PM	03_PM	04_PM	02_PM	04_PM	03_PM
airline:	SAB & DLH	Lufthansa	Lufthansa	DLH & SW	Air Namibia	Air Namibia	Air Namibia	Air Namibia
duration (days):	73	230	349	940	329	987	435	621
mean bias		-0.5	-0.1	-1.6	1.9	0.4	1.2	-0.2
% consistency:		79	89	78	86	68	80	83
# comparisons:	0	51	152	96	5	34	37	133
# points:		4144	20181	10323	435	2310	4042	11236

MOZAIC Lufthansa MSN-053

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8	FP n°9	FP n°10	FP n°11	FP n°12	FP n°13	FP n°14
start date:	2001/11/27	2002/07/04	2002/09/17	2003/06/29	2005/04/21	2005/11/03	2006/10/29	2007/09/04	2008/05/08	2010/10/17	2011/07/04	2012/01/18	2012/11/27	2014/02/18
instr. serial:	06_PM	03_PM	05_PM	04_PM	01_PM	04_PM	02_PM	06_PM	01_PM	05_PM	01_PM	05_PM	04_PM	05_PM
duration (days):	218	76	285	662	196	360	310	247	892	260	198	314	448	238
mean bias	-3.2		5.1	-0.2	3.7	-1.3	-2.6	1.7	1.3	-0.2	1.1	1.4	-0.7	-1.1
% consistency:	68		69	87	79	83	83	84	67	90	7	81	89	100
# comparisons:	4	0	22	229	68	148	71	56	139	38	7	81	151	1
# points:	148		2119	24066	7880	14747	9309	4934	14454	4017	605	12873	13663	86

MOZAIC Austrian MSN-075

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8	FP n°9
start date:	2002/02/04	2002/07/10	2002/12/09	2003/01/13	2004/03/04	2004/10/12	2005/12/02	2006/01/23	2006/05/12
instr. serial:	05_PM	06_PM	03_PM	06_PM	03_PM	02_PM	01_PM	02_PM	06_PM
duration (days):	157	151	36	416	222	415	52	109	171
mean bias		-6.4		-0.8	-2.4	-0.1			
% consistency:		63		80	88	78			
# comparisons:	0	1	0	8	3	10	0	0	0
# points:		269		777	524	792			

IAGOS Iberia MSN-221

field	FP n°1	FP n°2
start date:	2014/02/27	2016/02/17
instr. serial:	07_PM	05_PM
duration (days):	718	191
mean bias	3.1	
% consistency:	97	
# comparisons:	2	0
# points:	186	

IAGOS Lufthansa MSN-304

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8	FP n°9	FP n°10	FP n°11	FP n°12	FP n°13	FP n°14	FP n°15
start date:	2011/07/07	2011/10/04	2011/12/12	2012/02/08	2012/04/04	2012/07/12	2012/10/29	2013/05/29	2013/12/08	2014/09/02	2015/03/30	2016/04/13	2016/07/08	2018/02/22	2019/05/18
instr. serial:	03	03	03	03	03	02	03	03	03	04	03	04	03	02	09
duration (days):	90	43	58	7	99	109	164	115	266	209	380	86	594	450	171
mean bias		2.4	0.5	5.4	-0.1	-0.4	-0.1	-0.9	0.8		-1.1	-1.6	-2.5	-1.4	0.8
% consistency:		71	79	60	86	85	87	82	90		89	82	77	87	91
# comparisons:	0	6	22	3	43	44	81	40	27	0	50	28	44	28	18
# points:		736	1804	247	4293	4236	7339	2969	2142		4329	2710	3216	2462	1742

IAGOS Air France A340-313 MSN-377

field	FP n°1	FP n°2
start date:	2013/06/13	2016/04/19
instr. serial:	02	11
duration (days):	1040	609
mean bias	1.0	3.3
% consistency:	100	63
# comparisons:	1	13
# points:	66	1392

IAGOS Cathay Pacific MSN-421

field	FP n°1	FP n°2
start date:	2013/08/01	2014/05/31
instr. serial:	06	05
duration (days):	303	347
# comparisons:	0	0

IAGOS China Airlines MSN-433

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5
start date:	2012/06/21	2014/06/18	2014/12/17	2015/07/23	2016/05/10
instr. serial:	04	08	09	08	09
duration (days):	485	182	218	292	388
mean bias	-0.8			1.9	1.0
% consistency:	82			65	62
# comparisons:	40	0	0	27	78
# points:	2978			4232	6987

IAGOS China Airlines A330-302 MSN-861

field	FP n°1	FP n°2	FP n°3	FP n°4	FP n°5	FP n°6	FP n°7	FP n°8	FP n°9
start date:	2016/07/06	2016/09/05	2016/01/13	2016/09/24	2016/11/19	2018/02/22	2018/06/16	2018/09/10	2018/12/12
instr. serial:	14	16	10	08	04	09	15	04	11
duration (days):	61	449	255	56	459	114	86	93	63
mean bias	0.3	-1.6	1.7		1.4	0.7	3.0	2.3	
% consistency:	90	61	87		98	90	72	98	
# comparisons:	4	107	88	0	9	7	7	3	0
# points:	463	10330	6383		639	431	837	366	

IAGOS Lufthansa MSN-989

field	FP n°1	FP n°2	FP n°10	FP n°11	FP n°12	FP n°13
start date:	2015/03/08	2015/07/01	2019/02/13	2019/08/16	2019/10/24	2020/02/13
instr. serial:	10	04	04	16	07	04
duration (days):	115	196	184	69	112	77
mean bias		2.4	-0.4			
% consistency:		86	93			
# comparisons:	0	20	29	0	0	0
# points:		1658	2573			

Table 5. Same as Table 4 but for CO

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