ESA Climate Change Initiative (CCI)

User Requirements Document (URD)

for the Essential Climate Variable (ECV)

Greenhouse Gases (GHG)

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1 Summary

This document is User Requirements Document Version 1 (URDv1), which is a deliverable of the ESA project GHG-CCI. The GHG-CCI project started on 1st September 2010. The GHG-CCI project is one of several projects of ESA's Climate Change Initiative (CCI). The GHG-CCI project will deliver the Essential Climate Variable (ECV) Greenhouse Gases (GHG) in line with the "Systematic observation requirements for satellite-based products for climate" as defined by GCOS (Global Climate Observing System): "Product A.9: Distribution of greenhouse gases, such as CO_2 and CH_4, of sufficient quality to estimate regional sources and sinks".

The GHG-CCI project (http://www.esa-ghg-cci.org/) is 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).

In this document initial user requirements are formulated for the ECV Greenhouse Gases. This requires satellite observations which are sensitive to near-surface concentration variations of CO_2 and CH_4. Currently, there are two satellite instruments in orbit which are sensitive to near-surface CO_2 and CH_4 variations: SCIAMACHY on ENVISAT and TANSO onboard GOSAT. The following four data products can be retrieved from these instruments which are relevant for GHG-CCI:

- Column-averaged dry air mole fractions of CO_2, i.e., XCO_2 (in ppm), from SCIAMACHY (nadir mode) and TANSO.
- Column-averaged dry air mole fractions of CH_4, i.e., XCH_4 (in ppb), from SCIAMACHY (nadir mode) and TANSO.

These four data products are the core GHG ECV data products generated within GHG-CCI. In this document user requirements for these data products are formulated for the regional CO_2 and CH_4 surface flux applications. The user requirements are based on peer-reviewed publications, other documents where user requirements have been formulated and user consultation focussing on users which are (also) involved in the European MACC project (http://www.gmes-atmosphere.eu/). A close cooperation between GHG-CCI and MACC/GHG has been established for this purpose.

Within GHG-CCI algorithms and corresponding data products to obtain information on CO_2 and CH_4 in upper atmospheric layers, i.e., layers above the Planetary Boundary Layer (PBL), will also be further developed, improved and assessed. This includes mid/upper tropospheric CO_2 and/or CH_4 from AIRS and IASI, and upper tropospheric and stratospheric CO_2 profiles from ACE-FTS and CH_4 profiles from MIPAS and SCIAMACHY solar occultation (note: several other relevant products exist which are generated outside of this project, e.g., from TES or CH_4 from ACE-FTS). These data products will be used for comparisons and because they are considered useful for the regional CO_2 and CH_4 surface flux application as they have the potential to provide additional constraints for inverse modelling. Their information content with respect to regional surface fluxes is however limited 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 URDv1. However, requirements may be formulated in a future version of the URD as regular updates are planned.

Note that it is not the purpose of this document to specify a future satellite mission.

2 ECV Greenhouse Gases (GHG)

What is the ECV GHG? The ECV GHG is defined in **/GCOS-107/** (see **Annex A**). The ECV GHG is planned to be a (publicly available) data base and corresponding documentation of satellite retrieved GHG information useful to better constrain regional surface sources and sinks of the two most important anthropogenic GHGs carbon dioxide (CO_2) and methane (CH_4).

Two satellite instruments are currently in orbit whose measurements are sensitive to near-surface concentration changes of CO_2 and CH_4 and therefore can deliver information on regional CO_2 and CH_4 surface fluxes: SCIAMACHY **/Burrows et al., 1995/** /**Bovensmann et al., 1999/** onboard ENVISAT and TANSO onboard GOSAT **/Kuze et al., 2010/ /Yokota et al., 2004/**.

Key input data for (inverse) modelling activities to obtain information on CO_2 and CH_4 regional surface fluxes are column-averaged dry air mole fractions of CO_2 and CH_4, i.e., XCO_2 (in ppm) **/A-Scope, 2008/ /Baker et al., 2010/ /Barkley et al., 2006/ /Bösch et al., 2006/ /Bréon et al., 2010/ /Bril et al., 2007a/ /Bril et al., 2007b/ /Bril et al., 2008/ /Bril et al., 2009/ /Buchwitz et al., 2000/ /Buchwitz et al., 2005/ /Butz et al., 2009/ /Chevallier et al., 2005a/ /Chevallier et al., 2007/ /Chevallier et al., 2009b/ /Chevallier et al., 2010/ /Connor et al., 2008/ /Crisp et al., 2004/ / /Feng et al., 2009/ /Houweling et al., 2004/ /Hungershoefer et al., 2010/ /Kaminski et al., 2010/ Miller et al., 2007/ /Nakajima et al., 2010/ /Oshchepkov et al., 2008/ /Oshchepkov et al., 2009/ /Rayner and O'Brien, 2001/ /Reuter et al., 2010/ /Schneising et al., 2008/ /Schneising et al., 2010/ /Yokota et al., 2004/ /Yoshida et al., 2010/** and XCH_4 (in ppb) **/Bergamaschi et al., 2007/ /Bergamaschi et al., 2009/ /Bloom et al., 2010/ /Bousquet et al., 2010/ /Bréon et al., 2010/ /Buchwitz et al., 2000/ /Buchwitz et al., 2005/ /Frankenberg et al., 2005a/ /Frankenberg et al., 2005b/ /Frankenberg et al., 2006/ /Frankenberg et al., 2008/ /Frankenberg et al., 2011/ /Meirink et al., 2006/ /Nakajima et al., 2010/ /Schneising et al., 2009/ /Schneising et al., 2010/ /Yoshida et al., 2010/.**

Consequently, the four data products XCO_2 and XCH_4 from SCIAMACHY and TANSO are the four core products which will be 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 XCO_2 and XCH_4 from SCIAMACHY and TANSO, algorithms to obtain other satellite data products used for comparison and/or because they have the potential to constrain CO_2 and CH_4 in upper layers (i.e., layers above the planetary boundary layer (PBL)), are also further improved and evaluated with the GHG-CCI project (using "Additional Constraints Algorithms" (ACAs)). This comprises mid/upper tropospheric CO_2 from AIRS, mid/upper tropospheric CO_2 and CH_4 from IASI, stratospheric CH_4 from MIPAS and SCIAMACHY occultation and stratospheric CO_2 from ACE-FTS (note that a number of relevant data products are also generated outside of this project, e.g., from TES and CH_4 from ACE-FTS). The data products of these sensors provide only limited information on regional GHG surface fluxes as they are not sensitive to near-surface GHG variations (see, e.g., **/Chevallier et al., 2005a/** /**Bréon et al., 2010/**). For example in **/Chevallier et al., 2005a/** it is pointed out that: "It appears that atmospheric mixing makes the upper tropospheric CO_2 concentrations rather zonal, which indicates that AIRS data inform about very broad features of the surface fluxes only. Further, such a small variability imposes a stringent constraint on the size of retrieval biases and of transport model biases for the estimation of CO_2 surface fluxes."

3 URD approach

This document has been written by the GHG-CCI project team. This document is 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/** and the requirements formulated by the CCI Climate Modelling User Group (CMUG) **/CMUG-RBD, 2010/**.

This document refers to XCO_2 and XCH_4 as retrieved from the existing instruments SCIAMACHY and TANSO. For SCIAMACHY it has already been shown that the XCH_4 retrievals provide strong constraints on regional methane surface fluxes (e.g., **/Bergamaschi et al., 2009/**). It has also been shown that SCIAMACHY has the potential to deliver important information on CO_2 surface fluxes (e.g., **/Houweling et al., 2004/ /Hungershoefer et al., 2010/**) but inverse modelling has not yet been attempted due to potential retrieval biases caused by aerosols and thin clouds - a problem which likely can be solved using an advanced algorithm which will be further developed in this project **/Reuter et al., 2010/**. GOSAT is the world's first dedicated GHG mission and has been designed to deliver XCO_2 and XCH_4 useful for constraining CO_2 and CH_4 surface fluxes **/Yokota et al., 2004/ /Yoshida et al., 2010/ /Kuze et al., 2010/**. Both instruments are therefore considered useful for the regional CO_2 and CH_4 surface flux applications. Therefore, for certain requirements such as the observing cycle requirements, the known characteristics of SCIAMACHY and GOSAT are reported in this document but requirements have not been explicitly formulated although they may be interpreted at least as threshold requirements. Note that the purpose of this document is not to specify a new future mission such as CarbonSat /**Bovensmann et al., 2010/** or A-Scope **/A-Scope, 2008/ /Kaminski et al., 2010/**. Nevertheless, the potential capabilities of these future instruments may be interpreted as the more demanding breakthrough requirement. Other requirements which not only depend on the instrument but also on the retrieval algorithm, such as the XCO_2 and XCH_4 systematic error ("accuracy") requirements, are defined in this document based on available literature and user feedback.

The CCI CMUG has already 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).

4 Definitions

In this section important definitions are given. They are as much as possible identical with the definitions given in **/CMUG-RBD, 2010/** to ensure consistency with the other CCI projects. The GHG-CCI team however does not agree with the use of certain terms as given in **/CMUG-RBD, 2010/**. For example the use of the terms “Accuracy” and “Precision” is not consistent with (de facto) standard definitions given, e.g., by the Joint Committee for Guides in Metrology (JCGM/WG1). More details on this aspect are given below.

From **/CMUG-RBD, 2010/**: “For climate data records it is important to have a consistent definition of error characteristics of these datasets. Depending on the application there are several aspects of the measurements where the uncertainty needs to be defined. A recent meeting between meteorologists and metrologists attempted to define these different aspects of the errors which are given below. It is recommended by CMUG that CCI projects adopt a consistent definition for error characteristics and a first iteration is given below.**”** **Figure 1** is a graphical example of the different types of error.

Accuracy is the measure of the non-random, systematic error, or bias, that defines the offset between the measured value and the true value that constitutes the SI absolute standard. **/CMUG-RBD, 2010/**

*Note: According to **/JCGM, 2008/** (page 35) “Accuracy” is a qualitative concept. For the purpose of this document however a quantitative concept is needed. For this purpose we use the term “Systematic error” in this document.*

Systematic error: Quantitative measure of the systematic (i.e., non-random) offset, or bias, between the measured value and the true value that constitutes the SI absolute standard.

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

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

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

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: Similar remarks as given above for "Accuracy" are also valid for "Precision" which should also be used only qualitatively (see ***/NIST/*** *D.1.2). For the purpose of this document however a quantitative concept is needed. For this purpose we use the term "Random error" in this document.*

Random error: Quantitative measure of reproducibility or repeatability of the measurement without reference to an international standard so that random error is a measure of the random and not the systematic error. Suitable averaging can improve the random error of the measurement (retrieval) but does not establish the systematic error of the observation.

Important note:
After having pointed out the various definitions and their origins we point out that for practical purposes we strictly speaking do not distinguish between the qualitative and quantitative aspects of these terms in this document (mainly because the terms are also used in many peer-reviewed and other relevant publications):

- If the term "**Accuracy**" is used in this document the meaning is "Systematic error" (as defined above).
- We also use "**Relative accuracy**" for "Relative systematic error".
- We also use the term "**Precision**". If this term is used the meaning is "Random error" (as defined above).

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/**

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/**

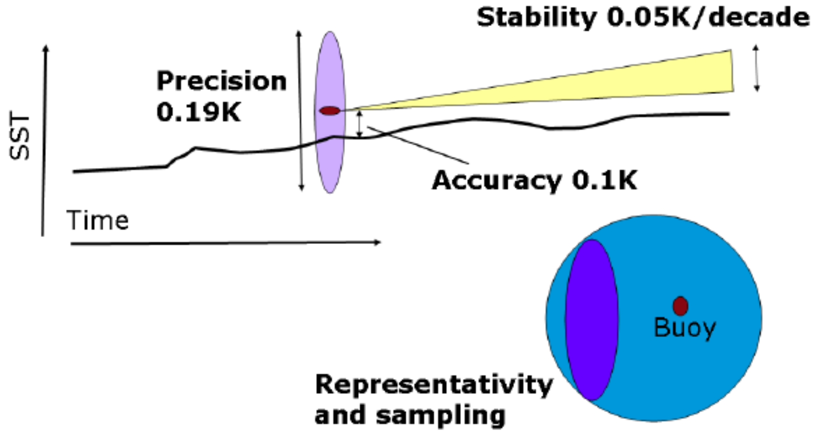

Figure 1: Graphical plot showing the different kinds of errors which may need to be defined for satellite Climate Data Records (CDRs). From /**CMUG-RBD, 2010/**. Note: The figure may suggest that precision refers to a 2-σ uncertainty. In this document however 1-σ uncertainties are used. Note also that in this document the terms "Systematic error" (instead of "Accuracy") and "Random error" (instead of "Precision") are used as explained in this section.

Threshold requirement: The **threshold** is the minimum requirement to be met to ensure that data are useful. **/CMUG-RBD, 2010/**

Note: A possible (extreme) interpretation of this requirement is that a data product is useless if the threshold requirement is not met. This interpretation is not used for this URD. Instead we interpret this requirement as follows: If the threshold requirement is met, the data are assumed to be useful at least to a certain extent. They are not necessarily considered very useful. If the threshold requirement is not met, the data product is not necessarily (entirely) useless. This means that the values chosen for threshold requirements are not exactly the (essentially unknown and not well defined) boundary between "useful" and "not useful" but are located within the "useful" interval.

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

Note: The more accurate and precise the satellite XCO_2 and XCH_4 data products are, the larger their information content. Therefore the goal requirement for accuracy should be "0.0 ppm" for XCO_2, for example (similar remarks are valid for the other requirements). It may however makes sense to define a value larger than "0.0", e.g., if other errors such as model transport errors do not allow to make use of 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.*

5 GHG ECV specific requirements

In this section GHG ECV specific requirements are formulated for the XCO_2 and XCH_4 data products to be retrieved from SCIAMACHY and TANSO.

5.1 General

The GHG ECV core data products XCO_2 and XCH_4 are retrieved from the two existing instruments SCIAMACHY (nadir mode) and TANSO. These instruments have known characteristics such as horizontal resolution and revisit time. These known characteristics are reported here but they are not explicitly formulated as requirements. Instead it is assumed here that the two satellite instruments are useful for GHG-CCI (and there are good reasons why this assumption is a valid one, see below). The purpose of this URD is to formulate requirements for GHG data products to be generated within the GHG-CCI project. It is not the purpose of this document to specify a future GHG satellite mission. Other characteristics of the data products such as accuracy not only depend on the instrument but also on the retrieval algorithm. For these type of data product characteristics, requirements have been formulated. The GHG ECV data products shall be useful for regional CO_2 and CH_4 surface flux inverse modelling. The requirements formulated in this document are therefore valid for this application. There are however also other potentially important applications, e.g., use of the data to improve our understanding of atmospheric transport and mixing.

In the following detailed requirements are given typically by specifying numerical thresholds. The purpose of the requirements is to make sure that the satellite data products are useful or to indicate that they are not useful because (certain) requirements cannot or have not (yet) been met. Specifying (typically) 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. Appropriate analysis shall be undertaken in order to identify which new knowledge can be / has be obtained from the satellite data products. *Note: This includes (but is not limited to) detailed comparisons with state-of-the-art models to identify model shortcomings (e.g., used surface flux data bases, emission/uptake process parameterizations, etc.). It is expected that this implies an iterative process which includes retrieval algorithm improvements and improved error characterization of the data products.*

5.2 Horizontal resolution

The typical horizontal resolution of the SCIAMACHY nadir measurements in the spectral regions relevant for GHG-CCI is 60 km (across track) times 30 km (along track).

The horizontal resolution of TANSO is 10.5 km (circular spot) in nadir.

The SCIAMACHY horizontal resolution is less than the TANSO one. Nevertheless, the SCIAMACHY data are useful for this project. For, SCIAMACHY XCH_4 this has already been demonstrated using real data (see, e.g., **/Bergamaschi et al., 2009/**). For SCIAMACHY XCO_2 this has been shown using simulations (see, e.g., **/Houweling et al., 2004/ /Hungershoefer et al., 2010/**).

The SCIAMACHY horizontal resolution (60x30 km^2) can therefore be interpreted as above the threshold requirement.

The GOSAT horizontal resolution (10.5 km) may be interpreted as breakthrough requirement although an even higher horizontal resolution (e.g., 1 km as planned for OCO **/Crisp et al., 2004/** or 2 km as foreseen for CarbonSat **/Bovensmann et al., 2010/**) would be even better due to significantly higher probability for cloud free scenes and because this enables to cover new application areas such as emission hot spot monitoring **/Bovensmann et al., 2010/**. A horizontal resolution of 2 km may therefore be considered as breakthrough requirement and 1 km as goal requirement (although an even smaller resolution would be even better).

Note: The probability for a cloud free scene typically increases with decreasing ground pixel size (see, e.g., **/Miller et al., 2007/***). Due to difficulties related to radiative transfer modelling of "cloud holes" (= cloud free area surrounded by clouds), a scene typically needs to be sufficiently cloud free also in the surroundings of a given "cloud hole". As the required size of this cloud free area (which is larger than the cloud hole) gets smaller the smaller the satellite footprint (ground pixel size) is, a smaller footprint results in a larger number of sufficiently cloud free observations (assuming the same total number of observations) even if the surrounding needs to be considered.*

Note: For inverse modelling of regional surface fluxes (or other methods to obtain information on sources and sinks such as CCDAS) the link to "Horizontal resolution" is typically "indirect" as the size of the target regions for the regional surface flux application is typically (much) larger than the satellite footprint size (there are however exceptions, e.g., if the targets are localized "hot spot" emission point sources such as power plants, see, e.g., ***/Bovensmann et al., 2010/****). What is needed is sufficiently high density of (sufficiently cloud free) data. The link is primarily due to the fact that the cloud free probability increases with better horizontal resolution (i.e., smaller ground pixel size). Assuming a constant total number of measurements this means higher data density if the horizontal resolution increases.*

Note also: The need for sufficiently high data density is covered (indirectly) by the "Random error" ("Precision") requirement for spatio-temporal averages (see Table 1). An explicit data density or ***spatio-temporal sampling requirement*** *has (therefore) not been formulated.*

5.3 Vertical resolution

Not applicable for XCO_2 and XCH_4 from SCIAMACHY (nadir mode) and TANSO. Therefore no requirements are given here.

5.4 Observing cycle / revisit time

For the two instruments used to generate the core ECV data products, i.e., SCIAMACHY/ENVISAT and TANSO/GOSAT, the observing cycle (= revisit time) has been defined pre-launch (however both instrument have capabilities for certain in-orbit optimization). Because these characteristics are essentially fixed (the SCIAMACHY measurements between 2002 and today are as they are and this is also true for the first 2 years of GOSAT data), the observing cycle / revisit time characteristics are reported here but requirements have not been formulated.

The swath width of SCIAMACHY is approx. 1000 km and SCIAMACHY performs alternative nadir / limb observations. Typically 50% of the dayside measurement time is used for nadir observations. Full global coverage of the nadir observations is achieved after approx. 6 days (with some gaps, e.g., around the poles). The geometrical revisit time (not considering, for example, clouds) for the nadir observations is approx. 6 days. The useful revisit time (considering clouds etc.) is larger (worse) and depends on location and season (for example, the number of (useful) high latitude observations in winter is very small due to snow/ice covered surface (with low reflectivity in the near-infrared), low sun, and more frequent cloud cover).

TANSO has a revisit time of 3 days in the sense that after 3 days the same position on Earth will be observed again. However, the TANSO data have large gaps. TANSO does not achieve full (geometrical) global coverage due to its scanning strategy (typically 4 measurements are taken across track with about 160 km gaps between these observations).

The SCIAMACHY (geometrical) revisit time of 6 days may therefore be interpreted as threshold requirement.

Of course shorter revisit times would be much better. However, even potential future satellites such as one CarbonSat satellite **/Bovensmann et al., 2010/** will only have a revisit time of 6 days (for laser-based missions the revisit time will likely be much larger including large data gaps due to the narrow swath). Achieving much shorter revisit times (few hours) **- as required by GCOS -** can only be achieved with, for example, a constellation of several CarbonSats or other satellites.

5.5 Random and systematic errors

In this section requirements for random errors ("precision") and systematic errors ("accuracy") for XCO_2 and XCH_4 are given (see Table 1).

They are valid for the XCO_2 and XCH_4 data products of SCIAMACHY and GOSAT to be generated within GHG-CCI.

Note that, as explained earlier, **threshold requirements** are defined such that a data product is considered at least partially useful (this implies that a data product may be useful to some extent even if the threshold requirement is not met - except of course if the deviation from the requirement is "very large").

Note also that the **goal requirement** as defined in this document is supposed to correspond to a performance where further improvements are not necessary. Ideally, this means that one has to specify "0.0" for precision and accuracy. In reality a value greater than "0.0" may be acceptable as one may expect that other errors dominate when interpreting the data such as model transport errors, which are (for current models significantly) larger than "0.0" (see, e.g., **/Houweling et al., 2010/**).

Note also that the requirements can only give an indication of the required values, i.e., are approximate values, which should not be over-interpreted.

Precision requirements are given for single measurements but also for spatio-temporal averages (1000x1000 km^2, 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 km^2 and not in deg^2, 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: An instrument with low single measurement precision but a large number of (sufficiently cloud free) data may 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 but needs to be combined with (estimates of) the number of (useful) data in a given spatio-temporal interval. Despite this, single measurement precisions requirements are given in this document (they offer the potential advantage of a more straight forward verification incl. radiative transfer modelling for single observations and simulated retrievals) but this requirement has to be interpreted with care.

Random error (precision) requirements for XCO_2:

In **/Rayner and O'Brien, 2001/** it has been shown that satellite retrievals of XCO_2 provide additional information on CO_2 surface fluxes if a precision of 2.5 ppm can be achieved for monthly averages in 8^o x 10^o large regions. This requirement has essentially been confirmed and refined in follow-on studies. For example, in **/Houweling et al., 2004/** it is shown that SCIAMACHY provides important information on CO_2 surface fluxes if a single measurement precision of 1% (3.6 ppm) can be achieved and if approx. 10% of the measurements are sufficiently cloud free. In **/Hungershoefer et al., 2010/** it has been shown that SCIAMACHY and GOSAT 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 (SZA) of 50^o, 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 GOSAT is 4.2 ppm (when computed using the formular given in **/Hungershoefer et al., 2010/**).

Approach to define the requirements for random errors: For this URD single measurement precisions and precisions for spatio-temporal averages (1000x1000 km^2, 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 km^2 large region.

For XCO_2 the threshold precision requirement for spatio-temporally averaged data has been obtained as follows: As the threshold requirement is defined such that the data products are useful for the GHG-CCI applications if this requirement is met, a threshold value of 1.3 ppm has been chosen, which is about a factor of two more demanding that 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). More demanding values have been chosen for the breakthrough and goal requirements. Here the required single measurement precisions are approximately a factor of 3 worse compared to the requirement for spatio-temporally averaged data.

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.

Random error (precision) requirements for XCH_4:

In **/Meirink et al., 2006/** it has been shown that SCIAMACHY contributes significantly to methane 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.

For the XCH_4 precision requirements for spatio-temporal averages similar remarks apply as given above for XCO_2, i.e., a factor of 3 improvement is required compared to the single measurement precisions.

Systematic error (accuracy) requirements:

The accuracy requirements 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 CO_2 surface flux inverse modelling "regional biases of a few tenth of a parts per million in column-averaged CO_2 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 absolute accuracy is not necessarily required as global offsets can be considered e.g. via bias correction (e.g., using comparisons with calibrated reference data such TCCON FTS retrievals) or as part of the inverse modelling step as done by **/Bergamaschi et al., 2009/**. Required is however high relative accuracy, 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 XCO_2 data and must be corrected below detectable levels". Because of this, relative accuracy requirements have been formulated for GOSAT **/Nakajima et al., 2010/**: "The mission of the GOSAT is to observe CO_2 and CH_4 column density with relative accuracy of 1% for CO_2 and 2% for CH_4 at 1000 km square spatial scale and in 3 months average". They are consistent with the GCOS requirements **/GCOS-107/**. However, according to the GHG-CCI CRG, more demanding requirements are needed for the global regional-scale CO_2 and CH_4 GHG-CCI surface flux applications. The GHG-CCI CO_2 threshold bias requirement is based on an extension of **/Chevallier et al., 2005a/** to GOSAT (performed by F. Chevallier). The idea is to have the bias about one order of magnitude smaller than the model-minus-observation departures. For GOSAT the CO_2 departures are a few ppm, so the bias needs to be a few tenth of a ppm. Although very demanding, these requirements seem not to be too strict when compared with a study based on LMDZ-GEOSchem **/Chevallier et al., 2010/.**

/Houweling et al., 2010/ and **/Chevallier et al., 2010/**, discussing model transport errors which limit the interpretation of the satellite retrievals in terms of surface fluxes, have been considered when defining the goal requirements.

For XCH_4 the requirements are similar but somewhat relaxed (as also done for GOSAT **/Nakajima et al., 2010/**), because XCH_4 is more variable compared to XCO_2 (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 methane 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 XCH_4 has also been found when using real SCIAMACHY data (**/Bergamaschi et al., 2009/ /Bergamaschi et al., 2007/**). As a consequence, also the CH_4 bias threshold requirement is challenging.

The requirements are valid for observations over land. This is because of 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 CO_2 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 lower signal levels (with some exceptions, e.g., sun-glint observations) and therefore larger noise.

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

REQ-GHGCCI-ERR-1	The XCO_2 and XCH_4 ECV data products over land shall meet the random error (precision) requirements given in Table 1. *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.*

Based on these considerations the requirements on systematic errors (accuracy) are:

REQ-GHGCCI-ERR-2	The XCO_2 and XCH_4 ECV data products over land shall meet the systematic error (accuracy) requirements given in Table 1. *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.*

Correlations:

When the data products are used for inverse modelling assumptions have to be made concerning error correlations. Inverse modelling will improve if information on error correlations will be 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	It shall be investigated how to reliably determine error correlations between the XCO_2 and XCH_4 values retrieved from individual ground-pixels.

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.

Requirements for regional CO_2 and CH_4 source/sink determination using SCIAMACHY/ENVISAT and TANSO/GOSAT					
Parameter	**Req. type**	**Random error** (“Precision”)		**Systematic error** (“Accuracy”)	**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)	As systematic error but per year
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative §))	-“-
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative #))	-“-

Table 1: GHG-CCI XCO_2 and XCH_4 random (“precision”) and systematic (“accuracy”) retrieval error requirements for measurements over land. Abbreviations: G=Goal, B=Breakthrough, T=Threshold requirement. §) Required systematic error after bias correction, where only the application of a constant offset / scaling factor independent of time and location is permitted for bias correction. #) Required systematic error after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor.

*Note on **Table 1**: Although absolute accuracy seems not to be required according to current knowledge (and is difficult to achieve) the information content of the data is higher if a bias correction can be avoided. To what extent this is significant still needs to be assessed. Because the goal requirement defines a performance beyond which no additional information can be obtained / extracted, absolute accuracy is specified for the goal requirement.*

5.6 Validation

Validation against high precision / high accuracy ground-based XCO_2 and XCH_4 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 XCO_2 and XCH_4 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 CO_2)."

According to **/Toon et al., 2009/**: "The precision of the resulting mole fractions retrieved from single spectra is about 0.15% for CO_2, 0.2% for CH_4, 0.3% for N_2O and 0.5% for CO. The absolute accuracy is limited by spectroscopic inadequacies (~1% for CO_2, ~2% for CH_4), but this can be substantially reduced by validation, i.e., airborne profiling using accurate in situ sensors."

This indicates that TCCON achieves high precision and relative accuracy and is therefore well suited for validation of the GHG-CCI XCO_2 and XCH_4 satellite data products.

REQ-GHGCCI-VAL-1	The XCO_2 and XCH_4 ECV data products shall be validated using TCCON. *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.*

Note: TCCON will be the basis for validation. There are however limitations mainly due to fact that the TCCON network is sparse. Within GHG-CCI the satellite data products will therefore also be compared with other measurements (e.g., NDACC column-averaged XCH_4 and WMO/AGAGE in-situ observations) and XCO_2 and XCH_4 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 XCO_2 and XCH_4 data products remains a research topic.

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: It is unlikely that this CMUG requirement can be fully met. E.g., currently no means exist to determine with confidence the systematic error of each single measurement.

Secondly the use of common ancillary fields will be 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 about 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 XCO_2 *and* XCH_4 *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 user 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 XCO_2 *and* XCH_4 *is highest (or that at least a good compromise between accuracy and processing speed can been obtained). For this reason and because* XCO_2 *and* XCH_4 *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.

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

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 XCO_2 and XCH_4 data products Averaging Kernels (AK) and (CO_2 and CH_4) 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.

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 model environments. The aim will be 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.

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	For each GHG ECV data product it needs to be properly documented which metadata have been used. 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. Additional information shall be given on the GHG-CCI website. This includes, for example, information on satellite or instrument related anomalies.

7.4 Map projections

Regional surface flux inverse modelling requires XCO_2 and XCH_4 retrievals for the individual ground pixels including exact geolocation (i.e., spatial) and time information. Therefore, the 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.

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/: "In order 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	There shall be a Product Specification Document (PSD), which shall provide a detailed description of the GHG ECV data products. 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://cf-pcmdi.llnl.gov/documents/cf-standard-names/standard-name-table/15/cf-standardname-table.html

In addition, the algorithms shall be described in sufficient detail.

REQ-GHGCCI-NCD-2	The retrieval algorithms shall be described in sufficient detail via an Algorithm Theoretical Basis Document (ATBD) and/or peer-reviewed publications.

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 XCO_2 and XCH_4 values for individual ground pixels, their errors, corresponding averaging kernels, used a-priori profiles, etc.

The users are happy with any format (e.g., the format currently used for SCIAMACHY XCH_4 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 user need Level 2 data products.

/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.

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.

/CMUG-RBD, 2010/: "As far as the location of the datasets is concerned they should be hosted on a node of the Earth System Grid so that users will have the same interface for European, US and other climate datasets. They need to be hosted on the Earth System Grid "data nodes" which publish to "gateway nodes". The BADC is currently connected to the Grid and would provide a suitable host for CCI datasets."

REQ-GHGCCI-DA-2	The GHG ECV data products shall be hosted on a node of the Earth System Grid.

8.4 Level of processing

The data products needed to obtain information on regional CO_2 and CH_4 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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10 Terms and acronyms

Terms

The terms listed below have been defined in **/CMUG-RBD, 2010/** and are repeated here as this document shall be consistent with **/CMUG-RBD, 2010/**.

Note: GHG-CCI does not necessarily agree with the definition of the terms given below but agreement is not required for this document as these terms mainly refer to modelling or other aspects out of the scope of this document such as trend monitoring over time periods much longer than considered for this phase of the project. Consequently, these terms are not used in this document.

Term	**Meaning**
Data assimilation	Observations directly influence the model initial state taking into account their error characteristics during every cycle of a model. This is used for reanalysis and NWP.
Model validation	Observations are compared with equivalent model fields to assess the accuracy of the model. This can be on short time scales for process studies or long time scales for climate trends.
Climate monitoring	This describes the use of a satellite only dataset to monitor a particular atmospheric or surface variable over a period > 15yrs to investigate whether there is a trend due to climate change.
Initialisation	To initialise prognostic quantities of the model with reasonable values at the beginning of the simulation but do not continuously update.
Prescribed boundary conditions	Prescribed boundary conditions for a model run for variables that are not prognostic (e.g. land cover, ice caps etc).

Acronyms

Abbreviation	Meaning
ACE-FTS	Atmospheric Chemistry Experiment-Fourier Transform Spectrometer
AAI	Absorbing Aerosol Index
AATSR	Advanced Along Track Scanning Radiometer
ACA	Additional Constraints Algorithm
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
ATBD	Algorithm Theoretical Basis Document
BESD	Bremen optimal EStimation DOAS
CCDAS	Carbon Cycle Data Assimilation System
CCI	Climate Change Initiative
CDR	Climate Data Record
CMUG	Climate Modelling User Group (of ESA's CCI)
COD	Cloud Optical Depth
COTS	Commercial Off-The-Shelf software
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

ESM	Earth System Model
FCDR	Fundamental Climate Data Record
FP	Full Physics
FSI-WFM-DOAS	Full Spectral Initiasation WFM-DOAS
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
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
IDL	Interactive Data Language
ITT	Invitation To Tender
IMAP-DOAS	Iterative Maximum A posteriori DOAS
IMLM	Iterative Maximum Likelihood Method
IODD	Input Output Data Definition
IPCC	International Panel in Climate Change
IPR	Intellectual Property Right
IUP	Institute of Environmental Physics (IUP) of the University of Bremen, Germany
JCGM	Joint Committee for Guides in Metrology
KO	Kick-Off
LMD	Laboratoire de Météorologie Dynamique
LUT	Look-up table
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
MRT	Mid-term Review
NA	Not applicable
NDACC	Network for the Detection of Atmospheric Composition Change
NASA	National Aeronautics and Space Administration
NIES	National Institute for Environmental Studies
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
OCO	Orbiting Carbon Observatory
OD	Optical Depth
OE	Optimal Estimation
PBL	Planetary Boundary Layer
PM	Progress Meeting
PMD	Polarization Measurement Device
PMP	Project Management Plan
PVP	Product Validation Plan
PVR	Product Validation Report
RD	Reference Document
RMS	Root-Mean-Square
RTM	Radiative transfer model
SCIATRAN	RTM for SCIAMACHY
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY
SoW	Statement of work
SQWG	SCIAMACHY Quality Working Group
SRD	Software Requirements Document
SUM	Software User Manual
SVR	Software Verification Report
TANSO	Thermal And Near infrared Sensor for carbon Observation
TBC	To be confirmed
TBD	To be defined / to be determined

TCCON	Total Carbon Column Observing Network
TES	Tropospheric Emission Spectrometer
TOVS	TIROS Observational Vertical Sounder
WFM-DOAS (or WFMD)	Weighting Function Modified DOAS
WG	Working Group

11 Annex A: GCOS GHG requirements

The following is from **/GCOS-107/**, section 3.1.9 “ECV Carbon Dioxide, Methane and other Greenhouse Gases”:

Carbon dioxide is the most important of the greenhouse gases 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 the cumulative anthropogenic emissions, rather than the current rate of emissions, due to its very long lifetime (up to thousands of years) in the atmosphere-ocean-terrestrial biosphere system.

Methane (CH_4) is the second most significant greenhouse gas, and its level has been increasing since the beginning of the 19th century. In addition to methane, other long-lived greenhouse gases (GHGs) include nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6), and perfluorocarbons (PFCs). The current direct radiative forcing from CH_4 is 20% of the total from all of the long-lived and globally-mixed greenhouse gases, and the other trace gases contribute another 20% of the changes in climate forcing since the start of the industrial revolution (IPCC, 2001). The Kyoto Protocol of the UN Climate Convention includes future restrictions on the release of GHGs, including CO_2, CH_4, N_2O, HFCs, SF6, and PFCs. The Montreal Protocol on Substances that Deplete the Ozone Layer includes mandatory restrictions on the production and consumption of those CFCs and HCFCs that are also GHGs for individual countries. Trace gas measurements are vital to international and national regulatory agencies, climate models, and scientists interested in atmospheric chemistry and transport.

The following is needed for these ECVs:

<u>Product A.9</u> Distribution of greenhouse gases, such as CO_2 and CH_4, of sufficient quality to estimate regional sources and sinks

Benefits

- Data products will allow monitoring of the spatial distribution and change over time of the key greenhouse gases
- Stabilization of the concentrations of these gases at a level that would prevent dangerous anthropogenic interference with the climate system is the ultimate objective of the UNFCCC
- Data products of sufficient accuracy would allow estimates of regional emissions, such as those related to wetlands and rice fields, land-use change and missing-sink processes
- Improved detection of global mean and meridional concentrations, as well as deduction of carbon sources and sinks on a regional or continental scale
- Satellite-based observations of total column values and vertical profiles of the mixing ratio of carbon dioxide, methane and nitrous oxide, when coupled with reanalysis, may provide a capability for monitoring of sources and sinks of greenhouse gases, especially CO_2 and CH_4

Target requirements

Research use and demonstration of currently available measurements in reanalysis is needed to provide a clear statement of essential data needs, in particular on the extent of needed detail to vertical sounding. Initial estimates are based on resolving the values of observed column fluctuations. Time scales that extend from the diurnal through the synoptic, monthly, seasonal, yearly to the decadal need to be resolved, to allow for a complete description of the processes determining the distribution of these atmospheric species. Spatial variability can be substantial in the planetary boundary layer, reflecting the variability of sources and sinks. Products can be useful for monitoring and source-sink inversion even without resolving the shortest space and time scales.

- Accuracy: CO_2: 3 ppm; CH_4: 20 ppb
- Spatial and temporal resolution: CO_2, CH_4: from 10-250 km horizontal resolution from troposphere to stratosphere; 3-hourly observing cycle
- Stability: CO_2: 3 ppm (climate forcing) and 1 ppm (sources and sinks)

Requirements for satellite instruments and satellite datasets

A research study is needed to establish the minimum needs for monitoring sources and sinks of these gases. At this stage note is made of immediate data needs.

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

- High spectral resolution IR sounding for the upper troposphere and stratosphere, as provided initially by AIRS and IASI
- Limb-sounding in IR and MW for distributions from upper troposphere to mesosphere
- Active NIR systems to obtain tropospheric vertical profiles
- Passive NIR operational missions for CO_2 and CH_4, building on the experience with SCIAMACHY, and the specialized missions GOSAT and OCO. Simultaneous total column CO, such as provided by SCIAMACHY, adds much value for CO_2 source characterization

Calibration, validation and data archiving needs

- The required comprehensive independent ground-based validation measurements can be provided by the WMO GAW Global CO_2 and CH_4 Monitoring Networks (both GCOS Comprehensive Networks), including ship and dedicated light aircraft profiles up to 8 km.
- A baseline network of surface-based total column CO_2 and CH_4 instruments, continued routine commercial aircraft observations, and observations planned by IAGOS/MOZAIC, are needed for validation of products

Adequacy/inadequacy of current holdings

- Satellite data are available for only recent years, and provision of products is a developmental activity
- An adequate measure of global values of these long-lived gases can be obtained from *in situ* data

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 operational measurements sufficient to deliver products of the required accuracy
- Support for the surface and free-tropospheric measurements needed for calibration and validation.
- Products may be derived from AIRS and SCIAMACHY from 2002 onwards
- Limb-sounding data for retrieval of stratospheric profiles from current instruments include those from HIRDLS (CH_4, N_2O), MIPAS (CH_4, N_2O) and MLS (N_2O)
- TES provides additional data for the retrieval of tropospheric CH_4
- Research towards improved future capabilities, including long-term monitoring of CO_2, CH_4 and other GHG, such as N_2O
- Coordination by WCRP SPARC, IGBP IGAC

Link to GCOS Implementation Plan

[GIP Action A25] Establish a plan for and implement a consistent surface- and satellite-based global observing system for the atmospheric composition ECVs, based on common standards and procedures, and encourage data submission to WDCs.

[GIP Action A26] Develop and implement a comprehensive plan to observe the vertical profiles of GHGs, ozone and aerosols utilizing commercial and research aircraft, pilotless aircraft, balloon systems, kites, ground-based lidars and satellites.

[GIP Action A27] Establish the GCOS/GAW baseline network for CO_2 and CH_4, and fill the gaps.

Other applications

Carbon dioxide fields may allow improved extraction of the temperature information from IR sounders for NWP and reanalysis.

The following is from **/GCOS-107/**, Appendix 2 “GCOS requirements in WMO/CEOS Database (13 July 2004)”:

		Observation Requirement	Hor Res	HR min	Vert Res	VR min	Obs Cycle	OC min	Delay	D min	Acc-RMS	Acc min
53	AOPC	Trace gas profile CH_4 - Higher strat & mesosphere (HS & M)	50 km	250 km	2 km	4 km	1 d		30 d	0.5 y	5%	30%
54	AOPC	Trace gas profile CH_4 - Higher troposphere (HT)	50 km	250 km	2 km	4 km	2 h		30 d	0.5 y	2 %	20%
55	AOPC	Trace gas profile CH_4 - Lower stratosphere (LS)	50 km	250 km	2 km	4 km	6 h		30 d	0.5 y	5%	30%
56	AOPC	Trace gas profile CH_4 - Lower troposphere (LT)	10 km	50 km	2 km	3 km	2 h		30 d	0.5 y	2 %	10 %
57	AOPC	Trace gas profile CH_4 - Total column	10 km	250 km			12 h		30 d	0.5 y	2%	10%
58	AOPC	Trace gas profile CH_4 - Tropospheric column	10 km	50 km			2 h		30 d	0.5 y	2%	10%
59	AOPC	Trace gas profile CO_2 - Higher strat & mesosphere (HS & M)	250 km	500 km	2 km	4 km	1 d		30 d	0.5 y	1%	2%
60	AOPC	Trace gas profile CO_2 - Higher troposphere (HT)	50 km	500 km	1 km	2 km	2 h		7 d	60 d	1%	2%
61	AOPC	Trace gas profile CO_2 - Lower stratosphere (LS)	250 km	500 km	1 km	4 km	1 d		30 d	0.5 y	1%	2%
62	AOPC	Trace gas profile CO_2 - Lower troposphere (LT)	10 km	500 km	0.5 km	2 km	2 h		7 d	60 d	1%	2%
63	AOPC	Trace gas profile CO_2 - Total column	50 km	500 km			1 d		30 d	0.5 y	1%	2%
64	AOPC	Trace gas profile CO_2 - Tropospheric column	10 km	500 km			2 h		7 d	60 d	1%	2%

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 CO_2 and CH_4 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 CO_2 and CH_4 produced in near-real-time (based on data assimilation of near-real-time data products, typically from operational satellites),

- 4-dimensional gridded fields of CO_2 and CH_4 produced in “delayed mode” (6 months delay, to allow data assimilation of research-mode satellite data products),

- 3-dimensional gridded fluxes of CO_2 and CH_4 produced in “delayed mode”,

- Re-analysed concentration and flux fields of CO_2 and CH_4 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.

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 CH_4 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.

End of document