C3S Greenhouse Gas (GHG: MTCO2 v10.1 & MTCH4 v10.2): Product Quality Assessment Report (PQAR)

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History of modifications

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Product Version	Issue	Date	Description of modification	Chapters / Sections
MTCO2 v10.1, MTCH4 v10.2	1	19-November-2024	New document	All
MTCO2 v10.1, MTCH4 v10.2	2	12-May-2025	Updated following revision of independent reviewers	All
MTCO2 v10.1, MTCH4 v10.2	3	28-August-2025	Minor adjustments after independent review and finalisation for publication	All

List of datasets covered by this document

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Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP1-DDP-GHG-v1	MTCO2_OBS4MIPS	CDR	10.1	31-Oct-2024
WP1-DDP-GHG-v1	MTCH4_OBS4MIPS	CDR	10.2	31-Oct-2024

Acronyms

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Acronym	Definition
AMSU	Advanced Microwave Sounding Unit
ATBD	Algorithm Theoretical Basis Document
BESD	Bremen optimal EStimation DOAS
CAR	Climate Assessment Report
C3S	Copernicus Climate Change Service
CCDAS	Carbon Cycle Data Assimilation System
CCI	Climate Change Initiative
CDR	Climate Data Record
CDS	(Copernicus) Climate Data Store
CMUG	Climate Modelling User Group (of ESA's CCI)
CRG	Climate Research Group
D/B	Data base
DOAS	Differential Optical Absorption Spectroscopy
EC	European Commission
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
EMMA	Ensemble Median Algorithm
ENVISAT	Environmental Satellite (of ESA)
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FoM	Figure of Merit
FP	Full Physics retrieval method
FTIR	Fourier Transform InfraRed
FTS	Fourier Transform Spectrometer
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GHG	GreenHouse Gas
GOS	GOSAT
GO2	GOSAT-2
GOME	Global Ozone Monitoring Experiment
GMES	Global Monitoring for Environment and Security
GOSAT	Greenhouse Gases Observing Satellite

GOSAT-2	Greenhouse Gases Observing Satellite 2
IASI	Infrared Atmospheric Sounding Interferometer
IMAP-DOAS (or IMAP)	Iterative Maximum A posteriori DOAS
IPCC	International Panel in Climate Change
IUP	Institute of Environmental Physics (IUP) of the University of Bremen, Germany
JAXA	Japan Aerospace Exploration Agency
JCGM	Joint Committee for Guides in Metrology
L1	Level 1
L2	Level 2
L3	Level 3
L4	Level 4
LMD	Laboratoire de Météorologie Dynamique
MACC	Monitoring Atmospheric Composition and Climate, EU GMES project
MT	Mid-tropospheric
NA	Not applicable
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Format
NDACC	Network for the Detection of Atmospheric Composition Change
NIES	National Institute for Environmental Studies
NIR	Near Infra Red
NLIS	LMD/CNRS *neuronal* network mid/upper tropospheric CO2 and CH4 retrieval algorithm
NOAA	National Oceanic and Atmospheric Administration
Obs4MIPs	Observations for Climate Model Intercomparisons
OCFP	OCO-2 Full Physics (FP) algorithm (used by Univ. Leicester)
OCO	Orbiting Carbon Observatory
OCPR	OCO-2 Proxy (PR) algorithm (used by Univ. Leicester)
ODR	Orthogonal Distance Regression
OE	Optimal Estimation
PBL	Planetary Boundary Layer
ppb	Parts per billion
ppm	Parts per million
PQAD	Product Quality Assurance Document
PQAR	Product Quality Assessment Report
PR	(light path) PRoxy retrieval method
PVIR	Product Validation and Intercomparison Report
QA	Quality Assurance
QC	Quality Control
RemoTeC	Retrieval algorithm developed by SRON
REQ	Requirement
RMS	Root-Mean-Square
RTM	Radiative transfer model
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY
SCIATRAN	SCIAMACHY radiative transfer model

SRON	SRON Netherlands Institute for Space Research
SRFP	SRON's Full Physics (FP) algorithm (also referred to a RemoTeC FP)
SRPR	SRON's Proxy (PR) algorithm (also referred to a RemoTeC PR)
SWIR	Short Wava Infra Red
TANSO	Thermal And Near infrared Sensor for carbon Observation
TANSO-FTS	Fourier Transform Spectrometer on GOSAT
TANSO-FTS-2	Fourier Transform Spectrometer on GOSAT-2
TBC	To be confirmed
TBD	To be defined / to be determined
TCCON	Total Carbon Column Observing Network
TIR	Thermal Infra Red
TR	Target Requirements
TRD	Target Requirements Document
WFM-DOAS (or WFMD)	Weighting Function Modified DOAS
UoL	University of Leicester, United Kingdom
URD	User Requirements Document
WMO	World Meteorological Organization
XGHG	Column-averaged GHG products (here: XCO_2 and XCH_4)
Y2Y	Year-to-year (bias variability)

General definitions

Essential climate variable (ECV): An ECV is a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate (Bojinski et al., 2014).

Climate data record (CDR): The US National Research Council (NRC) defines a CDR as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change (National Research Council, 2004).

Fundamental climate data record (FCDR): A fundamental climate data record (FCDR) is a CDR of calibrated and quality-controlled data designed to allow the generation of homogeneous products that are accurate and stable enough for climate monitoring.

Thematic climate data record (TCDR): A thematic climate data record (TCDR) is a long time series of an essential climate variable (ECV) (Werscheck, 2015).

Intermediate climate data record (ICDR): An intermediate climate data record (ICDR) is a TCDR which undergoes regular and consistent updates (Werscheck, 2015), for example because it is being generated by a satellite sensor in operation.

Satellite data processing levels: The NASA Earth Observing System (EOS) distinguishes six processing levels of satellite data, ranging from Level 0 (L0) to Level 4 (L4) as follows (Parkinson et al., 2006).

L0	Unprocessed instrument data
L1A	Unprocessed instrument data alongside ancillary information
L1B	Data processed to sensor units (geo-located calibrated spectral radiance and solar irradiance)
L2	Derived geophysical variables (e.g., XCO_2) over one orbit
L3	Geophysical variables averaged in time and mapped on a global longitude/latitude horizontal grid
L4	Model output derived by assimilation of observations, or variables derived from multiple measurements (or both)

Absolute systematic error or systematic error: Component of measurement error that in replicate measurements remains constant or varies in a predictable manner. Note that "systematic error" refers to the absolute systematic error (in contrast to "relative systematic error" defined below). For satellite GHG ECV products especially the relative systematic error is important.

Relative systematic error, relative accuracy or relative bias: Identical with "Systematic error" but after bias correction and without considering a possible global offset (overall mean bias). Reflects the importance of spatially and temporally correlated errors (spatio-temporal biases). Computed from standard deviations of spatial and temporal biases.

Bias: Estimate of a systematic measurement error.

Precision: Measure of reproducibility or repeatability of the measurement without reference to an international standard so that precision is a measure of the random and not the systematic error. Suitable averaging of the random error can improve the precision of the measurement but does not establish the systematic error of the observation (CMUG-RBD, 2012).
Note: Precision is quantified with the standard deviation (1-sigma) of the error distribution.

Stability: Term often invoked with respect to long-term records when no absolute standard is available to quantitatively establish the systematic error - the bias defining the time-dependent (or instrument-dependent) difference between the observed quantity and the true value (CMUG-RBD, 2012).
Note: Stability requirements cover inter-annual error changes. If the change in the average bias from one year to another is larger than the defined values, the corresponding product does not meet the stability requirement.

Representativity: Extent to which an average of a set of measured values corresponds to the true average, e.g., over a grid cell. It is important when comparing with or assimilating in models. Measurements are typically averaged over different horizontal and vertical scales compared to model fields. If the measurements are smaller scale than the model it is important. The sampling strategy can also affect this term (CMUG-RBD, 2012).

Threshold requirement: The threshold is the limit at which the observation becomes ineffectual and is not of use for climate-related applications (CMUG-RBD, 2012).

Goal requirement: The goal is an ideal requirement above which further improvements are not necessary (CMUG-RBD, 2012).

Breakthrough requirement: The breakthrough is an intermediate level between the "threshold" and "goal" requirements, which - if achieved - would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view when planning or designing observing systems (CMUG-RBD, 2012).

Horizontal resolution: Area over which one value of the variable is representative of (CMUG-RBD, 2012).

Vertical resolution: Height over which one value of the variable is representative of. Only used for profile data (CMUG-RBD, 2012).

Observing Cycle (or **Revisit Time**): Temporal frequency at which the measurements are required (CMUG-RBD, 2012).

Averaging kernel: Vertical sensitivity of the retrieval to greenhouse gas mixing ratios.

Executive summary

This document is a Product Quality Assessment Report (PQAR) generated in the framework of the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/). For C3S a large number of satellite-derived Essential Climate Variable (ECV) data products are generated and made available via the Copernicus Climate Data Store (CDS, https://cds.climate.copernicus.eu/).

This document describes the quality for two satellite-derived atmospheric carbon dioxide (CO_2) and methane (CH_4) C3S data products, v10.2 MTCO2_OBS4MIPS and v10.1 MTCH4_OBS4MIPS. These two products are mid-tropospheric-averaged air mixing ratios (mole fractions) of CO_2 and CH_4 products from observations made by Infrared Atmospheric Sounding Interferometer (IASI) and Advanced Microwave Sounding Unit-A (AMSU-A) instruments onboard the European Metop-A (July 2006-August 2021), Metop-B (since February 2013) and Metop-C (since May 2019) platforms (for more details, see MTGHG ATBD, 2024). The IASI hyperspectral observations in the thermal infrared at 7.7 µm for CH_4 and at 15 µm for CO_2 are sensitive to both temperature and gas concentrations of CH_4 / CO_2. These are used in conjunction with microwave observations form the AMSU-A instrument, which is only sensitive to temperature. These AMSU-A observations are used to decorrelate temperature variations from CO_2/CH_4 variations in the infrared radiance detected by IASI (Crevoisier et al., 2009a, 2009b, 2013).

The MTCO2_OBS4MIPS and MTCH4_OBS4MIPS products are merged multi-sensor MT-CO_2 and MT-CH_4 Level 3 (L3) products with daily time and 1^ox1^o spatial resolution generated using all available individual satellite sensor Level 2 (L2) products from Metop-A, -B and -C.

Validation is performed over a full suite of reference data: mixing ratios measured by aircraft, as well as mixing ratio profiles acquired by balloon-borne AirCore air samplers. Among these data, although limited to a few years, only the latter allows for a full validation of the mid-tropospheric column that can be derived from IASI observation. The aircraft network is used to evaluate long-term trends and latitudinal variations of the products.

The user requirements are listed in the Target Requirement and Gap Analysis Document (TR-GAD GHG, 2024). They are based on requirements as formulated in documents GCOS-154, GCOS-195, GCOS-200, GCOS-245 and CMUG-RBD, 2012.

1. Product validation methodology

Validation against high precision / low systematic errors reference observations is required for the mid/upper troposphere CO_2 and CH_4 data products. Unfortunately, measurements of both gases in the free troposphere and stratosphere are very sparse. Validation thus mostly relies on existing surface, aircraft and airborne measurements.

1.1. Description of reference data used for validation

1.1.1. Balloon-borne atmospheric samplers: AirCores

Balloon-borne air samplers AirCore give access to 0-30 km profiles of atmospheric mixing ratios of both CO_2 and CH_4 (Karion et al., 2010; Membrive et al., 2017). Averaging kernels can be applied to derive columns that can then be compared to those derived from space-borne observations. So far, only a few hundred profiles have been acquired, all in the northern hemisphere. In this validation exercise, use is made of CH_4 profiles extrapolated with the Copernicus Atmosphere Monitoring Service's (CAMS) profiles (version reanalysis “hb0k”) from all stations operated by European teams for which data are available: three stations located in France where monthly measurements are made in the framework of the French AirCore program (Aire-sur-l'Adour, Trainou, Reims), and two stations also managed by the French AirCore team (Timmins, Ontario, Canada and Kiruna in Sweden). Additional profiles acquired through a cooperation with the Finnish Meteorological Institute come from Sodankylä. Spanning 2014-2023, they are used to validate Metop-A, Metop-B and Metop-C retrievals. An example of AirCore methane profile is given in Figure 1 and the site locations are shown in Figure 2.

L3 MT-CO_2 Obs4MIPs products cover tropical airmasses, typically between 30°S to 30°N. Regular AirCore measurements are performed mostly over mid-latitudes in the Northern hemisphere where MT-CO_2 retrievals are not available. That is why there is no comparison between AirCores and MT-CO_2.

For the comparison, all L3 MT-CH_4 products falling in a 5°x5° grid cell centered on each AirCore profile for the same day are averaged. For that, the averaging kernel of each selected L3 MT-CH_4 is applied on the CH_4 profiles provided by the AirCore to obtain an AirCore IASI-like MT-CH_4. The averaging kernels are defined on the Thermodynamic Initial Guess Retrieval (TIGR) pressure grid (provided in the L3 MTGHG_OBS4MIPS netcdf files, see MTGHG PUGS, 2024 for more details). The CH_4 profiles provided by the AirCores are linearly interpolated as a function of pressure altitude on the TIGR pressure grid used in the retrieval. Thus, the CH_4 profiles of the AirCores and the averaging kernels are defined on the same pressure grid. To obtain the IASI-like MT-CH_4 from the AirCore measurements, we apply the following formula (Crevoisier et al., 2009b):

$$MTCH4^{IASI-like}_{AirCore} = \frac{\sum_{i=1}^{Nlayer} F_i \, \Delta \, p_i X_{i,ch4}}{\sum_{i=1}^{Nlayer} F_i \, \Delta \, p_i} \quad (1)$$

Where:

- $MTCH4^{IASI-like}_{AirCore}$ is the mid-tropospheric column of CH_4 obtained using the AirCore CH_4 profile and the vertical sensitivity of the L3 MT-CH_4;
- F_i is the value of the averaging kernel in the layer i ;
- Δp_i is the layer thickness in terms of pressure;
- $X_{i,ch4}$ is the value of the CH_4 mixing ratio provided by the AirCore measurement;
- $Nlayer$ is the number of layers in the TIGR database and equal to 42 layers;

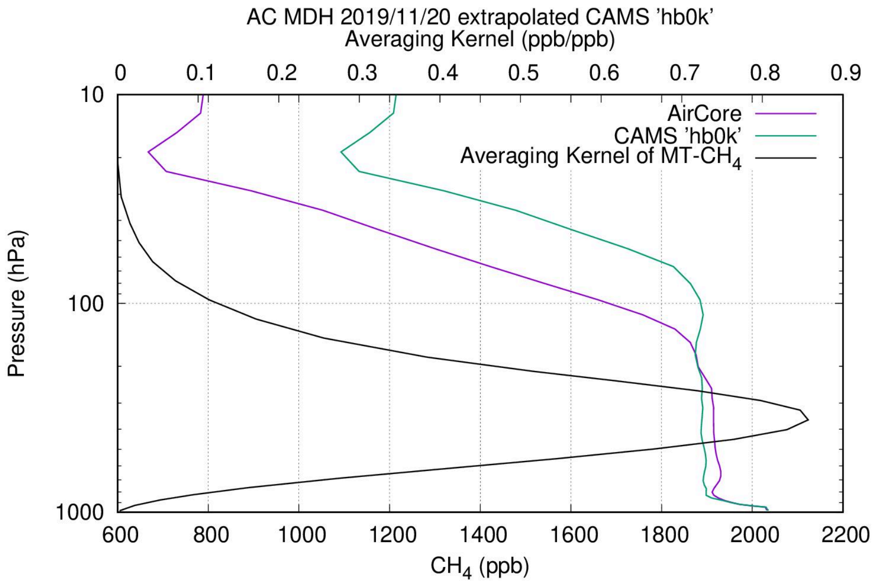

Figure 1: An example of a methane profile (purple line) extrapolated with CAMS 'hb0k' (green line), from AirCore launched at Reims, France and the typical averanging kernel of MT-CH_4 (black line).

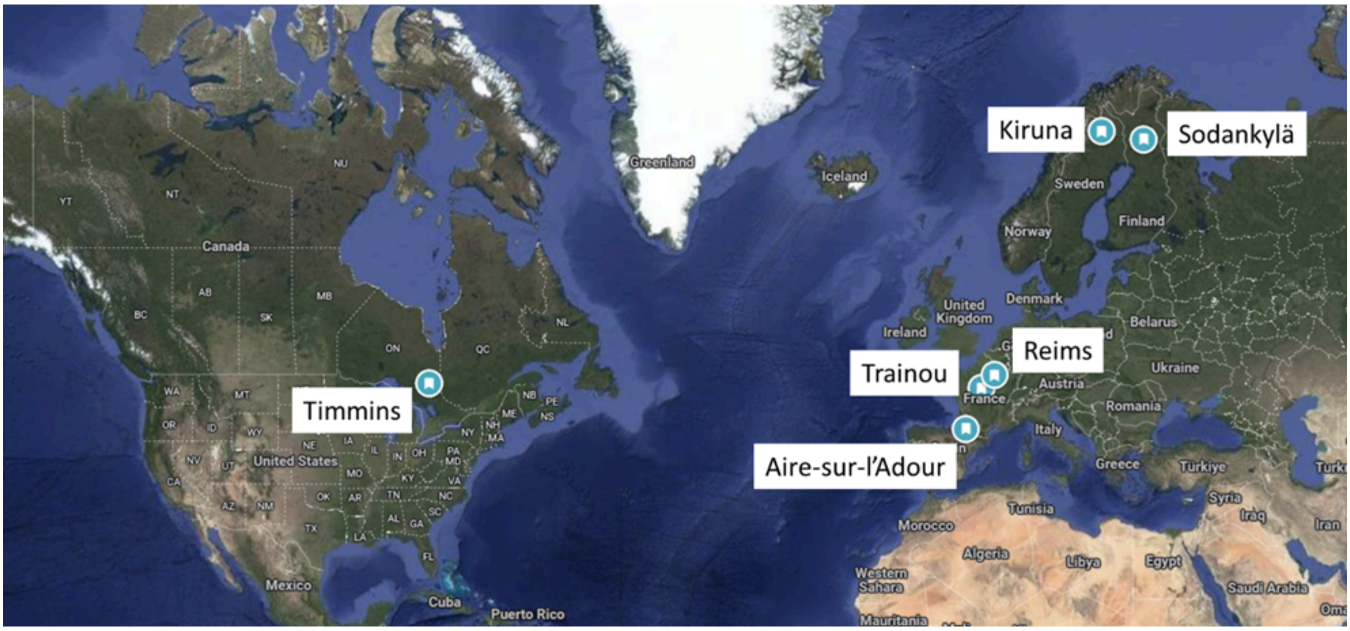

Figure 2: Location of launching sites of AirCore used in the validation. Most of the measurements come from the 3 French sites that form the AirCore-Fr network.

1.1.2. Aircraft: CONTRAIL

Additional validation data come from measurements performed by commercial aircraft made as part of the CONTRAIL project (Matsueda et al. 2008, Machida et al., 2008, Sawa et al., 2015). Mixing ratios of CO_2 and CH_4 are provided at the altitude of the flights, typically at 10-12 km for most of the flight, and as profile during ascent or descent at airports. The current dataset spans the period April 1993 to March 2022. Note that only CONTRAIL data after July 2007 are used in the validation as this is when the MT-CH_4/CO_2 Obs4MIPs data became available. Figure 3 shows the CO_2 (Figure 3(a)) and CH_4 (Figure 3(b)) measurement points above 10 km per year between 2007 and 2022. These observations, partly analyzed by Matsueda et al. (2002), are available on a monthly basis. They cover the altitude range 9–13 km. Several gaps have affected the measurements throughout the period, which prevents making robust statistics from them.

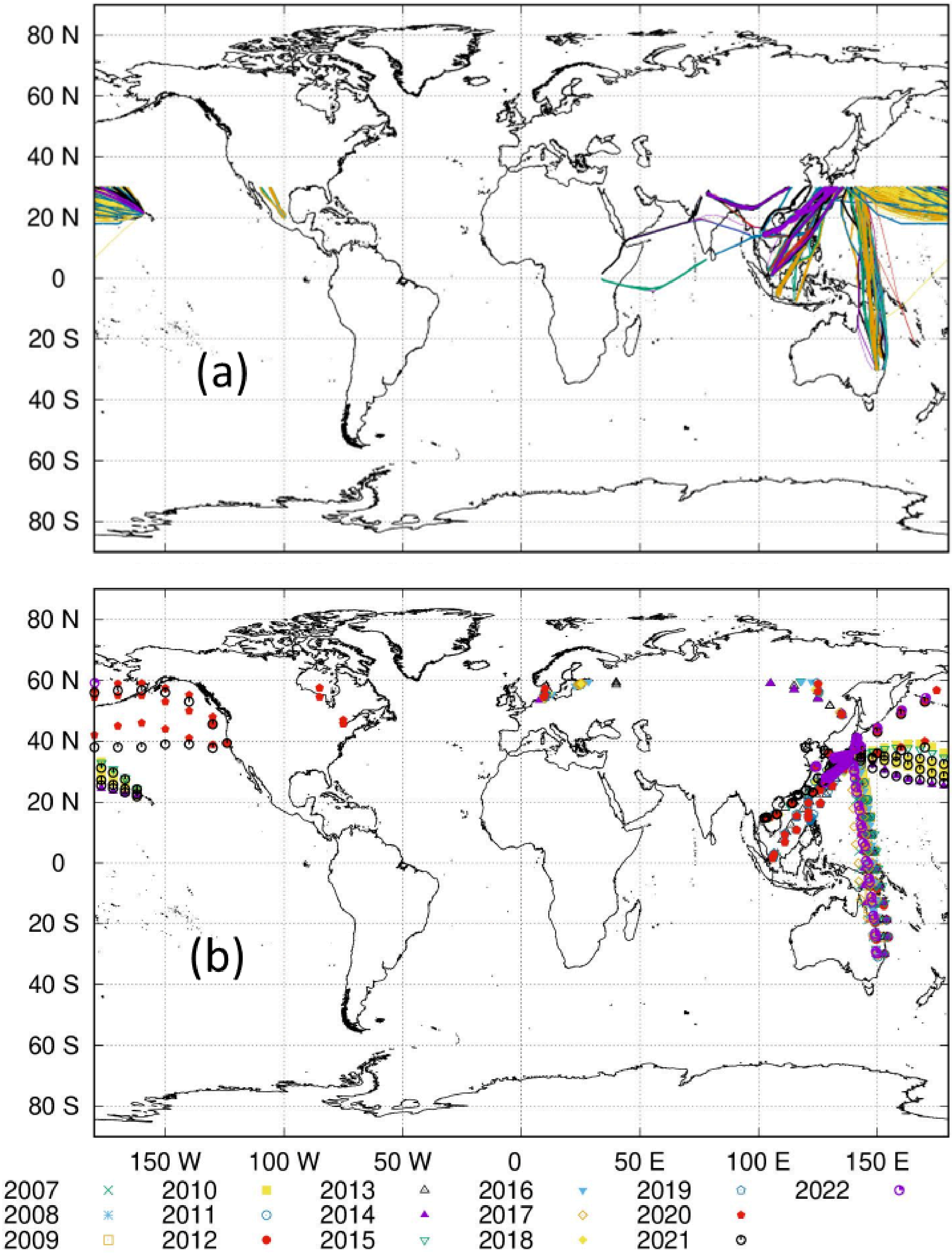

Figure 3: Trajectories of CONTRAIL measurement of CO_2 (a) and CH_4 (b) above 9 km and per year between 2007 and 2022

The CONTRAIL measurements used for validation are those carried out between 9 and 13 km altitudes, i.e. at the altitude where the sensitivities to CO_2 and CH_4 of MT-CO_2 and MT-CH_4 products are maximum. These measurements are then averaged in 1°X1° grids and per month to obtain monthly L3 CONTRAIL products.

In the following, CONTRAIL L3 CO_2 data and IASI L3 Obs4MIPs MT-CO_2 v10.1 are compared over 12 latitudinal bands of 5° each. CONTRAIL L3 CH_4 data and IASI L3 Obs4MIPs MT-CH_4 v10.2 are compared over 12 latitudinal bands of 5° each.

1.2. Validation methodology

1.2.1. Determination of the accuracies

To determinate the accuracy of MT-CO2_OBS4MIPS and MT-CH4_OBS4MIPS, we use the CONTRAIL measurements above 9 km, where the MT-CO_2 sensitivities to CO_2 are maximum. L3 CONTRAIL monthly means are compared with MT-CO2_OBS4MIPS monthly means in each 5° latitude band.

The "relative systematic errors" are the standard deviations of the mean per-latitudinal 10° band bias between 40°S and 60°N for MT-CH_4 Obs4MIPs and per-latitudinal 5° band bias between 30°S and 30°N for MT-CO_2 Obs4MIPs, computed over the whole time series and the “relative spatio-temporal bias” is the standard deviation of the seasonal mean bias in each latitudinal band (i.e. JFM, AMJ, JAS, OND).

For MT-CH4_OBS4MIPS, another validation over Mid-latitudes is performed using the AirCore CH_4 profiles (presented in section 1.1.1). All MT-CH_4 Obs4MIPs retrievals falling in a 5°x5° grid cell centered on each AirCore profile for the same day are averaged. For each couple of MT-CH4_OBS4MIPS and AirCores, the averaging kernel is applied to the CH_4 AirCore profile (Eq. 1) to obtain the mid-tropospheric column of CH_4 noted as, $MTCH4^{IASI-like}_{AirCore}$. We obtain the differences IASI-like MT-CH_4 from AirCore and MT-CH4_OBS4MIPS as:

$$\Delta^{AirCore} = \frac{1}{N_{coloc}} \sum_{i=1}^{N_{coloc}} \left(MTCH4^{i,IASI-like}_{AirCore} - MTCH4^{i}_{Obs4MIPS} \right) \qquad (2)$$

where:

- $\Delta^{AirCore}$ if the averaged difference of MT-CH_4 Obs4MIPs and IASI-like MT-CH_4 from the AirCore;
- $MTCH4^{i,IASI-like}_{AirCore}$ is the mid-tropospheric column of CH_4 obtained with the application of the averaging kernel of the $MTCH4^{i}_{Obs4MIPs}$ to the AirCore CH_4 profile;
- N_{coloc} is the number of co-location of MT-CH_4 Obs4MIPs and the AirCore profile (same day, and in a 5°x5° grid cell centered around the AirCore profile);

The difference between MT-CH_4 Obs4MIPs and AirCores are given as the mean and the associated standard deviation of $\Delta^{AirCore}$ over the 81 AirCores currently available. This standard deviation defines the "random error" of MT-CH_4 Obs4MIPs. We used AirCores to define the "random error" rather than aircraft measurements because AirCores allow comparisons of the mid-tropospheric columns of CH_4 while the aircraft comparison compares mid-tropospheric columns of CH_4 (MT-CH4_OBS4MIP) with measurement points around 9-10 km altitudes.

1.2.2. Determination of the stability

For the TR assessment, the stability assessment is limited to the linear bias trend / drift.

For MT_CO2_OBS4MIPS: We assume that CONTRAILS measurements are stable and accurately represent the evolution of CO_2 in the mid-tropospheric region. From the co-located CONTRAIL and MT-CO2 _OBS4MIPS data, we calculate the associated time series per 5° latitude bands. From these time series, we infer trends using a linear fit and by latitude band. The goal of working by latitude band is to demonstrate whether stability is verified in each latitude band.

For MT-CH4_OBS4MIPS, due to several gaps in the time series of CONTRAIL, it is not possible to compute the stability.

Stability is then defined as the difference in trend between CONTRAIL and MT-CO2_OBS4MIPS.

1.2.3. Limitation of validation

In the tropics, there are currently no independent validation sources that provide CO_2/CH_4 profiles between the surface and the lower stratosphere. Having regular AirCore launches in any tropical region would greatly improve the validation of IASI products as well as benefit the evaluation of model simulations. Therefore, we used CONTRAIL aircraft flights to determine the stability and accuracy of the MT-CO_2 Obs4MIPs and MT-CH_4 Obs4MIPs products. The limitations with CONTRAIL measurements are:

- CONTRAIL measurements do not cover all latitudes and longitudes;
- The time series of CONTRAIL measurements is impacted by several gaps in time coverage;
- These measurements don't provide a CO_2 profile but rather measurement points in the mid-troposphere;

The AirCore measurements are used to validate MT-CH_4 Obs4MIPs products over northern mid-latitudes. The limitation here is the number of AirCores and no AirCore is currently available in tropics and southern mid-latitudes.

The last limitation is that we don't have an independent source of validation of CH_4 profiles in the mid-troposphere and over the southern mid-latitudes.

2. Validation results

2.1. Validation results for Level 3 Obs4MIPs MT-CO_2 product

2.1.1. Validation with aircraft measurements

The validation of Level 3 Obs4MIPs MT-CO_2 product is performed using the CONTRAIL aircraft measurement described in Section 1.1.2.

Figure 4 shows comparison of IASI L3 MT-CO_2 with L3 CONTRAIL aircraft data as monthly means in 12 latitudinal bands of 5° each. Figure 5 shows the scatter plot of IASI L3 MTCO2 vs. L3 CONTRAIL CO_2 for the whole period. The R correlation coefficient is 0.99, the bias and the standard deviation of the difference between them being 0.60 ± 1.25 ppm.

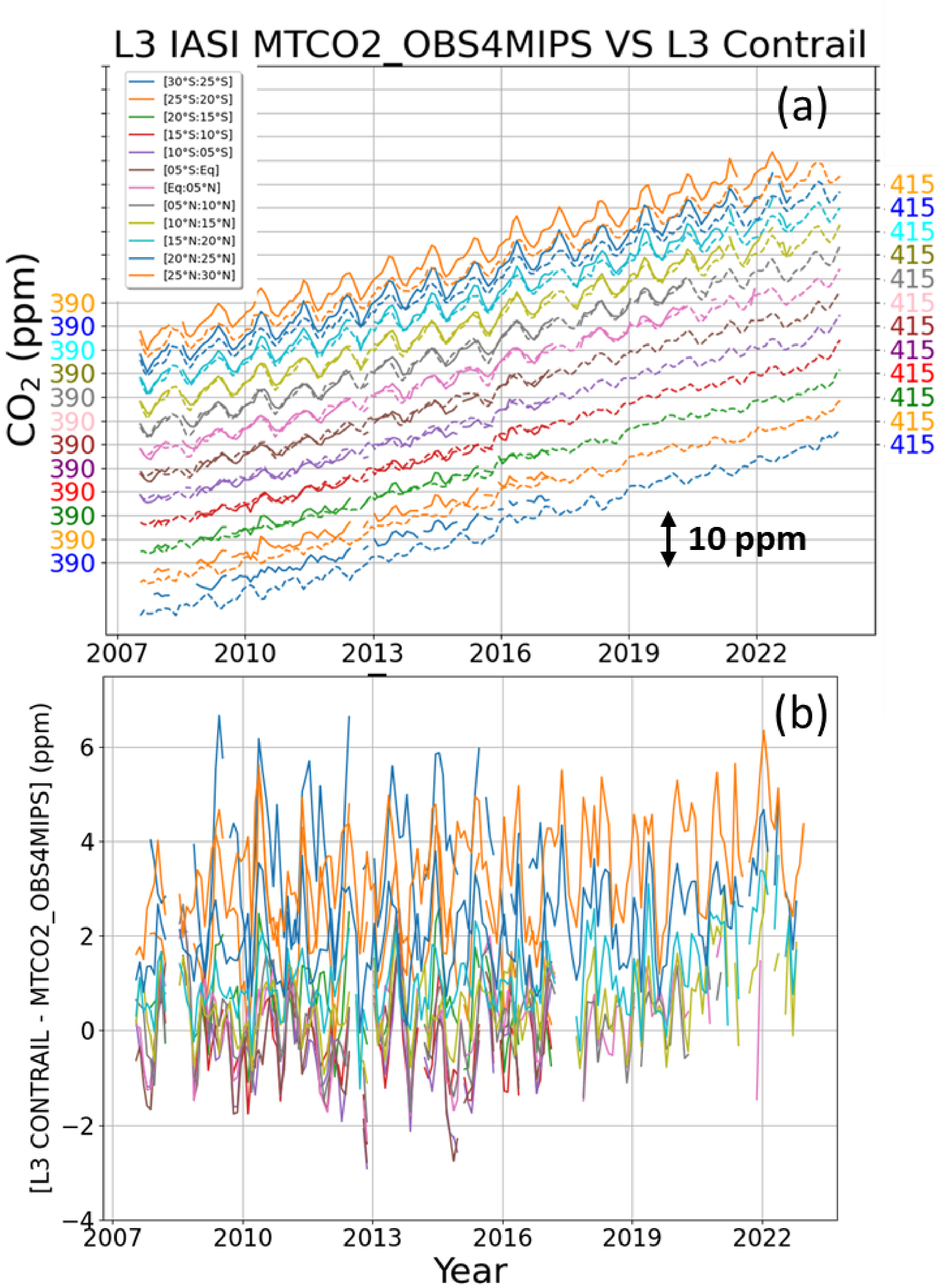

Figure 4: (a) Monthly mean of L3 IASI MT-CO_2 Obs4MIPs v10.1 (dashed line) from July 2007 to November 2022 and of L3 CONTRAIL CO_2 (full line) in 12 latitudinal bands of 5° each from 30°S to 30°N; (b) the associated differences between MT-CO_2 Obs4MIPs v10.1 and L3 CONTRAIL CO_2.

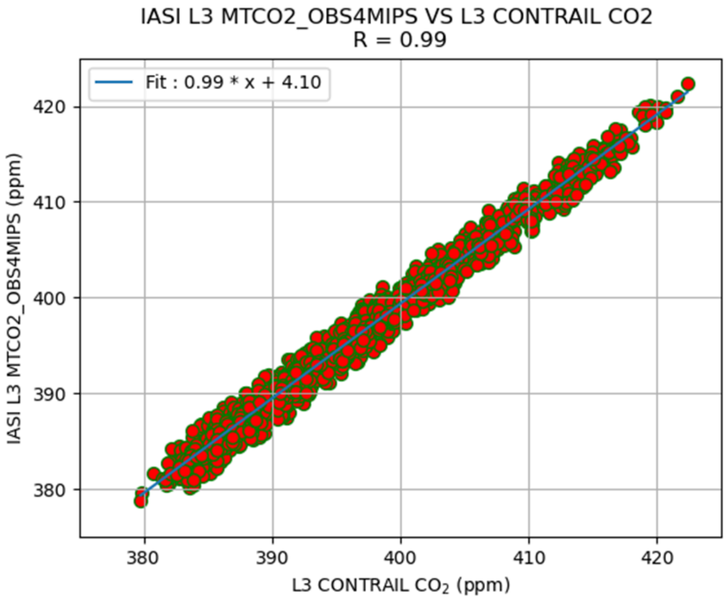

Figure 5: Scatter plot of L3 IASI mid-tropospheric CO_2 v10.1 vs. L3 CONTRAIL CO_2 measured at 10 km (1511 points of comparison) over the whole period available for CONTRAIL depicted in Fig. 4 (a) for measurements by aircraft at 10-12 km (Fig. 4 (a), dashed line) in 12 latitudinal bands of 5° each.

To compute the various parameters summarized in the following tables, the time series in each latitudinal band displayed in Figure 4 (a) have been used separately.

Table 1 shows the mean L3 CONTRAIL – L3 IASI Obs4MIPs MT-CO_2 difference together with the associated standard deviation recorded in each latitudinal band. The mean bias over all latitudinal band is 1.07 ppm. It comes down to 0.58 ppm when we restrict to 25S:25N, where most of the reference data are available.

Table 1: Mean and standard deviation (std) of CO_2 (ppm): difference between L3 CONTRAIL and IASI L3 Obs4MIPs MT-CO_2 v10.1 over 12 latitudinal bands of 5° each. Statistics over July 2007-November 2022

Latitudinal band	30S: 25S	25S: 20S	20S: 15S	15S: 10S	10S: 5S	5S :EQ	EQ: 5N	5N: 10N	10N:15N	15N:20N	20N:25N	25N:30N
CONTRAIL-MT-CO_2 (ppm)	3.67	2.03	0.55	-0.31	-0.40	-0.32	0.23	0.22	0.56	1.10	2.15	3.41
CONTRAIL- MT-CO_2 std (ppm)	1.37	1.19	0.86	0.79	0.96	0.99	0.92	0.90	0.82	0.81	0.91	1.06
Number of matchups	96	97	97	97	103	104	148	147	169	169	178	182

The relative systematic error is computed as the standard deviation of the L3 CONTRAIL – L3 MT-CO_2 bias obtained in each latitudinal band. It is computed as three values:

- The "systematic error", which is the standard deviation of the mean per-latitudinal band bias computed over the entire time series. This was found to be 1.07 ppm.
- The "relative spatio-temporal bias", which is the standard deviation of the seasonal mean bias in each latitudinal band (i.e. JFM, AMJ, JAS, OND). This was found to be 1.55 ppm.
- The "relative spatio-temporal error", which is the standard deviation of the mean bias in each latitudinal band over the whole time series. This was found to be 1.42 ppm between 30°N:30°S and 0.52 between 20°S and 20°N.

For each latitudinal band, the linear drift was computed as the slope of the linear regression of the mean L3 CONTRAIL – IASI L3 MT-CO_2 bias against time. Table 2 shows the resulting drift. The main drift, that define the stability, over all bands is 0.005 ± 0.04 ppm/year.

Table 2: Linear drift of CO2 (ppm/year)

Latitudinal band	30S: 25S	25S: 20S	20S: 15S	15S: 10S	10S: 5S	5S :EQ	EQ: 5N	5N: 10N	10N:15N	15N:20N	20N:25N	25N:30N
Linear drift [ppm/year]	0.04	-0.02	-0.07	0.00	-0.01	-0.08	0.05	0.01	0.01	0.04	0.03	0.04

2.2. Validation results for Level 3 Obs4MIPs MT-CH_4 product

For L3 Obs4MIPs MT-CH_4 products, only two quantities have been evaluated so far: single measurement precision, and mean bias with both aircraft and AirCore measurements. Due to limited time series of both aircraft and balloons, it has not yet been possible to evaluate the stability criteria.

2.2.1. Validation with aircraft measurements

L3 Obs4MIPs MT-CH_4 are compared with measurements made in the framework of the CONTRAIL project (Machida et al., 2007, 2008; Matsueda et al., 2008; Sawa et al., 2015). All L3 Obs4MIPs MT-CH_4 falling in a 5°x5° grid cell centered on each L3 CONTRAIL measurement are averaged. The larger difference between the partial column retrieved from IASI and the in-situ concentration measured at 10-12 km by CONTRAIL is due to a larger vertical variability for CH_4 than for CO_2, hence, the comparison between satellite weighted columns and aircraft point measurements is expected to be less satisfactory for CH_4. Figure 6 shows the scatter plot of each pair of CONTRAIL / L3 Obs4MIPs MT-CH_4.

Over the whole dataset, the difference between L3 CONTRAIL and L3 Obs4MIPs MT-CH_4 is -1.81 ± 17.3 ppb, with a correlation R factor of 0.84.

Note that due to the many gaps in the CONTRAIL CH_4 time series, it is not possible to calculate the stability of MT-CH_4 using CONTRAIL airborne measurements.

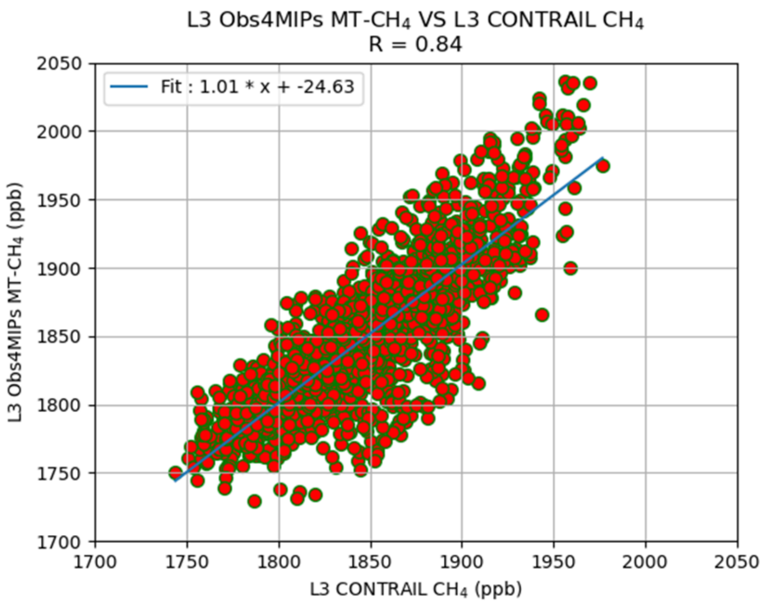

Figure 6: L3 CONTRAIL CH4 vs. L3 Obs4MIPs MT-CH_4 for all CONTRAIL measurements over July 2007-November 2022 (701 points of comparison). The 1x1 line is shown as blue.

Figure 7 shows the monthly evolution of CH_4 as measured by CONTRAIL (dashed lines) and retrieved by IASI (full line) for 10 latitudinal bands of 10° each. The monthly evolution observed on both datasets is consistent whatever the latitude is, both in terms of seasonality and amplitude. Table 3 summarizes the statistics (mean and standard deviation) obtained within each 10 latitudinal bands for IASI, CONTRAIL and the difference between both. Both datasets are statistically in agreement. The standard deviations of IASI and CONTRAIL inside a given latitudinal band are noticeably close to each other.

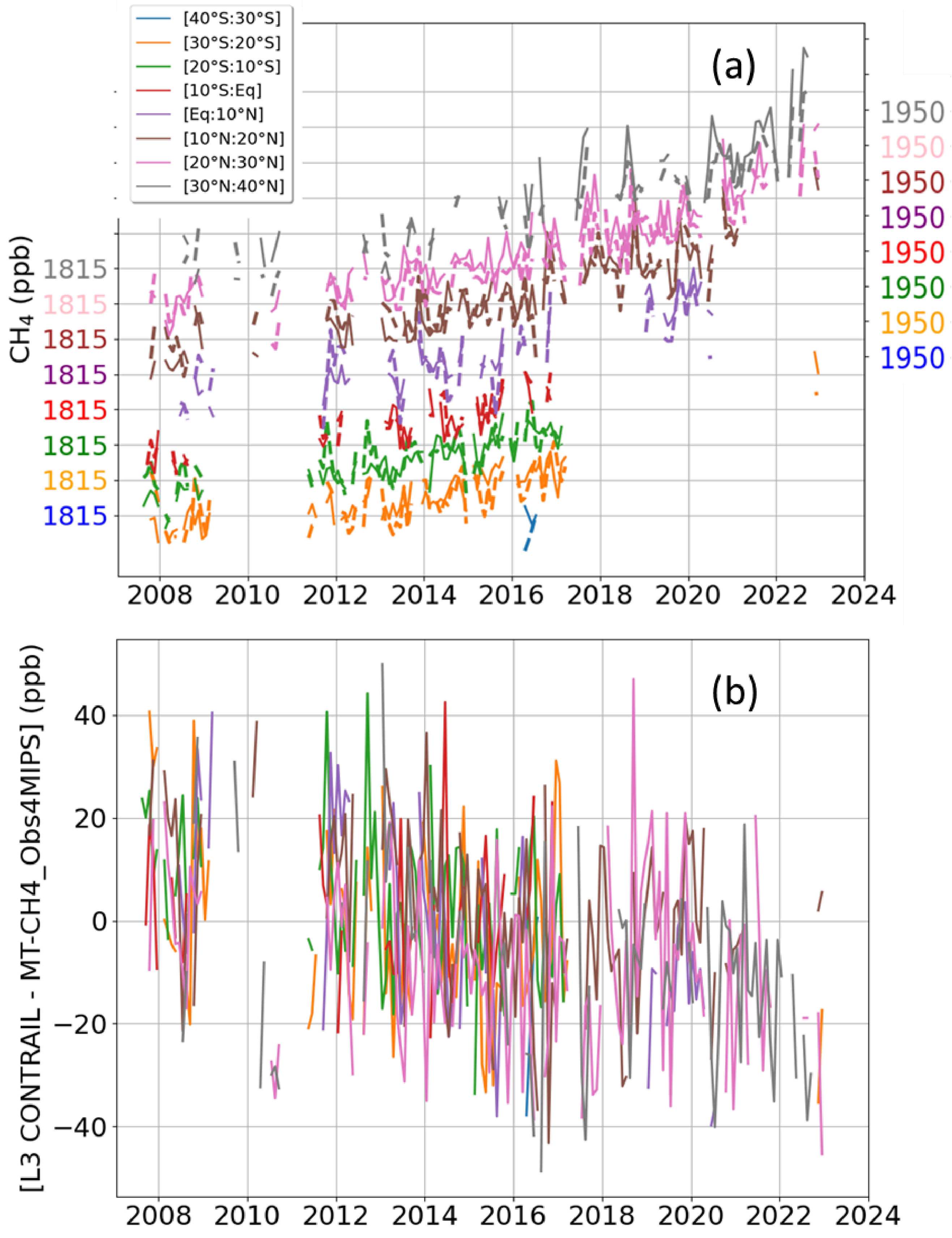

Figure 7: (a) Comparison between CONTRAIL and L3 MT-CH_4 over July 2007-November 2022. Monthly evolution of L3 CONTRAIL CH_4 (dashed line) and IASI L3 MT-CH_4 (full line) for 8 latitudinal bands of 10° each. Each series is shifted by 30 ppb (black arrow) to be displayed on the same figure. (b) the associated differences between MT-CH_4 Obs4MIPs v10.2 and L3 CONTRAIL CH_4.

Table 3: Means and standard deviations of: 5°X5° gridded L3 CONTRAIL aircrafts (1st line), L3 MT-CH_4 Obs4MIPs v10.2 (2nd line), the differences L3 CONTRAIL - L3 MT-CH_4 (3rd line) and the number of matchups (4th line) over 10 latitudinal bands of 10° each. Statistics over July 2007-November 2022.

Latitudinal band	30°S:40°S	30°S:20°S	20°S:10°S	10°S:EQ	EQ:10°N	10°N:20°N	20°N:30°N	30°N:40°N	40°N:50°N	50°N:60°N

L3 CONTRAIL (ppb)	1815.19 ± 20.23	1801.22 ± 25.62	805.13 ± 22.33	1803.41 ± 21.80	1832.12 ± 30.76	1852.66 ± 33.52	1853.47 ± 35.59	1870.85 ± 38.28	1874.05 ± 35.70	1861.53 ± 21.23
L3 MT-CH_4 (ppb)	1817.03 ±14.18	1803.52 ± 26.87	1801.63 ± 24.40	1802.35 ± 21.03	1832.43 ± 33.37	1851.26 ± 37.91	1861.49 ± 38.75	1878.85 ± 46.50	1874.35 ± 43.95	1861.74 ± 30.38
L3 CONTRAIL - L3 MT-CH_4 (ppb)	1.84 ± 22.95	2.30 ± 16.67	-3.50 ± 14.08	-1.06 ± 13.39	0.31 ± 17.90	-1.41 ± 16.73	8.02 ± 17.23	8.01 ± 19.45	0.31 ± 25.24	0.21 ± 22.64
Number of matchups	12	178	205	93	124	270	335	215	18	44

From Table 3, it is straightforward to compute the “relative spatial bias” of the “relative systematic error”, which is the standard deviation of the mean per-latitudinal band bias computed over the whole time series. The “relative systematic error”, which is the standard deviation of the mean bias in each latitudinal band over the whole time series, is found to be 3.80 ppb. Due to several gaps in the time series, as can be seen in Figure 7 (a), it is not possible to compute the “relative spatio-temporal bias” which is the standard deviation of the seasonal mean bias in each latitudinal band (i.e. JFM, AMJ, JAS, OND).

2.2.2. Validation with AirCore 0-30 km profiles

Here, IASI Obs4MIPs MT-CH_4 products are compared to several AirCore profiles (see Section 1.1.1). Figure 8 shows the scatter plot of each pair of AirCore/ L3 Obs4MIPs MT-CH_4. Over the whole dataset (81 pairs), the difference between AirCore and IASI CH_4 is -4.5 ± 17.5 ppb.

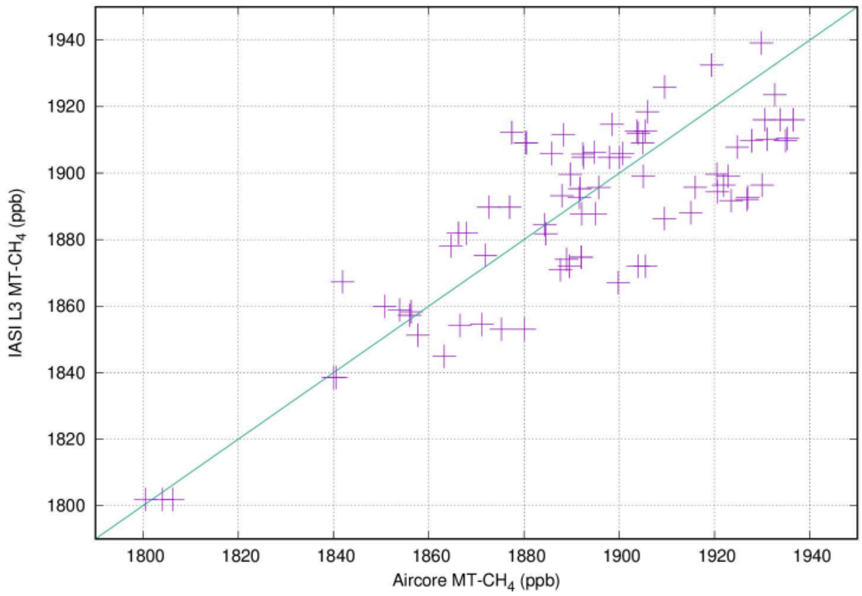

Figure 8: Comparison between IASI Obs4MIPs MT-CH_4 v10.2 and AirCore CH4. Correlation is 0.82.

3. Climate Change Assessment (to be implemented progressively)

In this section, reports on the output of the Climate Intelligence activities will be included as they become available.

4. Application(s) specific assessments

The v10.2 MT-CO2_OBS4MIPS and v10.1 MT-CH4_OBS4MIPS products validated in this document have not yet been used for application specific assessments in terms of peer-reviewed publications.

5. Compliance with user requirements concerning data quality

This section summarizes the achieved data quality including comparisons with the required data quality.

The user requirements are listed in the Target Requirement and Gap Analysis Document (TR-GAD GHG, 2024). They are based on requirements as formulated in documents GCOS-154, GCOS-195, GCOS-200, GCOS-245 and CMUG-RBD, 2012.

The TRD GAD GHG, 2024, document contains explicit requirements for random errors, systematic errors and stability of the Level 2 MTCO_2 and MTCH_4 data products in terms of goal (G), breakthrough (B)and threshold (T) requirements. Explicit requirements for Level 3 products are not formulated in TR-GAD GHG, 2024. Instead, it is assumed that the accuracy and stability requirements are also valid for Level 3 (i.e., spatio-temporally averaged) data products.

As explained in Section 2 of TR-GAD GHG, 2024, the GCOS requirements as formulated in GCOS-245, are not applicable for the data products as presented in this document as these new GCOS requirements are formulated for future missions (e.g., CO2M) and are not appropriate for existing satellite sensors are used for this project. The following is written in TR-GAD GHG, 2024: “Because these new requirements are for future missions, we use in this document (wherever possible) the requirements as have been formulated by the Climate Research Group (CRG) of the GHG-CCI project of ESA's Climate Change Initiative. We use the latest version, which is the User Requirements Document (URD) referred to ESA-CCI-GHG-URD, 2024.

Table 4 compares the required and the achieved performance for random error (precision), required accuracy (in terms of spatio-temporal biases) and stability (in terms of linear bias drift). The data quality level is also summarized in Section 5.1 for MT-CO_2 and Section 5.2 for MT-CH_4.

Table 4: Compliance with User Requirements. MT-CO_2 and MT-CH_4 Obs4MIPs random ("precision"), systematic error and stability requirements (from TRD GAD GHG, 2024). Abbreviations: G=Goal (green), B=Breakthrough (yellow), T=Threshold requirement (red). §) Required systematic error after an empirical bias correction, that does not use the verification data. #) Required systematic error and stability after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor

Parameter	Requirement type	Requirement			Reported value	Comments
		G	B	T		
CO_2	**Random error (precision) (1000^2 km^2 monthly) (ppm)**	< 0.3	**< 1.0**	< 1.3	0.97	This value is based on the comparison between partial column and point measurement. Probability that precision is inferior to the threshold requirement (T): 82 % Assuming that the error distribution follows normal distribution centered at 0 ppm and with a 0.97 ppm standard deviation
	Accuracy: Relative systematic error (ppm)	< 0.2 (absolute)	< 0.3 (relative§))	**< 0.5 (relative#))**	1.42	This value is based on the comparison between partial column and point measurement. This value reaches 0.52 ppm between 20° and 20°N.
	Stability: Linear bias trend (ppm/year)	**< 0.2** (absolute)	< 0.3 (relative§))	< 0.5 (relative#))	0.005	This value is based on the comparison between partial column and point measurement. Probability that linear bias trend is inferior the threshold requirement (T): 100 % Assuming that the linear bias trend distribution follows a normal distribution centered at 0 ppm/year and with a 0.005 ppm/year standard deviation
CH_4	**Random error (precision) (1000^2 km^2 monthly) (ppb)**	< 3	< 5	**< 11**	17.5	This value is based on the comparison wit the AirCores. Probability that precision is inferior to the threshold requirement (T): 47 % Assuming that the error distribution follows normal distribution centered at 0 ppb and with a 17.5 ppb standard deviation
	Accuracy: Relative systematic error (ppb)	< 1 (absolute)	**< 5 (relative§))**	< 10 (relative#))	3.80	This value is based on the comparison between partial column and point measurement.
	Stability: Linear bias trend (ppb/year)	< 1 (absolute)	< 2 (relative§))	< 3 (relative#))	NC	Time series of available aircraft/AirCore ob are not long enough to compute this parameter.

5.1. Summary data quality Level 3 MT-CO_2 product

The validation of Level 3 product MTCO2_OBS4MIPS can be summarized as follows:

- The overall monthly mean uncertainty is 1.25 ppm and the mean bias is 0.6 ppm. This value is based on the comparison between partial column (MT-CO_2) and point measurement (Aircraft measurements).
- Relative systematic error, i.e., the spatio-temporal error, is 1.42 ppm (1-sigma) between 30°S:30°N and 0.52 ppm (1-sigma) between 20°S and 20°N. These values are based on the comparison between partial column partial column (MT-CO_2) and point measurement (Aircraft measurements). The computed linear drift of 0.005±0.04 ppm (1-sigma) is small and not significant.
- Overall, this product has therefore reasonable accuracy and high stability.

5.2. Summary data quality Level 3 MT-CH_4 product

The validation of Level 3 product MTCH4_OBS4MIPS can be summarized as follows:

- The overall monthly mean uncertainty is 17.3 ppb and the mean bias is -1.81 ppb. Relative systematic error, i.e., the spatio-temporal error is 3.80 ppb (1-sigma).
- Overall, this product has therefore reasonable accuracy.

Acknowledments

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