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ESA Climate Change Initiative (CCI)

User Requirements Document (URD)

for the Essential Climate Variable (ECV)

Greenhouse Gases (GHG)

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Version 1 – Final	3 Feb. 2011	Final version Author: M. Buchwitz; Major contributions: F. Chevallier, P. Bergamaschi, I. Aben	New document
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Version 2.1 – Final	19 Oct. 2016	Final version Contributions: P. Bergamaschi, F. Chevallier, P. Palmer;	<ul style="list-style-type: none"> - Update of the stability requirement for CH₄, - Clarification in the definition of stability (to cover inter-annual error changes)



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1 Summary

This document states users' requirements for the products of ESA's GHG-CCI project **/Buchwitz et al., 2013/**. It is itself a deliverable of this project.

The GHG-CCI project (<http://www.esa-ghg-cci.org/>) is one of several projects of ESA's Climate Change Initiative (CCI) **/Hollmann et al., 2013/**. It started on 1 September 2010 and has been led by the Institute of Environmental Physics (IUP), University of Bremen, Germany, (Science Leader: M. Buchwitz) supported by the Univ. of Leicester, UK (Project Manager: H. Bösch). It is now in Phase 2.

The GHG-CCI project aims at delivering the Essential Climate Variable (ECV) for Greenhouse Gases (GHG) from satellite measurements in line with the "Systematic observation requirements for satellite-based products for climate" as defined by GCOS (Global Climate Observing System): "Product A.8.1. Retrievals of CO₂ and CH₄ of sufficient quality to estimate regional sources and sinks". The present user requirements exclusively address this application and may not apply to other applications or finer spatial scales.


Ideally, this objective requires satellite observations, which are sensitive to near-surface concentration variations of CO₂ and CH₄. Only three real satellite instruments have this asset: SCIAMACHY on ENVISAT (which was operational from March 2002 to April 2012), TANSO onboard GOSAT (which has been operational since early 2009), and OCO-2 (which was launched in July 2014). The following five data products can be retrieved from these instruments, which are relevant for GHG-CCI:

- Column-averaged dry air mole fractions of CO₂, i.e., XCO₂ (in ppm), from SCIAMACHY (nadir mode), TANSO and OCO-2.
- Column-averaged dry air mole fractions of CH₄, i.e., XCH₄ (in ppb), from SCIAMACHY (nadir mode) and TANSO.

Within Phase 1 of GHG-CCI, these data products (with the exception of OCO-2 that was not launched at the time) were the core ECV GHG data products generated within this project.

The present user requirements are based on peer-reviewed publications, other documents where user requirements have been formulated and user consultation including users who are (also) involved in the European MACC-II project (<http://www.copernicus-atmosphere.eu/>). A close cooperation between GHG-CCI and MACC-II/GHG has been established for this purpose.

Within GHG-CCI, algorithms and corresponding data products to obtain information on CO₂ and CH₄ in upper atmospheric layers, i.e., layers above the Planetary Boundary Layer (PBL), are also developed, improved and assessed. This includes mid/upper tropospheric CO₂ and/or CH₄ from AIRS and IASI, and upper tropospheric and stratospheric CO₂ profiles from ACE-FTS and CH₄ profiles from MIPAS and SCIAMACHY solar occultation. These data products provide additional constraints for inverse modelling, but their information content with respect to regional surface fluxes is more limited than XCO₂ and XCH₄ as they have no or only little sensitivity to the PBL. Therefore these data products are not the focus of GHG-CCI and detailed user requirements for these data products have not been formulated in URDv2. Requirements may be formulated in a future version of the URD as regular updates are planned.

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2 ECV Greenhouse Gases (GHG)


What is the ECV GHG? The ECV GHG follows the definition of **/GCOS-154/** (see **Annex A**). The ECV GHG is a publicly available database and corresponding documentation on satellite retrieved GHG information for improved quantification of regional surface sources and sinks. This is currently only possible for the two most important anthropogenic GHGs carbon dioxide (CO₂) and methane (CH₄), the other GHGs being not well monitored from space yet.

Three satellite instruments are sensitive to near-surface concentration changes of CO₂ and CH₄ and therefore can best deliver information on regional CO₂ and CH₄ surface fluxes: SCIAMACHY **/Burrows et al., 1995/ /Bovensmann et al., 1999/** onboard ENVISAT, TANSO onboard GOSAT **/Kuze et al., 2010/ /Yokota et al., 2004/** and OCO-2 **/Boesch et al., 2011/ /Crisp et al., 2004/**.

Key input data for (inverse) modelling activities to obtain information on CO₂ and CH₄ regional surface fluxes are column-averaged dry air mole fractions of CO₂ and CH₄, i.e., XCO₂ (in ppm) **/A-Scope, 2008/ /Baker et al., 2010/ /Barkley et al., 2006/ /Boesch et al., 2011/ /Bösch et al., 2006/ /Bréon et al., 2010/ /Bril et al., 2007a, 2007b, 2008, 2009/ /Buchwitz et al., 2000, 2005, 2013/ /Butz et al., 2009/ /Chevallier et al., 2005a, 2007, 2009b, 2010, 2014/ /Connor et al., 2008/ /Crisp et al., 2004/ /Feng et al., 2009/ /Heymann et al., 2012a, 2012b/ /Houweling et al., 2004/ /Hungershofer et al., 2010/ /Kaminski et al., 2010/ Miller et al., 2007/ /Nakajima et al., 2010/ /Oshchepkov et al., 2008, 2009/ /Rayner and O'Brien, 2001/ /Reuter et al., 2010, 2011, 2013/ /Schneising et al., 2008, 2010, 2011, 2012, 2013, 2014/ /Yokota et al., 2004/ /Yoshida et al., 2010/** and XCH₄ (in ppb) **/Bergamaschi et al., 2007, 2009/ /Bloom et al., 2010/ /Bousquet et al., 2010/ /Bréon et al., 2010/ /Buchwitz et al., 2000, 2005, 2013/ /Cressot et al., 2014/ /Frankenberg et al., 2005a, 2005b, 2006, 2008, 2011, 2013/ /Fraser et al., 2013, 2014/ /Meirink et al., 2006/ /Nakajima et al., 2010/ /Schneising et al., 2009, 2010, 2011, 2012/ /Yoshida et al., 2010/**.

The four data products XCO₂ and XCH₄ from SCIAMACHY and TANSO (OCO-2 calibrated radiances being not yet available) are the four core products, which are generated within this project (using “ECV Core Algorithms” (ECAs)) and compared with corresponding products generated elsewhere (e.g., at NIES in Japan and NASA/JPL in the US). Within this document user requirements for these data products are formulated.

In addition to the four core GHG-CCI ECV data products, other satellite data products are generated using so called “Additional Constraints Algorithms” (ACAs). These data products are primarily used for model comparison and/or because they have the potential to constrain CO₂ and CH₄ estimates in upper layers (i.e., layers above the planetary boundary layer (PBL)). This comprises mid/upper tropospheric CO₂ from AIRS, mid/upper tropospheric CO₂ and CH₄ from IASI, stratospheric CH₄ from MIPAS and SCIAMACHY occultation and stratospheric CO₂ from ACE-FTS (note that a number of relevant data products are also generated outside of this project, e.g., from TES and ACE-FTS). The data products of these sensors also provide some information on regional GHG surface fluxes, even though they are not sensitive to near-surface GHG variations (see, the discussions of **/Chevallier et al., 2005a/** and **/Bréon et al., 2010/** about CO₂ and the results of **/Cressot et al., 2014/** for CH₄). User requirements for these products in the context of regional flux inversion could be expressed. However, the current lack of validation data (i.e. the equivalent of the TCCON measurements used for total column retrievals) prevents verifying whether usual requirements expressed in terms of precision and systematic errors are met by the partial column products. AirCore measurements (**/Karion et al. 2010/**) may fill this gap in the future. In the mean time, requirements could be expressed in terms of realism of the inverted fluxes within their uncertainties (**/Chevallier et al. 2014/**, **/Cressot et al. 2014/**), but this is not attempted here.


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3 URD approach

This document has been written by the GHG-CCI project team, based on inputs from key users who are part of the GHG-CCI Climate User Group (CRG) and other inputs, most notably peer-reviewed publications (e.g., /Rayner and O'Brien, 2001/ /Bergamaschi et al., 2007/ /Bergamaschi et al., 2009/ /Bloom et al., 2010/ /Bousquet et al., 2010/ /Chevallier et al., 2007/ /Chevallier et al., 2009b/ /Houweling et al., 2004/ /Hungershoefer et al., 2010/ /Meirink et al., 2006/ /Miller et al., 2007/) and other publications such as the GCOS requirements /GCOS-107/ /GCOS-154/ and the requirements formulated by the CCI Climate Modelling User Group (CMUG) /CMUG-RBD, 2010/.

This document refers to XCO₂ and XCH₄ as retrieved from the SCIAMACHY and TANSO instruments. For both instruments, it has already been shown that the XCH₄ retrievals provide strong constraints on regional surface fluxes of CH₄ (e.g., /Bergamaschi et al., 2009/). It has also been shown that these instruments have the potential to deliver important information on CO₂ (e.g., /Houweling et al., 2004/ /Hungershoefer et al., 2010/), although inverse modelling has not provided reliable CO₂ flux estimates from them yet. This is a topic of active research, in particular within GHG-CCI. One of the reasons is that the requirement on systematic errors, as stated in this URD, is not satisfied with the current generation of products. However, other issues like transport model systematic errors and flawed statistical models play a role as well. In the second phase of the project, retrieval algorithms will be further developed and more effort will be spent on inverse modelling by involving more European groups.

CCI CMUG compiled a requirements document relevant for this URD /CMUG-RBD, 2010/ derived from GCOS requirements /GCOS-107/ and other sources. This URD has been written to be as much as possible consistent (mostly identical) with the definitions and requirements formulated in /CMUG-RBD, 2010/. This also refers to which requirements are covered. If possible, requirements as formulated in /CMUG-RBD, 2010/ are directly included in this URD. However, for certain requirements this was not possible as even the CMUG/GCOS threshold (i.e., minimum) requirements are too demanding for the only two currently existing key instruments SCIAMACHY and TANSO used within this project (although these instruments are useful for the GHG-CCI applications).

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4 Definitions

In this section key definitions are given. They are identical with the definitions given in **/CMUG-RBD, 2010/** to ensure consistency with the other CCI projects. However, for the sake of clarity within and outside CCI, we ban the use of the word “accuracy” in the following (except in verbatim quotations) because **/CMUG-RBD, 2010/** (after **/GCOS-107/**, but contradicted later by **/GCOS-154/** that acknowledges the international norm) defines it inconsistently with the international standard for metrology (i.e. ISO 5725). We replace CMUG’s “accuracy” with the expression “Systematic error”, following the international norm.

Systematic error: component of measurement error that in replicate measurements remains constant or varies in a predictable manner

Note: “Systematic error” = “Absolute systematic error” (in contrast to “Relative systematic error” defined below).

For GHG-CCI especially the “Relative systematic error” is important. The definition for GHG-CCI is as follows:

Relative systematic error: Identical with “Systematic error” but after bias correction.

Bias: estimate of a systematic measurement error **/JCGM, 2008/**.

Precision is the 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, 2010/**


Note: We quantify precision here with the standard deviation of the error distribution.

Stability is a 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, 2010/**

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 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, 2010/**

Threshold requirement: The **threshold** is the limit at which the observation becomes ineffectual and is not of use for the climate-related application. **/CMUG-RBD, 2010/**

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Note 1: Threshold requirements are given for statistical quantities (average and standard deviation of an error distribution) rather than for individual soundings. This means that some sub-ensembles of a dataset can be useful and some others not.

Note 2: Threshold requirements are fully driven by the target application (here regional flux inversions), irrespective of available technology.

Goal requirement: The **goal** is an ideal requirement above which further improvements are not necessary. /CMUG-RBD, 2010/

Note: This requirement is relative to a given state of the art for the target application. Indeed, the more accurate and precise the satellite XCO₂ and XCH₄ data products are, the larger their information content is. However other errors such as model transport errors do not allow exploiting the additional information content data have if they are more accurate than the specified goal requirement.


Breakthrough requirement: The **breakthrough** is an intermediate level between “threshold” and “goal”, 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, 2010/

Horizontal resolution is the area over which one value of the variable is representative of. /CMUG-RBD, 2010/

Vertical resolution is the height over which one value of the variable is representative of. Only used for profile data. /CMUG-RBD, 2010/

Observing Cycle is the temporal frequency at which the measurements are required. /CMUG-RBD, 2010/

Note: In this document also the term “Revisit time” is used. The definition is identical with the definition of “Observing cycle”. Both terms refer to the (average) temporal frequency at a given location.

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5 GHG ECV specific requirements

In this section GHG ECV specific requirements are formulated for the XCO₂ and XCH₄ data products to be retrieved from SCIAMACHY, TANSO, and OCO-2.

5.1 General

The purpose of this URD is to formulate requirements for GHG data products to be generated within the GHG-CCI project for regional CO₂ and CH₄ surface flux inverse modelling. There are however also other potentially important applications, e.g., use of the data to improve our understanding of atmospheric transport and mixing or city-scale emission estimation, for which the requirements will most likely be different.

In the following detailed requirements are given typically by specifying numerical thresholds. Specifying single numbers is difficult and not unproblematic because of the complexity of the process needed to relate satellite observations to surface fluxes. Requirements may depend on time and location (and on each other) and this is likely also true for the quality of the satellite retrievals. It is therefore important not to over-interpret the numerical values given in the requirements. To consider this and in order not to forget what all this is about a very general “overarching” requirement has been formulated. This overarching general requirement is:

REQ-GHGCCI-GEN-1	The purpose of the GHG-CCI CO ₂ and CH ₄ ECV data products is to enhance our knowledge about atmospheric CO ₂ and CH ₄ and their (surface) sources and sinks and underlying processes. Contributions to such new knowledge obtained from the satellite data products shall be identified and listed. The list shall be made available to the users.
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5.2 Horizontal resolution


The utility of satellite retrievals of CO₂ and CH₄ for the estimation of regional sources and sinks has been demonstrated using global model simulations made at resolution much coarser than current satellite soundings (see, e.g., /Houweling et al., 2004/ /Meirink et al., 2006/). Typically, model grid box in these studies span at least a couple of degrees in latitude and longitude, while the soundings that are available with the coarser resolution are from the SCIAMACHY nadir measurements with 60 km (across track) × 30 km (along track) footprint. Existing studies report a modest impact stemming from this inconsistency (e.g., /Corbin et al. 2008/). Therefore no requirements are formulated here.

5.3 Vertical resolution

Similarly, such utility has been demonstrated for column-average measurements without any vertical resolution. Therefore no requirements are given here.

5.4 Observing cycle

Similarly, such utility has been demonstrated for the observing cycle of existing satellites or irrespective of any specific observing cycle. The observing cycle does not seem to be a

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critical parameter for regional flux inversion as long as measurements are assimilated at appropriate time. Therefore no requirements are given here.

5.5 Random and systematic errors

In this section requirements for random errors (“precision”) and systematic errors for XCO₂ and XCH₄ are given (see Table 1) in the context of regional flux inversion.

Precision requirements are given for single measurements but also for spatio-temporal averages (1000x1000 km², monthly). Requirements for spatio-temporal averages have been formulated to ensure that a significant number of measurements per month and region are available, at least on average. Alternatively one could have formulated a requirement for the number of measurements for a given spatio-temporal interval. Note that the size of the region is given in km² and not in deg², i.e., refer to equal size areas on the Earth’s surface.


Single measurement precisions are determined by instrument noise plus likely additional “retrieval noise” contributions from random errors caused by, for example, variability of aerosols, (undetected) clouds and variations of the surface spectral reflectance.

Note: If the noise is really random, an instrument with low single measurement precision but a large number of (sufficiently cloud free) data can provide the same information content with respect to regional GHG sources and sinks as an instrument delivering fewer data but with higher single measurement precision. A stand-alone and instrument-independent single measurement precision requirement is therefore not very meaningful in itself but needs to be combined with (estimates of) the number of (useful) data in a given spatio-temporal interval. However, this URD gives single measurement precisions requirements because they offer the potential advantage of a straight forward verification incl. radiative transfer modelling for single observations and simulated retrievals. Further, a poor precision is usually accompanied with state-dependent systematic errors that cannot be damped by averages over many retrievals.

Random error (precision) requirements for XCO₂:

In **/Rayner and O’Brien, 2001/** it has been shown that satellite retrievals of XCO₂ provide additional information on CO₂ surface fluxes if a precision of 2.5 ppm can be achieved for monthly averages in 8° x 10° large regions. This requirement has essentially been confirmed and refined in follow-on studies. For example, **/Houweling et al., 2004/** showed that SCIAMACHY provides important information on CO₂ surface fluxes if a single measurement precision (defined in this report as the standard deviation, see above) of 1% (3.6 ppm) can be achieved and if approx. 10% of the measurements are sufficiently cloud free.

/Hungershofer et al., 2010/ showed that SCIAMACHY and TANSO have the potential to deliver data which result in significant uncertainty reduction of regional weekly and annual surface fluxes when used for inverse modelling. The uncertainty reductions for the weekly fluxes are about 70% for Europe and about 80% for South America for the two instruments. The assumed single measurement retrieval precisions depend on air mass factor, surface albedo at 1.6 µm and aerosol optical depth but are typically in the range 2-8 ppm. For example, for a solar zenith angle of 50°, a surface albedo at 1.6 µm of 0.1 (vegetation), and an aerosol optical depth of 0.2, the assumed single measurement precision for TANSO is 4.2 ppm (when computed using the formula given in **/Hungershofer et al., 2010/**).

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Approach to define the requirements for random errors: For this URD single measurement precisions and precisions for spatio-temporal averages (1000x1000 km², monthly) have been formulated. The precisions for spatio-temporal averages are (mostly) a factor of 3 better compared to the single measurement precisions. If the achieved single measurement precision is identical with the required single measurement precision and if one assumes that the precision improves with the square root of the number of measurements added, this implies that at least 10 (uncorrelated) observations are available per month and per 1000x1000 km² large region.

For XCO₂ the threshold precision requirement for spatio-temporally averaged data has been set at 1.3 ppm (standard deviation), i.e. a twofold factor more demanding than the 2.5 ppm value of **/Rayner and O'Brien, 2001/**. The required single measurement precision is approximately a factor of 6 relaxed, i.e., 8 ppm (this implies that approx. 36 uncorrelated measurements per month and region have to be averaged to achieve the 1.3 ppm requirement of the single measurement precision is (only) 8 ppm). Note that the variability of XCO₂ at the global scale and along the year is less than 4 ppm (standard deviation, obtained from MACC-II global simulations run at 16-km resolution) so that the threshold requirement is very loose, even though it is tighter than **/Rayner and O'Brien, 2001/**. More demanding values have been chosen for the breakthrough and goal requirements.

Note: It is unlikely that the requirements can be met for all regions during all time periods. For example, the number of data products will be (very) sparse and noisy at high latitudes during winter (low sun, low snow/ice albedo, clouds, etc.). The precision requirements therefore refer to global long-term statistics. Sub-samples of lesser quality should be identified with appropriate quality flags and/or appropriate uncertainty values.

Random error (precision) requirements for XCH₄:


/Meirink et al., 2006/ showed that SCIAMACHY contributes significantly to CH₄ emission uncertainty reduction on monthly timescales for regions of size ~500 km assuming a single measurement precision of 1.5-2% (approx. 25-34 ppb). For the single measurement precision a value of 34 ppb (2%) has therefore been chosen for the threshold requirement.

The XCH₄ precision requirements for spatio-temporal averages are chosen as for XCO₂, i.e., a factor 3 improvement compared to the single measurement precisions.

Systematic error requirements:

The requirements about systematic errors are based on studies using synthetic data (e.g., **/Chevallier et al., 2005a/ /Chevallier et al., 2007/ /Chevallier et al., 2009b/ /Meirink et al., 2006/ /Miller et al., 2007/**) and analysis of real data (e.g., **/Bergamaschi et al., 2009/ /Bergamaschi et al., 2007/**).

For example it has been shown in **/Chevallier et al., 2007/** that for CO₂ surface flux inverse modelling “regional biases of a few tenth of a parts per million in column-averaged CO₂ can bias the inverted yearly subcontinental fluxes by a few tenth of a gigaton of carbon”. Similar conclusions have been drawn in **/Miller et al., 2007/**. Note that systematic errors can be tolerated as global offsets can be accounted for, e.g., via bias correction (e.g., using comparisons with calibrated reference data such TCCON FTS retrievals) or as part of the

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inverse modelling step as done by **/Bergamaschi et al., 2009/**. Low relative systematic errors are required however, see e.g., **/Bergamaschi et al., 2009/** or **/Miller et al., 2007/**: “Coherent biases on 100–5000 km horizontal scales pose the greatest threat to the integrity of space-based XCO₂ data and must be corrected below detectable levels”. The GHG-CCI CO₂ threshold requirement for systematic errors is based on an extension of **/Chevallier et al., 2005a/** to TANSO (performed by F. Chevallier). The idea is to have the bias about one order of magnitude smaller than the model-minus-observation departures (computed from individual soundings). For TANSO the CO₂ departures are a few ppm, so the bias needs to be a few tenth of a ppm. Although very demanding from a remote sensing point of view, such requirements seem nevertheless justified by the results of **/Houweling et al., 2010/**, **/Chevallier et al., 2010/** and **/Chevallier et al., 2010/**.


For XCH₄ the requirements are similar but somewhat relaxed (as also done for TANSO **/Nakajima et al., 2010/**), because XCH₄ is more variable compared to XCO₂ (of course in terms of percentage variations, not in terms of ppm). Nevertheless, also for methane, biases are critical and need to be as small as possible. As shown in **/Meirink et al., 2006/**, even systematic biases “well below 1%” have a dramatic impact on the derived CH₄ emissions. They demonstrated that a systematic regional bias of 0.5% (e.g. caused by the presence of aerosols) may lead to an overestimate of regional emissions by ~60%. This strong dependence of the retrieved emissions on small changes of the retrieved XCH₄ has also been found when using real SCIAMACHY data (**/Bergamaschi et al., 2009/ /Bergamaschi et al., 2007/**). As a consequence, also the CH₄ bias threshold requirement is challenging.

The requirements are valid for observations over land, due to two main reasons:

- (i) The main application of the GHG-CCI ECV data products is to improve our knowledge of GHG sources and sinks located on land, most notably to reduce uncertainties of the CO₂ fluxes of the terrestrial biosphere and land-based sources of methane such as wetlands, rice paddies, ruminants, etc.
- (ii) The low reflectivity of water in the 1.6 μm region used to retrieve the GHG columns typically results in low signal levels (with some exceptions, e.g., sun-glint observations) and therefore large noise.

Based on these considerations the requirements on random errors (precision) are:

REQ-GHGCCI-ERR-1	<p>The XCO₂ and XCH₄ ECV data products over land shall meet the random error (precision) requirements given in Table 1.</p> <p><i>The required thresholds refer to global long-term statistics (i.e., they refer to the ensemble of data products, i.e., of individual retrievals). Locally in space and time larger values may be acceptable.</i></p>
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Based on these considerations the requirements on systematic errors are:

REQ-GHGCCI-ERR-2	<p>The XCO₂ and XCH₄ ECV data products over land shall meet the systematic error requirements given in Table 1.</p> <p><i>The required thresholds refer to global long-term statistics (i.e., they refer to the ensemble of data products, i.e., individual retrievals). Locally in space and time larger values may be acceptable.</i></p>
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Correlations:

When the data products are used for inverse modelling purposes, assumptions have to be made concerning error correlations. Inverse modelling will improve if information on error correlations is provided in addition to the uncertainty of the individual retrievals. Error correlation information can be used to deal with systematic observation errors (at least to some extent). How to reliably determine error correlations, i.e., to quantify how the errors of the single ground-pixel retrievals are correlated, has not yet been studied in detail but is an important (new) research topic. As error correlations are expected to depend on time and location (aerosols, residual clouds, surface reflectance, etc.) this is a complex issue. To consider this user need, the following requirement has been formulated:

REQ-GHGCCI-ERR-3	<p>Estimates of the error correlations between the XCO₂ and XCH₄ values retrieved from individual ground-pixels shall be reported.</p> <p><i>No requirement is given yet here on the actual values of these correlations.</i></p>
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Note: It is unlikely that this information can be obtained for each single measurement but it may be possible to determine spatial and temporal error correlation lengths (which likely depend on spatial position and time). A possible approach could be to analyze differences with respect to accurate and precise TCCON FTS retrievals as a function of time/space lags. As this approach has limitations because the TCCON sites are sparse in space and the satellite retrievals are sparse in time, it needs to be studied to what extent state-of-the-art model data can be used to extend the analysis.



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Requirements for regional CO₂ and CH₄ source/sink determination

Parameter	Req. type	Random error ("Precision")		Systematic error	Stability
		Single obs.	1000 ² km ² monthly		
XCO ₂	G	< 1 ppm	< 0.3 ppm	< 0.2 ppm (absolute)	As systematic error but per year
	B	< 3 ppm	< 1.0 ppm	< 0.3 ppm (relative [§])	-"
	T	< 8 ppm	< 1.3 ppm	< 0.5 ppm (relative [#])	-"
XCH ₄	G	< 9 ppb	< 3 ppb	< 1 ppb (absolute)	< 1 ppb/year (absolute)
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative [§])	< 2 ppb/year (relative [§])
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative [#])	< 3 ppb/year (relative [#])

Table 1: GHG-CCI XCO₂ and XCH₄ random ("precision") and systematic retrieval error requirements for measurements **over land**. Abbreviations: G=Goal, B=Breakthrough, T=Threshold requirement. [§] 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.

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5.6 Validation

Validation against high precision / low systematic errors ground-based XCO₂ and XCH₄ retrievals is required.

The most appropriate network for this purpose is TCCON (Total Carbon Column Observing Network; <http://www.tccon.caltech.edu/>), which is a network of FTS sites designed for the purpose of validating satellite XCO₂ and XCH₄ retrievals.


According to **/Wunch et al., 2010/**: “Total Carbon Column Observing Network (TCCON) achieves an accuracy and precision in total column measurements that is unprecedented for remote sensing observations (better than 0.25% for CO₂).”

According to **/Toon et al., 2009/**: “The precision of the resulting mole fractions retrieved from single spectra is about 0.15% for CO₂, 0.2% for CH₄, 0.3% for N₂O and 0.5% for CO. The absolute accuracy is limited by spectroscopic inadequacies (~1% for CO₂, ~2% for CH₄), but this can be substantially reduced by validation, i.e., airborne profiling using accurate in situ sensors.”

This indicates that TCCON has low errors and is therefore well suited for validation of the GHG-CCI XCO₂ and XCH₄ satellite data products. However, we note that TCCON data may not meet the challenging systematic error requirements yet (e.g., https://tccon-wiki.caltech.edu/Network_Policy/Data_Use_Policy/Data_Description#Laser_Sampling_Errors) and therefore may not allow verifying this requirement in the satellite retrievals.

REQ-GHGCCI-VAL-1	<p>The XCO₂ and XCH₄ ECV data products shall be validated using TCCON.</p> <p><i>Note: A proper validation requires to consider also the averaging kernels and a-priori profiles of the satellite AND FTS retrievals (see, e.g., /Rodgers, 2000/ and /Rodgers and Connor, 2003/). This information therefore needs to be provided as part of the data product(s) and used for validation.</i></p>
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Note: TCCON will be the basis for validation. Some limitations exist though, mainly due to the sparseness of the TCCON measurement network. Because of limited TCCON coverage, validation is possible only for a limited range of conditions. Within GHG-CCI the satellite data products will therefore also be compared with other measurements (e.g., NDACC column-averaged XCH₄ and WMO/AGAGE in-situ observations) and XCO₂ and XCH₄ obtained from state-of-the-art models. However, all these approaches (and appropriate combinations of the available reference data) also have their limitations. How to optimally validate the satellite XCO₂ and XCH₄ data products remains a research topic.

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6 Across-ECV requirements

The following shall be considered (from /CMUG-RBD, 2010/ except *Notes in italic*):

To ensure consistency between ECV datasets, which is important for climate modelling and reanalyses, there are a number of considerations that should be respected for the CCI projects.

Firstly, the specification of error characteristics should be provided in a consistent way and, where appropriate, separated into precision, accuracy and stability. The errors should also be specified, where possible, for each single measurement.

Note: consistency will be facilitated by the adoption of international terminology (ISO 5725), which is not the case at present.


Secondly, the use of common ancillary fields is important. ERA-Interim will be a good source of atmospheric fields from 1989 onwards with ERA-40 available before that. This would ensure a consistent assumption on the atmospheric state for all ECV datasets. The next reanalysis will be ERA-CLIM with improvements to the model and observational datasets. This, however, will not be ready in time for the CCI projects at least in phase 1. For surface fields an agreed SINGLE source for surface albedo, vegetation (LAI, FAPAR), emissivity, ice caps and glacier climatology, sea ice, SST etc. should be defined and agreed by the CCI projects. If this is not done inevitable inconsistencies will be seen in the products which will be only due to different representations of the atmosphere/surface being assumed.

Note: It is not clear why this should be the case. The requirements on meteorological data, surface albedo, etc., may differ significantly between the CCI sub-projects. For example, the albedo depends on ground pixel size, wavelength, etc., and the optimal albedo for GHG-CCI and other projects (e.g., GHG-SST) may differ significantly. Similar remarks are also valid for the other parameters. What is essential for GHG-CCI is that those parameters are used which result in the highest quality XCO₂ and XCH₄ retrievals.

Thirdly, horizontal grids should be common to level 3 products to enable easy comparisons and processing of data from different ECV CDRs. Similarly the definition of atmospheric layering should be common across ECVs (e.g. aerosol and clouds) for level 2 and 3 products.


Note: GHG-CCI users require Level 2 for surface flux inverse modelling, not Level 3. For GHG-CCI the atmospheric layering must be such that the quality of the retrieved XCO₂ and XCH₄ is highest (or that at least a good compromise between retrieval error and processing speed can be obtained). For this reason and because XCO₂ and XCH₄ are column-averaged quantities, the use of a common layering is not necessarily appropriate for GHG-CCI.

Fourthly, the CCI should converge on terminology as this can be different for each ECV project and will enhance communication across the project.

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Note: This convergence should be consistent with international standards (ISO 5725), which is not the case at present.

Finally, and this is addressed below, the formats and projections of the dataset should be as common as possible and familiar to climate modellers. CCI datasets should be located at a common data centre which can provide a common easy to use interface to all the datasets.

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7 Requirements for observation operators and other tools

In this section requirements for observation operators and other tools are given.

7.1 Observation operators


In order to construct appropriate observation operators for the GHG-CCI XCO₂ and XCH₄ data products Averaging Kernels (AK) and (CO₂ and CH₄) a-priori profiles as used by the retrieval algorithms need to be made available to the users.

REQ-GHGCCI-OO-1	For each ECV data product all information needed to construct the corresponding observation operator such as Averaging Kernels (AK) and used CO ₂ and CH ₄ a-priori profiles need to be made available.
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7.2 Routines and documentation to ingest CDRs

The following shall be considered (from /CMUG-RBD, 2010/):

It is vital that climate modellers are able to easily ingest the CCI datasets into their modelling environments. The aim is to make the format as familiar to users as possible (see next section) so they probably have the tools they need already but nevertheless the option of tools to read in the data should be provided. One way to ensure easy to use datasets is to impose a consistent naming convention across the ECV projects and beyond. To make reading the datasets as easy as possible a small software package consisting of source code, documentation, build scripts, and installation tests (sample input data and expected output from test programs in order to verify correct installation) is envisaged as an effective solution by climate modellers.

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7.3 Metadata

Various metadata are required to generate satellite CDRs such as the GHG ECV data products. This requires appropriate documentation.

REQ-GHGCCI-META-1	<p>Each GHG ECV data product needs a proper documentation of which metadata have been used.</p> <p>Metadata information shall be given in the Product Specification Document (PSD). This refers to information on the underlying Level 1 data product and auxiliary data products used such as meteorological data.</p> <p>Additional information shall be given on the GHG-CCI website. This includes, for example, information on satellite or instrument related anomalies.</p>
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7.4 Map projections

Regional surface flux inverse modelling requires XCO₂ and XCH₄ retrievals for the individual ground pixels including exact geolocation (i.e., spatial) and information on the timing. Therefore, Level 2 data products (swath data, not gridded) are the required input data products for inverse modelling and related applications (e.g., CCDAS).

Level 3 data (e.g., gridded weekly or monthly data products) will not be used as input to obtain information on regional GHG surface sources and sinks. Therefore requirements for map projections have not been formulated.

7.5 Colocation software and data

Data products will be made available for the FTS sites used for validation. Requirements for collocation software have not yet been formulated.

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8 Requirements for data formats and access

In this section requirements for data formats and data access are given.

8.1 Naming convention and documentation

The Level 2 data products need to be properly documented. A dedicated document, the Product Specification Document (PSD), is required where the data products are described in detail. Consistent naming conventions shall be used across the different GHG ECV (sub)products but also, if possible, taking into account the naming conventions used within the other ECV projects.

The following also needs to be considered:

/CMUG-RBD, 2010/: "To make life simple for users the naming conventions for files, datasets and variables must be commonly agreed between users and data producers. A recommended naming convention for individual variables for the CDRs can be accessed here:

<http://cf-pcmdi.llnl.gov/documents/cf-standard-names/standard-name-table/15/cf-standardname-table.html>


together with guidance on what the convention is:

<http://cf-pcmdi.llnl.gov/documents/cf-standard-names/guidelines>".

REQ-GHGCCI-NCD-1	<p>There shall be a Product Specification Document (PSD), which provides a detailed description of the GHG ECV data products.</p> <p>Consistent naming conventions shall be used for the different GHG ECV (sub)products but also, if possible, by adopting the naming conventions used for the other ECV projects and available standard naming conventions, most notably the naming conventions given in http://cfconventions.org/</p>
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In addition, the algorithms shall be described in sufficient detail.

REQ-GHGCCI-NCD-2	<p>The retrieval algorithms shall be described in sufficient details via an Algorithm Theoretical Basis Document (ATBD) and/or peer-reviewed publications.</p>
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8.2 Data formats

The users of the GHG ECV data products, as represented by the GHG-CCI CRG, need data products which contain all the information required for surface flux inverse modelling such as retrieved XCO₂ and XCH₄ values for individual ground pixels, their errors, corresponding averaging kernels, used a-priori profiles, etc.

The users are happy with most standard formats (e.g., the format currently used for SCIAMACHY XCH₄ inverse modelling) as long as the data product contains all the required information and is properly documented. Consequently, requirements on the data format have not been formulated.

The users need Level 2 data products rather than Level 3.

/CMUG-RBD, 2010/: “The use of swath based data (levels 1 and 2) in NetCDF is still under development but remains the preferred option.”

Based on this the following requirement has been formulated:

REQ-GHGCCI-DFO-1	The GHG ECV data products shall be in NetCDF format (preferred option) but other data formats are also useful/possible.
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8.3 Data access


There shall be a single website where all relevant information about the GHG ECV data products is given including links to documentation and data access information. This website shall be part of the GHG-CCI website. GHG ECV data products shall be made available via the GHG-CCI project website either via web access via a browser or via ftp

REQ-GHGCCI-DA-1	The GHG ECV data products shall be made available via the GHG-CCI project website.
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8.4 Level of processing


The data products needed to obtain information on regional CO₂ and CH₄ surface fluxes are the Level 2 data products. Higher level data products will be generated (e.g., Level 3 such as gridded monthly data) but these data products are not required for the main application of the ECV GHG data products.

REQ-GHGCCI-PROC-1	There shall be GHG ECV Level 2 data products appropriate to obtain information on regional CO ₂ and CH ₄ surface sources and sinks.
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9 References

- /A-Scope, 2008/** Ingman, P., et al., a-scope – advanced space carbon and climate observation of planet earth, ESA Report for Assessment, Nov 2008, SP1313/1, 2008.
- /Baker et al., 2010/** Baker, D. F., Bösch, H., Doney, S. C., O'Brien, D., and Schimel, D. S.: Carbon source/sink information provided by column CO₂ measurements from the Orbiting Carbon Observatory, *Atmos. Chem. Phys.*, 10, 4145-4165, doi:10.5194/acp-10-4145-2010, 2010.
- /Barkley et al., 2006/** Barkley, M. P., Monks, P. S., and Engelen, R. J.: Comparison of SCIAMACHY and AIRS CO₂ measurements over North America during the summer and autumn of 2003, *Geophys. Res. Lett.*, 33, L20805, doi:10.1029/2006GL026807, 2006.
- /Bergamaschi et al., 2009/** Bergamaschi, P., Frankenberg, C., Meirink, J. F., Krol, M., Villani, M. G., Houweling, S., Dentener, F., Dlugokencky, E. J., Miller, J. B., Gatti, L. V., Engel, A., and Levin, I.: Inverse modeling of global and regional CH₄ emissions using SCIAMACHY satellite retrievals, *J. Geophys. Res.*, 114, D22301, doi:10.1029/2009JD012287, 2009.
- /Bergamaschi et al., 2007/** Bergamaschi, P., Frankenberg, C., Meirink, J.F., Krol, M., Dentener, F., Wagner, T., Platt, U., Kaplan, J.O., Körner, S., Heimann, M., Dlugokencky, E.J., and Goede, A.: Satellite cartography of atmospheric methane from SCIAMACHY onboard ENVISAT: 2. Evaluation based on inverse model simulations, *J. Geophys. Res.*, 112, D02304, doi:10.1029/2006JD007268, 2007.
- /Bloom et al., 2010/** Bloom, A. A., Palmer, P. I., Fraser, A., Reay, D. S., and Frankenberg, C.: Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data, *Science*, 327, 322–325, doi:10.1126/science.1175176, 2010.
- /Boesch et al., 2011/** Boesch, H., D. Baker, B. Connor, D. Crisp, and C. Miller, Global characterization of CO₂ column retrievals from shortwave-infrared satellite observations of the Orbiting Carbon Observatory-2 mission, *Remote Sensing*, 3 (2), 270-304, 2011.
- /Bösch et al., 2006/** Bösch, H., Toon, G. C., Sen, B., Washenfelder, R. A., Wennberg, P. O., Buchwitz, M., de Beek, R., Burrows, J. P., Crisp, D., Christi, M., Connor, B. J., Natraj, V., and Yung, Y. L.: Space-based near-infrared CO₂ measurements: Testing the Orbiting Carbon Observatory retrieval algorithm and validation concept using SCIAMACHY observations over Park Falls, Wisconsin, *J. Geophys. Res.*, 111, D23302, doi:10.1029/2006JD007080, 2006.
- /Bousquet et al., 2010/** Bousquet, P., et al., Source attribution of the changes in atmospheric methane for 2006-2008, *Atmos. Chem. Phys. Discuss.*, 10, 27603-27630, 2010.
- /Bovensmann et al., 1999/** Bovensmann, H., J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. H. P. Goede, SCIAMACHY - Mission objectives and measurement modes, *J. Atmos. Sci.*, 56, (2), 127-150, 1999.
- /Bovensmann et al., 2010/** Bovensmann, H., Buchwitz, M., Burrows, J. P., et al., A remote sensing technique for global monitoring of power plant CO₂ emissions from space and related applications, *Atmos. Meas. Tech.*, 3(4), 781–811, doi:10.5194/amt-3-781-2010, 2010.

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/Bréon et al., 2010/ Bréon, F.-M. and Ciais, P.: Spaceborne remote sensing of greenhouse gas concentrations, *C. R. Geosci.*, 342, 412–424, doi:10.1016/j.crte.2009.09.012, 2010.

/Bril et al., 2007a/ Bril, A., Oshchepkov, S., Yokota, T., and Inoue, G.: Parameterization of aerosol and cirrus cloud effects on reflected sunlight spectra measured from space: application of the equivalence theorem, *Applied Optics*, Vol.46(13), 2460-2470, 2007.

/Bril et al., 2007b/ Bril A., Oshchepkov S., Yokota T., Carbon dioxide retrieval from reflected sunlight spectra in the presence of cirrus cloud: model studies. *Proc.SPIE*, 6745 (674502), 1-8, 2007.

/Bril et al., 2008/ Bril A., Oshchepkov S., Yokota T., Correction of atmospheric scattering effects in space-based observations of carbon dioxide: model study of desert dust aerosol. *J.Quant.Spectrosc.Radiat.Transfer*, 109 (10), 1815-1827, 2008.

/Bril et al., 2009/ Bril A., Oshchepkov S., Yokota T., Retrieval of atmospheric methane from high spectral resolution satellite measurements: a correction for cirrus cloud effects. *Appl.Opt.*, 48 (11), 2139-2148, 2009.

/Buchwitz et al., 2000/ Buchwitz, M., Rozanov, V. V., and Burrows, J. P.: A near infrared optimized DOAS method for the fast global retrieval of atmospheric CH₄, CO, CO₂, H₂O, and N₂O total column amounts from SCIAMACHY/ENVISAT-1 nadir radiances, *J. Geophys. Res.*, 105, 15231-15246, 2000.


/Buchwitz et al., 2005/ Buchwitz, M., R. de Beek, J. P. Burrows, H. Bovensmann, T. Warneke, J. Notholt, J. F. Meirink, A. P. H. Goede, P. Bergamaschi, S. Körner, M. Heimann, and A. Schulz, Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: Initial comparison with chemistry and transport models, *Atmos. Chem. Phys.*, 5, 941-962, 2005.

/Buchwitz et al., 2013/ Buchwitz, M., M. Reuter, O. Schneising, H. Boesch, S. Guerlet, B. Dils, I. Aben, R. Armante, P. Bergamaschi, T. Blumenstock, H. Bovensmann, D. Brunner, B. Buchmann, J. P. Burrows, A. Butz, A. Chedin, F. Chevallier, C. D. Crevoisier, N. M. Deutscher, C. Frankenberg, F. Hase, O. P. Hasekamp, J. Heymann, T. Kaminski, A. Laeng, G. Lichtenberg, M. De Maziere, S. Noel, J. Notholt, J. Orphal, C. Popp, R. Parker, M. Scholze, R. Sussmann, G. P. Stiller, T. Warneke, C. Zehner, A. Bril, D. Crisp, D. W. T. Griffith, A. Kuze, C. ODell, S. Oshchepkov, V. Sherlock, H. Suto, P. Wennberg, D. Wunch, T. Yokota, Y. Yoshida, The Greenhouse Gas Climate Change Initiative (GHG-CCI): comparison and quality assessment of near-surface-sensitive satellite-derived CO₂ and CH₄ global data sets, *Remote Sensing of Environment*, doi:10.1016/j.rse.2013.04.024, pp. 19, in press, 2013.

/Burrows et al., 1995/ Burrows, J. P., Hölzle, E., Goede, A. P. H., Visser, H., and Fricke, W.: SCIAMACHY – Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, *Acta Astronautica*, 35, 445–451, 1995.

/Butz et al., 2009/ Butz, André, Otto P. Hasekamp, Christian Frankenberg, and Ilse Aben, "Retrievals of atmospheric CO₂ from simulated space-borne measurements of backscattered near-infrared sunlight: accounting for aerosol effects," *Appl. Opt.* 48, 3322-3336 (2009)

/Chevallier et al., 2005a/ Chevallier, F., R. J. Engelen, and P. Peylin, 2005: The contribution of AIRS data to the estimation of CO₂ sources and sinks. *Geophys. Res. Lett.*, 32, L23801, doi:10.1029/2005GL024229.

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/Chevallier et al., 2005b/ Chevallier, F., M. Fisher, P. Peylin, S. Serrar, P. Bousquet, F.-M. Bréon, A. Chédin, and P. Ciais, 2005: Inferring CO₂ sources and sinks from satellite observations: method and application to TOVS data. *J. Geophys. Res.*, 110, D24309, doi:10.1029/2005JD006390.

/Chevallier et al., 2007/ Chevallier, F., F.-M. Bréon, and P. J. Rayner, 2007: Contribution of the Orbiting Carbon Observatory to the estimation of CO₂ sources and sinks: Theoretical study in a variational data assimilation framework. *J. Geophys. Res.*, 112, D09307, doi:10.1029/2006JD007375.

/Chevallier et al., 2009a/ Chevallier, F., R. J. Engelen, C. Carouge, T. J. Conway, P. Peylin, C. Pickett-Heaps, M. Ramonet, P. J. Rayner and I. Xueref-Remy, 2009: AIRS-based vs. surface-based estimation of carbon surface fluxes. *J. Geophys. Res.*, 114, D20303, doi:10.1029/2009JD012311.

/Chevallier et al., 2009b/ Chevallier, F., S. Maksyutov, P. Bousquet, F.-M. Bréon, R. Saito, Y. Yoshida, and T. Yokota, 2009: On the accuracy of the CO₂ surface fluxes to be estimated from the GOSAT observations. *Geophys. Res. Lett.*, 36, L19807, doi:10.1029/2009GL040108.

/Chevallier et al., 2010/ Chevallier, F., Feng, L., Boesch, H. Palmer, P., and Rayner, P., On the impact of transport model errors for the estimation of CO₂ surface fluxes from GOSAT observations, *Geophys. Res. Lett.*, 37, L21803, 2010.

/Chevallier et al., 2014/ Chevallier, F., P. I. Palmer, L. Feng, H. Boesch, C. O'Dell, and P. Bousquet, Towards robust and consistent regional CO₂ flux estimates from in situ and space-borne measurements of atmospheric CO₂, *Geophys. Res. Lett.*, 41, doi:10.1002/2013GL058772.


/CMUG-RBD, 2010/ Climate Modelling User Group Requirements Baseline Document, Deliverable 1.2, Number D1.2, Version 1.3, 2 Nov 2010.

/Connor et al., 2008/ Connor, B. J., H. Boesch, G. Toon, B. Sen, C. Miller, and D. Crisp (2008), Orbiting Carbon Observatory: Inverse method and prospective error analysis, *J. Geophys. Res.*, 113, D05305, doi:10.1029/2006JD008336.

/Corbin et al., 2008/ Corbin, K. D., A. S. Denning, L. Lu, J.-W. Wang, and I. T. Baker (2008), Possible representation errors in inversions of satellite CO₂ retrievals, *J. Geophys. Res.*, 113, D02301, doi:10.1029/2007JD008716.

/Cressot et al., 2014/ Cressot, C., F. Chevallier, B. Bousquet, C. Crevoisier, E. J. Dlugokencky, A. Fortems-Cheiney, C. Frankenberg, R. Parker, I. Pison, R. A. Scheepmaker, S. A. Montzka, P. B. Krummel, L. P. Steele, and R. L. Langenfelds (2014),: On the consistency between global and regional methane emissions inferred from SCIAMACHY, TANSO-FTS, IASI and surface measurements, *Atmos. Chem. Phys.*, 14, 577-592, doi:10.5194/acp-14-577-2014

/Crisp et al., 2004/ Crisp, D., Atlas, R. M., Breon, F.-M., Brown, L. R., Burrows, J. P., Ciais, P., Connor, B. J., Doney, S. C., Fung, I. Y., Jacob, D. J., Miller, C. E., O'Brien, D., Pawson, S., Randerson, J. T., Rayner, P., Salawitch, R. S., Sander, S. P., Sen, B., Stephens, G. L., Tans, P. P., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Yung, Y. L., Kuang, Z., Chudasama, B., Sprague, G., Weiss, P., Pollock, R., Kenyon, D., and Schroll, S.: The Orbiting Carbon Observatory (OCO) mission, *Adv. Space Res.*, 34, 700-709, 2004.

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/Dlugokencky et al., 2009/ Dlugokencky, E. J., Bruhwiler, L., White, J. W. C., Emmons, L. K., Novelli, P. C., Montzka, S. A., Masarie, K. A., Lang, P. M., Crotwell, A. M., Miller, J. B., and Gatti, L. V.: Observational constraints on recent increases in the atmospheric CH₄ burden, *Geophys. Res. Lett.*, 36, L18803, doi:10.1029/2009GL039780, 2009.

/Feng et al., 2009/ Feng L., Palmer P. I., Boesch H., and Dance S., Estimating surface CO₂ fluxes from space-borne CO₂ dry air mole fraction observations using an ensemble Kalman Filter, *Atmos. Chem. Phys.*, 2009.

/Frankenberg et al., 2005a/ Frankenberg, C., Platt, U., and Wagner, T.: Iterative maximum a posteriori (IMAP-)DOAS for retrieval of strongly absorbing trace gases: Model studies for CH₄ and CO₂ retrieval from near-infrared spectra of SCIAMACHY onboard ENVISAT, *Atmos. Chem. Phys.*, 5, 9-22, 2005.

/Frankenberg et al., 2005b/ Frankenberg, C., Meirink, J. F., van Weele, M., Platt, U., and Wagner, T.: Assessing methane emissions from global spaceborne observations, *Science*, 308, 1010-1014, 2005.

/Frankenberg et al., 2006/ Frankenberg, C., Meirink, J. F., Bergamaschi, P., Goede, A. P. H., Heimann, M., Körner, S., Platt, U., van Weele, M., and Wagner, T., Satellite cartography of atmospheric methane from SCIAMACHY onboard ENVISAT: Analysis of the years 2003 and 2004, *J. Geophys. Res.*, 111, D07303, 2006.

/Frankenberg et al., 2008/ Frankenberg, C., Bergamaschi, P., Butz, A., Houweling, S., Meirink, J. F., Notholt, J., Petersen, A. K., Schrijver, H., Warneke, T., and Aben, I., Tropical methane emissions: A revised view from SCIAMACHY onboard ENVISAT, *Geophys. Res. Lett.*, 35, L15881, 2008.


/Frankenberg et al., 2011/ Frankenberg, C., Aben, I., Bergamaschi, P., Dlugokencky, E. J., van Hees, R., Houweling, S., van der Meer, P., Snel, R., and Tol, P., Global column-averaged methane mixing ratios from 2003-2009 as derived from SCIAMACHY: Trends and variability, *J. Geophys. Res.* (in press), 2011.

/Fraser et al., 2013/ Fraser, A., Palmer, P. I., Feng, L., Boesch, H., Cogan, A., Parker, R., Dlugokencky, E. J., Fraser, P. J., Krummel, P. B., Langenfelds, R. L., O'Doherty, S., Prinn, R. G., Steele, L. P., van der Schoot, M., and Weiss, R. F. Estimating regional methane surface fluxes: the relative importance of surface and GOSAT mole fraction measurements, *Atmos. Chem. Phys.*, 13, 5697-5713, doi:10.5194/acp-13-5697-2013, 2013.

/Fraser et al., 2014/ Fraser, A., Palmer, P. I., Feng, L., Bösch, H., Parker, R., Dlugokencky, E. J., Krummel, P. B., and Langenfelds, R. L. Estimating regional fluxes of CO₂ and CH₄ using space-borne observations of XCH₄ : XCO₂, *Atmos. Chem. Phys. Discuss.*, 14, 15867-15894, doi:10.5194/acpd-14-15867-2014, 2014.

/GCOS-107/ Global Climate Observing System (GCOS), SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED PRODUCTS FOR CLIMATE, Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC", Prepared by World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission, United Nations Environment Programme (UNEP), International Council for Science, Doc.: GCOS 107 (WMO/TD No. 1338), Sept 2006, 2006.

/GCOS-154/ Global Climate Observing System (GCOS), SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED PRODUCTS FOR CLIMATE, Supplemental

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details to the satellite-based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 update)”, Prepared by World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission, United Nations Environment Programme (UNEP), International Council for Science, Doc.: GCOS 154, 2010.

/Heymann et al., 2012b/ Heymann, J., H. Bovensmann, M. Buchwitz, J. P. Burrows, N. M. Deutscher, J. Notholt, M. Rettinger, M. Reuter, O. Schneising, R. Sussmann, and T. Warneke SCIAMACHY WFM-DOAS XCO₂: reduction of scattering related errors, *Atmos. Meas. Tech.*, 5, 2375-2390, 2012.

/Heymann et al., 2012a/ Heymann, J., O. Schneising, M. Reuter, M. Buchwitz, V. V. Rozanov, V. A. Velazco, H. Bovensmann, and J. P. Burrows, SCIAMACHY WFM-DOAS XCO₂: comparison with CarbonTracker XCO₂ focusing on aerosols and thin clouds, *Atmos. Meas. Tech.*, 5, 1935-1952, 2012.

/Hollmann et al., 2013/ Hollmann, C.J. Merchant, R. Saunders, C. Downy, M. Buchwitz, A. Cazenave, E. Chuvieco, P. Defourny, G. de Leeuw, R. Forsberg, T. Holzer-Popp, F. Paul, S. Sandven, S. Sathyendranath, M. van Roozendaal, W. Wagner, The ESA Climate Change Initiative: satellite data records for essential climate variables, *Bulletin of the American Meteorological Society (BAMS)*, 0.1175/BAMS-D-11-00254.1, pp. 12, 2013.

/Houweling et al., 2010/ Houweling, S., Aben, I., Bréon, F.-M., Chevallier, F., Deutscher, N., Engelen, R., Gerbig, C., Griffith, D., Hungershofer, K., Macatangay, R., Marshall, J., Notholt, J., Peters, W., and Serrar, S.: The importance of transport model uncertainties for the estimation of CO₂ sources and sinks using satellite measurements, *Atmos. Chem. Phys.*, 10, 9981–9992, doi:10.5194/acp-10-9981-2010, 2010.


/Houweling et al., 2005/ Houweling, S., Hartmann, W., Aben, I., Schrijver, H., Skidmore, J., Roelofs, G.-J., and Breon, F.-M.: Evidence of systematic errors in SCIAMACHY-observed CO₂ due to aerosols, *Atmos. Chem. Phys.*, 5, 3003–3013, 2005.

/Houweling et al., 2004/ Houweling, S., Breon, F.-M., Aben, I., Rödenbeck, C., Gloor, M., Heimann, M. and Ciais, P.: Inverse modeling of CO₂ sources and sinks using satellite data: A synthetic inter-comparison of measurement techniques and their performance as a function of space and time, *Atmos. Chem. Phys.*, 4, 523-538, 2004.

/Hungershofer et al., 2010/ Hungershofer, K., Breon, F.-M., Peylin, P., Chevallier, F., Rayner, P., Klonecki, A., Houweling, S., and Marshall, J., Evaluation of various observing systems for the global monitoring of CO₂ surface fluxes, *Atmos. Chem. Phys.*, 10, 10503-10520, 2010.

/IPCC, 2007/ Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L.: *Climate change 2007: The physical science basis*, Contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge (UK), New York (USA), 996 pp, 2007.

/JCGM, 2008/ JCGM/WG 1, Working Group 1 of the Joint Committee for Guides in Metrology, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf, 2008.

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/Kaminski et al., 2010/ Kaminski, T., Scholze, M. and Houweling, S.: Quantifying the benefit of A-SCOPE data for reducing uncertainties in terrestrial carbon fluxes in CCDAS, *Tellus*, 62B(5), 784–796, 2010.

/Karion et al., 2010/ Karion, A., Sweeney, C., Tans, P., and Newberger, T., 2010: AirCore: An Innovative Atmospheric Sampling System. *J. Atmos. Oceanic Technol.*, 27, 1839–1853, 2010.

/Kuze et al., 2010/ Kuze, A., Suto, H., Nakajima, M., and Hamazaki, T., Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gas monitoring, *Applied Optics*, Vol. 48, No. 35, 6716-6733, 2010.

/Meirink et al., 2006/ Meirink, J.-F., Eskes, H. J., and Goede, A. P. H.: Sensitivity analysis of methane emissions derived from SCIAMACHY observations through inverse modelling, *Atmos. Chem. Phys.*, 6, 1275-1292, 2006.

/Miller et al., 2007/ Miller, C. E., Crisp, D., DeCola, P. L., et al.: Precision requirements for space-based X_{CO_2} data, *J. Geophys. Res.*, 112, D10314, doi:10.1029/2006JD007659, 2007.

/Nakajima et al., 2010/ Nakajima, M., A.Kuze, S.Kawakami, K.Shiomi, H.Suto, MONITORING OF THE GREENHOUSE GASES FROM SPACE BY GOSAT, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, Volume XXXVIII, Part 8, Kyoto, Japan, 2010.

/NRC, 2010/ NRC 2010: National Research Council – Committee on Methods for Estimating Greenhouse Gas Emissions, *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements*, ISBN: 0-309-15212-7, 144 pages, <http://www.nap.edu/catalog/12883.html>, 2010.

/Oshchepkov et al., 2008/ Oshchepkov S., Bril A., Yokota T., PPDF-based method to account for atmospheric light scattering in observations of carbon dioxide from space. *J.Geophys.Res.*, 113, D23210, 2008.


/Oshchepkov et al., 2009/ Oshchepkov S., Bril A., Yokota T., An improved photon path length probability density function -based radiative transfer model for space-based observation of greenhouse gases. *J.Geophys.Res.*, 114, D19207, 2009.

/Peters et al., 2007/ Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., Miller, J. B., Bruhwiler, L. M. P., Petron, G., Hirsch, A. I., Worthy, D. E. J., van der Werf, G. R., Randerson, J. T., Wennberg, P. O., Krol, M. C., and Tans, P. P.: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, *Proceedings of the National Academy of Sciences (PNAS) of the United States of America*, 27 November 2007, 104(48), 18925-18930, 2007.

/Rayner and O'Brien, 2001/ Rayner, P. J., and O'Brien, D.M.: The utility of remotely sensed CO_2 concentration data in surface inversions, *Geophys. Res. Lett.*, 28, 175-178, 2001.

/Reuter et al., 2010/ Reuter, M., Buchwitz, M., Schneising, O., Heymann, J., Bovensmann, H., and Burrows, J. P., A method for improved SCIAMACHY CO_2 retrieval in the presence of optically thin clouds, *Atmos. Meas. Tech.*, 3, 209-232, 2010.

/Reuter et al., 2011/ Reuter, M., Bovensmann, H., Buchwitz, M., et al., Retrieval of atmospheric CO_2 with enhanced accuracy and precision from SCIAMACHY: Validation with

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FTS measurements and comparison with model results, *J. Geophys. Res.*, 116, D04301, doi:10.1029/2010JD015047, 2011.

/Reuter et al., 2013/ Reuter, M., H. Boesch, H. Bovensmann, A. Bril, M. Buchwitz, A. Butz, J. P. Burrows, C. W. O'Dell, S. Guerlet, O. Hasekamp, J. Heymann, N. Kikuchi, S. Oshchepkov, R. Parker, S. Pfeifer, O. Schneising, T. Yokota, and Y. Yoshida, A joint effort to deliver satellite retrieved atmospheric CO₂ concentrations for surface flux inversions: the ensemble median algorithm EMMA, *Atmos. Chem. Phys.*, 13, 1771-1780, 2013.

/Rigby et al., 2008/ Rigby, M., Prinn, R. G., Fraser, P. J., Simmonds, P. G., Langenfelds, R. L., Huang, J., Cunnold, D. M., Steele, L. P., Krummel, P. B., Weiss, R. F., O'Doherty, S., Salameh, P. K., Wang, H. J., Harth, C. M., Mühle, J., and Porter, L. W.: Renewed growth of atmospheric methane, *Geophys. Res. Lett.*, 35, L22805, doi:10.1029/2008GL036037, 2008.

/Rodgers, 2000/ Rodgers, C. D., *Inverse methods for atmospheric sounding – Theory and practice*, World Scientific Series on Atmospheric, Ocean and Planetary Physics Vol. 2, 2000.

/Rodgers and Connor, 2003/ Rodgers, C. D., and B. J. Connor, Intercomparison of remote sounding instruments, *J. Geophys. Res.*, 108(D3), 4116, doi:10.1029/2002JD002299, 2003.

/Schneising et al., 2014/ Schneising, O., M. Reuter, M. Buchwitz, J. Heymann, H. Bovensmann, and J. P. Burrows, Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in response to interannual surface temperature variability, *Atmos. Chem. Phys.*, 14, 133-141, 2014.

/Schneising et al., 2013/ Schneising, O., J. Heymann, M. Buchwitz, M. Reuter, H. Bovensmann, and J. P. Burrows, Anthropogenic carbon dioxide source areas observed from space: assessment of regional enhancements and trends, *Atmos. Chem. Phys.*, 13, 2445-2454, doi:10.5194/acp-13-2445-2013, 2013.


/Schneising et al., 2012/ Schneising, O., P. Bergamaschi, H. Bovensmann, M. Buchwitz, J. P. Burrows, N. M. Deutscher, D. W. T. Griffith, J. Heymann, R. Macatangay, J. Messerschmidt, J. Notholt, M. Rettinger, M. Reuter, R. Sussmann, V. A. Velasco, T. Warneke, P. O. Wennberg, and D. Wunch, Atmospheric greenhouse gases retrieved from SCIAMACHY: comparison to ground-based FTS measurements and model results, *Atmos. Chem. Phys.*, 12, 1527-1540, 2012.

/Schneising et al., 2011/ Schneising, O., Buchwitz, M., Reuter, M., Heymann, J., Bovensmann, H., Burrows, J. P., Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, *Atmos. Chem. Phys.*, 11, 2881-2892, 2011.

/Schneising et al., 2010/ Schneising, O., Buchwitz, M., Reuter, M., Heymann, J., Bovensmann, H., and Burrows, J. P., Long-term analysis of carbon dioxide and methane column-averaged mole fractions retrieved from SCIAMACHY, *Atmos. Chem. Phys. Discuss.*, 10, 27479-27522, 2010.

/Schneising et al., 2009/ Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, H., Bergamaschi, P., and Peters, W., Three years of greenhouse gas column-averaged dry air mole fractions retrieved from satellite - Part 2: Methane, *Atmos. Chem. Phys.*, 9, 443-465, 2009.

/Schneising et al., 2008/ Schneising, O., Buchwitz, M., Burrows, J. P., Bovensmann, H., Reuter, M., Notholt, J., Macatangay, R., and Warneke, T., Three years of greenhouse gas

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column-averaged dry air mole fractions retrieved from satellite - Part 1: Carbon dioxide, Atmos. Chem. Phys., 8, 3827-3853, 2008.

/Stephens et al., 2007/ Stephens, B. B., Gurney, K. R., Tans, P. P., Sweeney, C., Peters, W., Bruhwiler, L., Ciais, P., Ramonet, M., Bousquet, P., Nakazawa, T., Aoki, S., Machida, T., Inoue, G., Vinnichenko, N., Lloyd, J., Jordan, A., Heimann, M., Shibistova, O., Langenfelds, R. L., Steele, L. P., Francey, R. J., and Denning, A. S.: Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO₂, Science, 316, 1732-1735, 2007.

/Toon et al., 2009/ Toon, Geoffrey, Jean-Francois Blavier, Rebecca Washenfelder, Debra Wunch, Gretchen Keppel-Aleks, Paul Wennberg, Brian Connor, Vanessa Sherlock, David Griffith, Nick Deutscher, Justus Notholt, Total Column Carbon Observing Network (TCCON), publication OSA FTS Meeting, 2009.


Link: http://www.tcccon.caltech.edu/publications/OSA_FTS_Meeting_20090323.pdf

/Wunch et al., 2010/ Wunch, D, G. C. Toon, J.-F. L. Blavier, R. A. Washenfelder, J. Notholt, B. J. Connor, D. W. T. Griffith, V. Sherlock and P. O. Wennberg. The Total Carbon Column Observing Network. Phil. Trans. R. Soc. A, 2011, in press.

Link: <https://tcccon-wiki.caltech.edu/@api/deki/files/885/=ProofTCCON.pdf>

/Yokota et al., 2004/ Yokota, T., Oguma, H., Morino, I., and Inoue, G.: A nadir looking SWIR sensor to monitor CO₂ column density for Japanese GOSAT project, Proceedings of the twenty-fourth international symposium on space technology and science. Miyazaki: Japan Society for Aeronautical and Space Sciences and ISTS, pp. 887–889, 2004.

/Yoshida et al., 2010/ Yoshida, Y., Ota, Y., Eguchi, N., Kikuchi, N., Nobuta, K., Tran, H., Morino, I., and Yokota, T., Retrieval algorithm for CO₂ and CH₄ column abundances from short-wavelength infrared spectral observations by Greenhouse Gases Observing Satellite, Atmos. Meas. Tech. Discuss., 3, 4791-4833, 2010.

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10 Acronyms

Abbreviation	Meaning
ACE-FTS	Atmospheric Chemistry Experiment-Fourier Transform Spectrometer
AATSR	Advanced Along Track Scanning Radiometer
ACA	Additional Constraints Algorithm
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
ATBD	Algorithm Theoretical Basis Document
CCDAS	Carbon Cycle Data Assimilation System
CCI	Climate Change Initiative
CMUG	Climate Modelling User Group (of ESA's CCI)
CRG	Climate Research Group
D/B	Data base
DOAS	Differential Optical Absorption Spectroscopy
DPM	Detailed Processing Model
EC	European Commission
ECA	ECV Core Algorithm
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FCDR	Fundamental Climate Data Record
FP	Full Physics
FTIR	Fourier Transform InfraRed
FTS	Fourier Transform Spectrometer
GCOS	Global Climate Observing System




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GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GHG	GreenHouse Gas
GOME	Global Ozone Monitoring Experiment
GMES	Global Monitoring for Environment and Security
GOSAT	Greenhouse Gases Observing Satellite
GTOS	Global Terrestrial Observing System
IASI	Infrared Atmospheric Sounding Interferometer
IPCC	International Panel in Climate Change
IUP	Institute of Environmental Physics (IUP) of the University of Bremen, Germany
JCGM	Joint Committee for Guides in Metrology
LMD	Laboratoire de Météorologie Dynamique
MACC	Monitoring Atmospheric Composition and Climate, EU GMES project
MERIS	Medium Resolution Imaging Spectrometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MODIS	Moderate Resolution Imaging Spectrometer
NA	Not applicable
NDACC	Network for the Detection of Atmospheric Composition Change
NASA	National Aeronautics and Space Administration
NIES	National Institute for Environmental Studies
NOAA	National Oceanic and Atmospheric Administration
OCO	Orbiting Carbon Observatory
PBL	Planetary Boundary Layer
RMS	Root-Mean-Square
RTM	Radiative transfer model
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY
TANSO	Thermal And Near infrared Sensor for carbon Observation
TCCON	Total Carbon Column Observing Network
TES	Tropospheric Emission Spectrometer

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11 Annex A: GCOS GHG requirements

The following is from **/GCOS-154/**, section 3.1.8 “ECV Carbon Dioxide, Methane and other Greenhouse Gases”. URDv1 used the previous version of this document **/GCOS-107/**

Carbon dioxide is the dominant greenhouse gas emitted by anthropogenic activities. The atmospheric build-up is caused mostly by the combustion of coal, oil, and natural gas and reflects to a significant extent cumulative anthropogenic emissions rather than the current rate of emissions.


Methane (CH₄) is the second most significant anthropogenically emitted greenhouse gas, and its level has also been increasing since preindustrial times.. Other long-lived GHGs include nitrous oxide (N₂O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF₆), and perfluorocarbons (PFCs). The relative radiative forcing of CH₄ in 2008 was about 18 per cent of the total radiative forcing caused by all long-lived greenhouse gases in the atmosphere since the beginning of industrial time. The Kyoto Protocol of the UNFCCC includes future restrictions on the release of GHGs, including CO₂, CH₄, N₂O, HFCs, SF₆, and PFCs. The Montreal Protocol on Substances that Deplete the Ozone Layer includes mandatory restrictions for individual countries on the production and consumption of those CFCs and HCFCs that are also GHGs.

Satellite measurements are emerging as an important component of the overall observing system for CO₂ and CH₄. Methane was first measured in the stratosphere by SAMS in the 1980s and then by HALOE (1991-2005.). The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) instrument made the first global measurements of tropospheric CH₄, and its data are being used in inverse modelling studies to quantify CH₄ emissions. Methane data are also provided currently by ACE-FTS. The AIRS, TES and IASI high-resolution IR sounders are providing information on both CO₂ and CH₄, although with limited vertical range, and their data also have been used in inverting fluxes via data assimilation. The recently launched Greenhouse Gases Observing Satellite (GOSAT) is starting to provide more complete information. Experience in using the data from GOSAT and the future OCO-2 mission will guide the development of the space-based component of the observing system for these two majors GHGs. The planned Sentinel-5p and Sentinel-5 missions will also measure CH₄. Satellite measurements can potentially provide unique information on global emission source identification, which is not possible with ground-based measurements alone.

In the context of this document, detection of sources and sinks of greenhouse gases is the main focus for space-based measurements. Monitoring of global trends of CO₂ and CH₄ as long-lived gases is adequately covered by surface in situ measurements.

The following is needed for these ECVs:

Product A.8.1 Retrievals of CO₂ and CH₄ of sufficient quality to estimate regional sources and sinks

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Benefits

- Improvement in estimates of global means and facilitation of monitoring of the spatial distribution of the key greenhouse gases.
- Satellite-based observations of column values and vertical profiles of the mixing ratio of carbon dioxide, methane and other greenhouse gases, when coupled with reanalysis, providing a tool for assessment of sources and sinks of greenhouse gases, especially CO₂ and CH₄;
- Potential provision of additional background information on the measures on stabilization of the mixing ratios of key greenhouse gases at a level that would prevent dangerous anthropogenic interference with the climate system;
- Provision of estimates of localized surface emissions such as those related to wetlands and rice fields for CH₄ and land-use change for CO₂, where the data products are of sufficient accuracy and resolution.

Target requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Tropospheric CO ₂ column	5-10 km	N/A	4 h	1 ppm	0.2 ppm
Tropospheric CO ₂	5-10 km	5 km	4 h	1 ppm	0.2 ppm
Tropospheric CH ₄ column	5-10 km	N/A	4 h	10 ppb	2 ppb
Tropospheric CH ₄	5-10 km	5 km	4 h	10 ppb	2 ppb
Stratospheric CH ₄	100-200 km	2 km	Daily	5%	0.3%

Rationale: Requirements for tropospheric CO₂ and CH₄ are driven by detection and quantification of the different emission sources via inverse modelling. The primary measurement needed is the tropospheric column, as it provides sensitivity down to the Earth's surface where most of the sinks and sources are located. Research and study of the use of currently available measurements – in situ as well as satellite – in reanalysis is needed to provide a more firmly based statement of essential data requirements, in particular on the extent of detail required in vertical sounding. Initial estimates are based on resolving the values of observed column fluctuations. Time scales that extend from the diurnal to the decadal need to be resolved to allow for a complete description of the processes that determine the distributions of these gases. Spatial variability can be substantial in the planetary boundary layer, reflecting the variability of sources and sinks. Products can, however, be useful for source-sink inversion without resolving the shortest space and time scales.

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CH₄ is not well mixed in the stratosphere, where it is the main chemical source of H₂O. The stratospheric product is needed to support the attribution of water-vapour trends and for determining the radiative influences of stratospheric CH₄ and water vapour.

The global trends, seasonal cycle, and latitudinal gradients of the long-lived greenhouse gases N₂O, CFCs, HCFCs, HFCs, SF₆, and PFCs in the troposphere are well-monitored, using present-day surface networks. Short-term and regional variability of these long-lived gases is mainly in the stratosphere, in relation to their chemical breakdown at these altitudes. Observing the spatio-temporal variability of these gases is important in the stratosphere, where they also provide information on ‘age of air’, but these measurements are largely dependent on the limb/occultation type of satellite observations which are not part of the operational suite of satellite measurements. Some monitoring of the stratospheric distribution changes of long-lived gases is needed for the assessment of radiative and dynamical feedbacks in the stratosphere related to composition changes. Future research studies of these greenhouse gases will, at intervals, require future satellite missions.

Requirements for satellite instruments and satellite datasets

FCDR of appropriate NIR/SWIR/IR radiances, for example through:


- Passive NIR/SWIR operational missions for CO₂ and CH₄, building on the experience with SCIAMACHY and the specialized missions GOSAT and OCO-2 (simultaneous total column CO, such as provided by SCIAMACHY, adds much value for CO₂ source characterization);
- High spectral resolution IR sounding for the upper troposphere and stratosphere, as provided initially by ACE-FTS, AIRS, and IASI;
- Limb-sounding in IR and MW for distributions in the upper troposphere and stratosphere;
- Active NIR/SWIR systems to obtain tropospheric vertical profiles.

Calibration, validation and data archiving needs

- The required comprehensive independent ground-based validation measurements can be provided by the WMO Global Atmosphere Watch (GAW) Global CO₂ and CH₄ Monitoring Networks, including ship and dedicated light aircraft profiles up to 8 km; both these GAW networks are designated by GCOS as comprehensive networks, and subsets are designated as baseline networks;
- A network of surface-based total column CO₂ and CH₄ instruments (TCCON) and continued routine commercial aircraft observations (e.g. CONTRAIL and observations planned by IAGOS-ERI), needed for validation of products;
- Aircraft observations of CO₂ and CH₄, needed to validate the transport in the models that are used in the surface emission inversions using total-column data (part of the total-column variability is related to transport in the upper-troposphere/lower-stratosphere and should not be assigned to the lower troposphere affecting the emission inversion).

Adequacy/inadequacy of current holdings

- Satellite products are still under development, and accuracy requirements have not yet been met (except for CH₄ total column);
- In situ observations of the long-lived gases do not provide a complete 3D distribution in the atmosphere and are rather unevenly distributed in space; most networks are designed for trend detection in the background atmosphere, with minimal sensitivity to (nearby) emissions.

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Immediate action, partnerships and international coordination


- Support for the generation of products through retrieval or, in appropriate cases, data assimilation;
- Execution of planned missions and development and implementation of a plan for sustained measurements sufficient to deliver products of the required accuracy;
- Support for the surface and free-tropospheric measurements needed for calibration and validation;
- Derivation of products from AIRS and SCIAMACHY from 2002 onwards, IASI from 2008, GOSAT from 2009 and, in the future, from OCO-2 and from Sentinel-5p/TROPOMI and Sentinel-5 for CH₄;
- Limb-sounding data for retrieval of stratospheric profiles from current instruments, including those from ACE-FTS (CH₄, N₂O), MIPAS (CH₄, N₂O), and MLS (N₂O);
- Additional data provided by TES for the retrieval of tropospheric CH₄;
- Research towards improved future capabilities, including long-term monitoring of CO₂, CH₄ and other GHGs such as N₂O;
- Coordination by WCRP SPARC and IGBP IGAC.

Link to GCOS Implementation Plan

- [IP-10 Action A26] Establish long-term limb scanning satellite measurements of profiles of water vapour, ozone and other important species from the UT/LS up to 50km;
- [IP-10 Action A28] Maintain and enhance the WMO GAW Global Atmospheric CO₂ and CH₄ Monitoring Networks as major contributions to the GCOS Comprehensive Networks for CO₂ and CH₄;
- [IP-10 Action A29] Assess the value of the data provided by current space-based measurements of CO₂ and CH₄ and develop and implement proposals for follow-on missions accordingly.

Other applications

Carbon dioxide and other greenhouse gas distributions may allow improved retrieval of the temperature and water vapour information from IR sounders for NWP and reanalysis; N₂O measurements are needed for constraining the effects of NO_x on ozone.

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12 Annex B: CMUG GHG requirements

The following is from /CMUG-RBD, 2010/:

A comprehensive understanding of greenhouse gases is crucial for informing societal response to climate change. Applications with a need for observations of greenhouse gases such as CO₂ and CH₄ include Model Development, Decadal Forecasting and Regional Source/Sink Determination. As shown in **Table B.1**, each application has somewhat different observational requirements reflecting the particular aspect of greenhouse gases under consideration.

To elaborate on the GHG observational requirements for Regional Source/Sink Determination, the tabulated values are based on the activities undertaken within the frame of the MACC sub-project on greenhouse gases. The principal products from that sub-project are:

- 4-dimensional gridded fields of CO₂ and CH₄ produced in near-real-time (based on data assimilation of near-real-time data products, typically from operational satellites),
- 4-dimensional gridded fields of CO₂ and CH₄ produced in “delayed mode” (6 months delay, to allow data assimilation of research-mode satellite data products),
- 3-dimensional gridded fluxes of CO₂ and CH₄ produced in “delayed mode”,
- Re-analysed concentration and flux fields of CO₂ and CH₄ for the period 2003-2010.

Flux fields are an important factor for decision-makers at several levels, and need to be estimated with confidence. The fidelity of flux estimates is strongly influenced by accuracy and stability of the observations that are used as input to the data assimilation and re-analysis systems. This drives the requirements given in **Table B.1** for some of the required parameters.

Horizontal Resolution and Observing Cycle requirements are consistent with GCOS, and reflect the spatial and temporal variability of important classes of regional sources and sinks.



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Parameter	Application	Horizontal Resolution	Vertical Resolution	Observing Cycle	Precision	Accuracy	Stability	Types of error
Trace gas profile CH ₄ - Troposphere column	Regional source/sink determination	10/20/50 km	N/A	3/4/6 h	2/4/10% 20/40/100 ppb	0.5/0.7/1.0% 5/7/10 ppb	0.5/0.7/1.0 %/yr 5/7/10 ppb/yr	SSEOB
Trace gas profile CH ₄ - Total column	model development	25km	N/A	1 day	10%	10%	N/A	SSEOB
	decadal f/c	500km	N/A	1 year	2/4/10% 20/40/100 ppb	0.5/0.7/1.0% 5/7/10 ppb	0.5/0.7/1.0 %/yr 5/7/10 ppb/yr	SSAOB
	Regional source/sink determination	10/50/250 km	N/A	3/4/6 h	2/4/10% 20/40/100 ppb	0.5/0.7/1.0% 5/7/10 ppb	0.5/0.7/1.0 %/yr 5/7/10 ppb/yr	SSEOB
Trace gas profile CO ₂ - Total column	model development	100km		monthly	0.5/1ppm	0.5/1ppm	N/A	SSEOB
	decadal f/c	500km	N/A	1 year	1/1.3/2% 3/4/6 ppm	0.15/0.2/0.3% 0.5/0.7/1.0 ppm	0.15/0.2/0.3 %/yr 0.5/0.7/1.0 ppm/yr	SSAOB
	Regional source/sink determination	50/100/500 km	N/A	3/4/6 h	1/1.3/2% 3/4/6 ppm	0.15/0.2/0.3% 0.5/0.7/1.0 ppm	0.15/0.2/0.3 %/yr 0.5/0.7/1.0 ppm/yr	SSEOB
Trace gas profile CO ₂ - Troposphere column	Regional source/sink determination	10/50/500 km	N/A	3/4/6 h	1/1.3/2% 3/4/6 ppm	0.15/0.2/0.3% 0.5/0.7/1.0 ppm	0.15/0.2/0.3 %/yr 0.5/0.7/1.0 ppm/yr	SSEOB

Table B.1: Requirements for satellite observations of greenhouse gases (from /CMUG-RBD, 2010/).

The need for good flux estimates makes the current requirements for accuracy and stability more demanding than previous GCOS requirements. The requirements are given for tropospheric and total column only, in recognition that requirements for profile data would be very demanding for existing satellite data. In the event that data providers consider it feasible to provide profile data approaching GCOS requirements, then more refined user requirements could be given in a future update of this document. The user community increasingly asks for horizontal and vertical resolution in the Lower Stratosphere to be the same as that for the Higher Troposphere, in contrast to previous GCOS requirements. As mentioned above, other applications of greenhouse gas observations may have different sets of requirements. For example, the detection of CH₄ emissions from pipelines or similar small sources would require higher horizontal resolution and vertical resolution in the lower troposphere.

Similar to the ozone section above, it would be important to provide not only merged GHG products but also products from single sensors as separate datasets.

Turning now to the GHG observation requirements for decadal forecasting, it is principally the distribution of the trace gases at the start of the forecast that can be important to help define the atmospheric fields. Long period averages are sufficient for this purpose.



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