CHAPTER 6

QUALITY ASSURANCE/QUALITY CONTROL AND VERIFICATION

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6 QUALITY ASSURANCE/QUALITY CONTROL AND VERIFICATION

ELABORATION/UPDATE OF VOLUME 1, CHAPTER 6 OF THE 2006 GUIDELINES AND NEW GUIDANCE IN THE 2019 REFINEMENT.

6.1 INTRODUCTION

Elaboration of Section 6.1 (Box 6.1) of the *2006 IPCC Guidelines*.

An important goal of IPCC inventory guidance is to support the development of national greenhouse gas inventories that can be readily assessed in terms of quality. It is *good practice* to implement quality assurance/quality control (QA/QC) and verification procedures in the development of national greenhouse gas inventories to accomplish this goal. The procedures as described in this chapter also serve to drive inventory improvement.

The guidance is designed to achieve practicality, acceptability, cost-effectiveness, incorporation of existing experience, and the potential for application on a worldwide basis. A QA/QC and verification system contributes to the objectives of *good practice* in inventory development, namely to improve transparency, consistency, comparability, completeness, and accuracy of national greenhouse gas inventories.

QA/QC and verification activities should be integral parts of the inventory process. The outcomes of QA/QC and verification may result in:

- improvements in the estimates of emissions or removals;
- reassessment of inventory or category uncertainty estimates.

For example, the results of the QA/QC process may point to particular variables within the estimation methodology for a certain category that should be the focus of improvement efforts.

The terms ‘quality control’, ‘quality assurance’, and ‘verification’ are often used in different ways. The definitions of QC, QA, and verification in Box 6.1 will be used for the purposes of this guidance.

BOX 6.1
DEFINITIONS OF QA/QC AND VERIFICATION

Quality Control (QC) is a system of routine technical activities to assess and maintain the quality of the inventory as it is being compiled. Personnel compiling the inventory perform it. The QC system is designed to:

(i) Provide routine and consistent checks to ensure data integrity, correctness, and completeness;

(ii) Identify and address errors and omissions;

(iii) Document and archive inventory material and record all QC activities.

QC activities include general methods such as accuracy checks on data acquisition and calculations, and the use of approved standardised procedures for emission and removal calculations, measurements, estimating uncertainties, archiving information and reporting. QC activities also include technical reviews of categories, activity data, emission factors, other estimation parameters, and methods.

Quality Assurance (QA) is a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process. In carbon markets, a formalized version of this type of independent review is referred to as verification. Reviews, preferably by independent third parties, are performed upon a completed inventory following the implementation of QC procedures. Reviews verify that measurable objectives (data quality objectives, see Section 6.5, QA/QC Plan.) were met, ensure that the inventory represents the best possible estimates of emissions and removals given the current state of scientific knowledge and data availability, and support the effectiveness of the QC programme.

Verification refers to the collection of activities and procedures conducted during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of the inventory. For the purposes of this guidance, verification refers specifically to those methods that are external to the inventory and apply independent data, including comparisons with inventory estimates made by other bodies or through alternative methods. Verification activities may be constituents of both QA and QC, depending on the methods used and the stage at which independent information is used. It is important to distinguish verification, as defined by in the IPCC guidelines, from the term verification used in carbon markets, which is synonymous with an independent audit. Such an audit would fall under the scope of a QA procedure in the terminology of the IPCC Guidelines. For example, in under the UNFCCC Clean Development Mechanism verification is defined as the periodic independent review and *ex post* determination by an auditing body of monitored reductions in anthropogenic emissions by sources of GHGs that have occurred as a result of a registered CDM project activity during the verification period.

Before implementing QA/QC and verification activities, it is necessary to determine which techniques should be used, and where and when they will be applied. QC procedures may be *general* with a possible extension to *category specific* procedures. There are technical and practical considerations in making these decisions. The technical considerations related to the various QA/QC and verification techniques are discussed in general in this chapter, and specific applications to categories are described in the category-specific guidance in Volumes 2 to 5. The practical considerations involve assessing national circumstances such as available resources and expertise, and the particular characteristics of the inventory (e.g., whether or not a category is *key*).

6.2 PRACTICAL CONSIDERATIONS IN DEVELOPING QA/QC AND VERIFICATION SYSTEMS

No refinement.

6.3 ELEMENTS OF A QA/QC AND VERIFICATION SYSTEM

No refinement.

6.4 ROLES AND RESPONSIBILITIES

No refinement.

6.5 QA/QC PLAN

No refinement.

6.6 GENERAL QC PROCEDURES

No refinement.

6.7 CATEGORY-SPECIFIC QC PROCEDURES

No refinement.

6.7.1 Emissions factor QC

No refinement.

6.7.1.1 IPCC DEFAULT EMISSION FACTORS

No refinement.

6.7.1.2 COUNTRY-SPECIFIC EMISSION FACTORS

No refinement.

6.7.1.3 DIRECT EMISSION MEASUREMENTS

No refinement.

6.7.2 Activity data QC

No refinement.

6.7.2.1 NATIONAL LEVEL ACTIVITY DATA

Following are fundamental QC checks that should be considered for assessing the quality of national level activity data. In all cases, it is important to have a well-defined and documented data set from which appropriate checks can be developed.

QC checks of reference source for national activity data: When using national activity data from secondary data, it is *good practice* for the inventory compiler to evaluate and document the associated QA/QC activities. This is particularly important with regard to activity data, since most activity data are originally prepared for purposes other than as input to estimates of greenhouse gas emissions. Many statistical organisations, for example, have their own procedures for assessing the quality of the data independently of what the end use of the data may be.

The inventory compiler should determine if the level of QC associated with secondary activity data includes, at a minimum, those QC procedures listed in Table 6.1 of the *2006 IPCC Guidelines*. In addition, the inventory compiler may check for any peer review of the secondary data and document the scope of this review. If the QA/QC associated with the secondary data is adequate, then the inventory compiler can simply reference the data source and document the applicability of the data for use in its estimates (see Box 6.2 for an example of this procedure).

If the QC associated with the secondary data is inadequate or if the data have been collected using standards/definitions that deviate from this guidance, then the inventory compiler should establish QA/QC checks on the secondary data. The uncertainty of estimates should be reassessed in the light of the findings. The inventory compiler should also reconsider how the data are used and whether any alternative data and international data sets may provide a better estimate of emissions or removals. If no alternative data sources are available, the inventory compiler should document the inadequacies associated with the secondary data QC as part of its summary report on QA/QC.

BOX 6.2
EVALUATION OF DATA QUALITY ON EXTERNAL DATA IN THE TRANSPORTATION SECTOR

Countries typically use either fuel usage or kilometer (km) statistics to develop emissions estimates. The national statistics on fuel usage and km travelled by vehicles are usually prepared by a specialised agency. However, it is the responsibility of the inventory compiler to determine which QA/QC activities were implemented by the agency that prepared the original fuel usage and km statistics for vehicles. Questions that may be asked in this context are:

- Does the statistical agency have a QA/QC plan that covers the collection and handling of the data?
- Was an adequate sampling protocol used to collect data on fuel usage or km travelled?
- How recently was the sampling protocol reviewed?
- Has any potential bias in the data been identified by the statistical agency?
- Has the statistical agency identified and documented uncertainties in the data?
- Has the statistical agency identified and documented errors in the data?

Comparisons with independently compiled data sets: Where possible, a comparison check of the national activity data with independently compiled activity data sources should be undertaken. For example, many of the agricultural source-categories rely on government statistics for activity data such as livestock populations and production by crop type. Comparisons can be made to similar national statistics disseminated via FAOSTAT (http://www.fao.org/faostat) by the United Nations Food and Agriculture Organization (FAO). Similarly, the International Energy Agency (IEA) maintains a database on national energy production and usage that can be used for checks in the energy. Industry trade associations, university research, and scientific literature are also possible sources of independently derived activity data to use in comparison checks. Activity data may also derive from balancing approaches – see Section 6.7.2.2 for a description and an example. As part of the QC check, the inventory compiler should ascertain whether alternative activity data sets are really based on independent data. International information is often based on national reporting which is not independent from the data used in the inventory. Available scientific or technical literature may also be used for a national inventory. In some cases, the same data are treated differently by different agencies to meet varying needs. Comparisons may need to be made at a regional level or with a subset of the national data since many alternative references for such activity data have limited scope and do not cover the entire nation.

Comparisons with samples: The availability of partial data sets at sub-national levels may provide opportunities to check the reasonableness of national activity data. For example, if national production data are being used to calculate the inventory for an industrial category, it may also be possible to obtain plant-specific production or capacity data for a subset of the total population of plants. Extrapolation of the sample production data to a national level can then be done using a simple approximation method. The effectiveness of this check depends on how representative the sub-sample is of the national population, and how well the extrapolation technique captures the national population.

Trend checks of activity data: National activity data should be compared with previous year's data for the category being evaluated. *Activity* data for most categories tend to exhibit relatively consistent changes from year to year without sharp increases or decreases. If the national activity data for any year diverge greatly from the historical trend, they should be checked for errors. If a calculation error is not detected, the reason for the sharp change in activity should be confirmed and documented. A more thorough approach to take advantage of similarities between years has been described in Chapter 5, Time Series Consistency.

6.7.2.2 SITE-SPECIFIC ACTIVITY DATA

No refinement.

6.7.3 Calculation-related QC

No refinement.

6.8 QA PROCEDURES

No refinement.

6.9 QA/QC AND UNCERTAINTY ESTIMATES

No refinement.

6.10 VERIFICATION

No refinement.

6.10.1 Comparisons of national estimates

Update of section 6.10.1 of the *2006 IPCC Guidelines*.

There are a number of practical verification techniques that do not require specialised modelling expertise or extended analyses. Most of these can be considered as method-based comparisons that consider the differences in national estimates based on using alternative estimation methodologies for the same category or set of categories. These comparisons look for major calculation errors and exclusion of major source categories or sub-source categories. Method-based comparisons can be designed around the multi-tier level of methods outlined for each category in the sector guidance, through comparisons to independent estimates developed by other institutions, and, to a limited extent, through cross-country comparisons. The choice of method will depend on the method used in the inventory, a clear definition and correlation of categories between methods, and the availability of alternative data.

These checks can be extremely useful in confirming the reasonableness of national inventory estimates and may help identify any gross calculation errors. Some of these techniques, such as the compilation of the reference approach for Energy Sector estimates, should be considered as part of the inventory development process.

Discrepancies between inventory data and data compiled using alternative methods do not necessarily imply that the inventory data are in error. When analysing discrepancies, it is important to consider that there may be large uncertainties associated with the alternative calculations themselves.

Applying lower tier methods: Lower tier IPCC methods typically are based on ‘top-down’ approaches that rely on highly aggregated data at a summary category level. Inventory compilers using higher tier, ‘bottom-up’ approaches may consider using comparisons to lower-tier methods as a simple verification tool. As an example, for carbon dioxide (CO_2) from fossil fuel combustion, a reference calculation based on apparent fuel consumption per fuel type is specified as a verification check in the Energy Sector procedures (see Volume 2: Energy). As an additional example, since 2014 the EU performs annually a full QA of its EU-28 GHG Inventories for agriculture, using the FAOSTAT emissions estimates for verification. This reference approach estimate can be compared to the sum of sectoral-based estimates from a Tier 1, 2, or 3 approach. While the quality of the reference approach is typically lower than that of the sectoral approach, it remains useful as a simple approximation method. It is less sensitive to errors due to its simplicity and can be used as a top-down completeness check. Another example, where emissions are calculated as the sum of sectoral activities based on the consumption of a specific commodity, e.g., fuels or products like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) or sulphur hexafluoride (SF_6), the emissions could be estimated using apparent consumption figures, e.g., national total production + import – export ± stock changes, taking into consideration any possible time lags in actual emissions.

Similar checks can be performed for industrial type sources, e.g., nitrous oxide (N_2O) estimates for nitric acid production, where inventory estimates were determined for each individual production plant based on plant-specific data. The check of emission estimates would consist of the comparison between the sum of the individual plant-level emission estimates and a top-down emission estimate based on national nitric acid production figures and IPCC default Tier 1 factors. Large differences do not necessarily indicate that there are problems with the inventory estimate. As lower tier methods typically rely on more highly aggregated data, there may be relatively large uncertainties with the Tier 1 approach compared to an inventory estimated using a bottom up approach based on *good practice*. If differences cannot easily be explained, the inventory compiler may consider the following questions in any further QA/QC checks:

- Are there inaccuracies associated with any of the individual plant estimates (e.g., an extreme outlier may be accounting for an unreasonable quantity of emissions)?
- Are the plant-specific emission factors significantly different from each other?
- Are the plant-specific production rates consistent with published national level production rates?
- Is there any other explanation for a significant difference, such as the effect of controls, the manner in which production is reported or possibly undocumented assumptions?

This is an example of how the results of a relatively simple emission check can lead to a more intensive investigation of the representativeness of the emissions data. Knowledge of the category is required to isolate the parameter that is causing the difference in estimates and to understand the reasons for the difference.

Applying higher tier methods: Higher tier IPCC methods typically are based on detailed 'bottom-up' approaches that rely on highly disaggregated data and a well-defined subcategorisation of sources and sinks. Inventory compilers may find that they can not fully implement a higher tier approach because they are lacking sufficient data or resources. However, the availability of even partial estimates for a subcategory of sources may provide a valuable verification tool for the inventory. An estimate based on higher tier data derived from a proportion of the total sources in a country can be extrapolated to the national level, provided that the sample is representative. Such an extrapolation can be used to corroborate the national estimate.

Comparisons with independently compiled estimates: Comparisons with other independently compiled inventory data on national level (if available) are useful option to evaluate completeness, assess approximate emission (removal) levels and correct category allocations. Although the inventory compiler is ultimately responsible for preparing the national greenhouse gas inventory, other independent publications on this subject may be available e.g., from scientific literature or publication by other institutes or agencies. For example, national level CO_2 emissions estimates associated with the combustion of fossil fuel are compiled by the International Energy Agency (IEA), British Petroleum (BP), the Carbon Dioxide Information and Analysis Centre (CDIAC) and Emission Database for Global Atmospheric Research (EDGAR) (http://edgar.jrc.ec.europa.eu). Use of multiple data sources in the comparison is advantageous as the data show differences between datasets even for relatively well-known emissions of carbon dioxide (Ciais *et al.*, 2010). Estimates of emissions of other gases are available from the EDGAR, Regional Emission inventory in Asia (REAS, https://www.nies.go.jp/REAS), and US Environment Protection Agency (EPA). World Resources Institute (WRI, http://cait.wri.org) combines data from several sources mentioned in this section to provide sector-specific emission estimates. FAO compiles and disseminates in FAOSTAT national emissions and removals for AFOLU, using the underlying national statistics as activity data and IPCC Tier 1 methodologies. If other independently compiled datasets use IPCC Tier 1 methodologies, the same considerations discussed above will apply.

While national data are normally considered more reliable as they may be are able to accommodate more detailed country-specific information, and international data are normally compiled at a lower tier, these international data sets provide a good basis for comparison as they are consistent between countries. Additionally, databases from international agencies such as IEA and FAO, use as activity data the underlying national statistics, providing enhanced opportunities for QA analysis. The comparisons can be made for different greenhouse gases at national, sectoral, category, and subcategory levels, as far as the differences in definitions enable them. Before conducting these types of comparisons, it is important to check the following items.

- Confirm that the underlying data for the independent estimate are not the same as that used for the inventory; a comparison is only meaningful if data being compared are different.
- Determine if the relationships between the sectors and categories in the different inventories can be defined and matched appropriately.

- Account for the data quality (e.g., QA/QC system or review) and for any known uncertainties in the estimate used for the comparison to help interpret results.

Comparisons of intensity indicators between countries: Emission (removal) intensity indicators, e.g., those commonly referred to as 'implied emission (removal) factors', may be compared between countries (e.g., emissions per capita, industrial emissions per unit of value added, transport emissions per car, emissions from power generation per kWh of electricity produced, emissions from dairy ruminants per tonne of milk produced). These indicators provide a preliminary check and verification of the order of magnitude of the emissions or removals. Different practices and technological developments as well as the varying nature of the source categories will be reflected in the emission intensity indicators. Thus differences between countries need to be expected. However, these checks may flag potential anomalies at the country or sector level.

6.10.2 Comparisons with atmospheric measurements

Update/elaboration of Section 6.10.2 of the *2006 IPCC Guidelines*.

6.10.2.1 INTRODUCTION TO EMISSION ESTIMATES BASED ON ATMOSPHERIC MEASUREMENTS

This section addresses the advancements in the state of science and its applications to estimating national emissions. The most notable advances were achieved in the application of inverse models of atmospheric transport for emission estimates at national and subcontinental scales. In contrast to the other methods described in this chapter, inventory comparisons with emission estimates based on atmospheric measurements are not yet established as a standard tool for verification used in national inventory report preparation processes because those emission estimates require specialized modelling and observation skills and are cost- and labor-intensive. In many cases, the uncertainties associated with the estimates based on atmospheric data (depending on sparsity of the observations, noise in the observations and errors in the transport models used in the inverse modelling) themselves may be too large for inverse models to be used effectively as a verification tool.

Nevertheless, considerable progress in this area needs to be noted and inventory compilers may consider taking advantage of this approach for verification. Atmospheric measurements can be used to provide useful quality assurance of greenhouse gas emission estimates (Manning *et al.*, 2011; Henne *et al.*, 2016; Fraser *et al.*, 2014). Under the right measurement and modelling conditions, they can provide a perspective on the trends and magnitude of GHG emission estimates which is largely independent from inventories. The scale of such models can be designed around local, regional, or global boundaries and can provide information on the magnitude, geographical distribution and trends in emissions. Some brief examples of these techniques are provided in this section; however further discussion and elaboration can be found in more comprehensive summaries and examples of the use of these methods for inventory verification (Miller *et al.*, 2017; Bergamaschi *et al.*, 2017; Rypdal *et al.*, 2005; DeCola *et al.*, 2017; Jacob *et al.*, 2016).

The concentrations of greenhouse gases (GHG) that are observed at monitoring sites, mobile observing platforms or remotely sensed from satellites can be used to provide emission estimates by a technique known as inverse modelling. Inverse models calculate emissions by optimally combining concentration observations with an atmospheric transport model. In doing so, the inverse model must take into account estimates of uncertainty from both the observations and the atmospheric model. We note that flux assessments from inverse modelling necessarily include the contribution from all sectors (anthropogenic and natural sources/sinks) as well as international transport from region to region. As a result, it remains challenging to attribute estimated fluxes to specific source categories or regions using currently available sparse observation networks, which complicates the application of inverse modelling approaches to source-specific emissions verification (Miller *et al.*, 2017), although it is expected to be less difficult with more dense observation networks in future (Pison *et al.*, 2017). The quality of the derived emissions critically depends on the quality and quantity of measurements and the quality of the atmospheric model, since inverse methods typically propagate estimated observation and model errors, the latter usually being the more dominant component (Bergamaschi *et al.*, 2017). The most demanding, but proven, approach for verification is establishment and operation of a national or regional/multi-national GHG observing network combined with inverse modelling and analysis (Andrews *et al.*, 2014; Bergamaschi *et al.*, 2017; Lopez-Coto *et al.*, 2017). Despite the availability of inverse modelling tools, specialized training is required to apply them and obtain robust flux estimates that can be used to verify emission estimates from a greenhouse gas inventory. More implementation details are presented in the IG3IS (Integrated Global Greenhouse Gas Information System) plan prepared by the Global Atmospheric Watch program of WMO (DeCola *et al.*, 2017), which will be an up to date guide for implementing observations and inverse modelling for inventory verification.

At sub-national scales, such as city-scale, facility and basin-scale, studies using regional atmospheric monitoring networks or targeted observation campaigns are being used for improving the knowledge about regional and facility level emissions and contributing to updating the emission factors for selected emission categories, including the oil and gas sector, urban emissions, and emissions from agriculture (Zavala-Araiza *et al.*, 2015; McKain *et al.*, 2015; Viatte *et al.*, 2017).

6.10.2.2 SUMMARY OF NEEDS FOR GHG EMISSION INVENTORY VERIFICATION USING ATMOSPHERIC MEASUREMENTS

Establishing a system for verifying National Greenhouse Gas Inventories with Atmospheric Observations and Inverse Modelling involves overcoming technical challenges and costs. Analysis needs to be undertaken by atmospheric scientists informed by GHG inventory priorities and needs. The following key elements needed are summarized below:

- **In-situ Atmospheric measurement (observations)** and input to their conditions of measurement by, usually, meteorological agencies and measurement site operators. The observations need to be from an established network of GHG monitoring stations with data that meet high standards involving air sample analysis, data processing, reference gas maintenance, calibration correction against international standards, and submission to global databases such as WDCGG (World Data Centre for Greenhouse Gases). Establishing a national GHG monitoring network involves optimal network design in order to set up the observation locations that maximize the effect of the observations on reducing the uncertainty of the emission estimates (Nickless *et al.*, 2015; Lopez-Coto *et al.*, 2017). The guidelines for observation techniques and reference gas maintenance are provided by the WMO Global Atmospheric Watch Program[1], and AGAGE Network (Prinn *et al.*, 2000).
- **Satellite retrievals:** While *in situ* measurements have the advantage of directly measuring concentrations within the boundary layer, providing strong constraints on regional emissions, satellite retrievals are integrated over a larger portion of the atmospheric column and are subject to biases. However, due to their greater spatial coverage, additional observations from satellites are used to improve the inverse model estimates for methane, by Ganesan *et al.*, (2017) for India, and Turner *et al.*, (2015) for US and, in future, planned for carbon dioxide.
- **Inverse Modeling tools** backed by participation of the modelling community. A number of transport models - Flexpart (Stohl *et al.*, 2005), NAME (Jones *et al.*, 2007), STILT (Lin *et al.*, 2003) - and inverse-modelling tools: Flexinvert (Thompson *et al.*, 2014), NAME-InTEM (Manning *et al.*, 2011), and Carbontracker (van der Laan-Luijkx *et al.*, 2017) are available from the developer groups for use in emission estimates.
- **Gridded prior inventory data as input for inverse modeling.** For use in inverse modeling the national greenhouse-gas inventory needs to be spatially and temporally disaggregated and presented as gridded emission dataset, typically at 1 km to 10 km spatial resolution for regions (Tsagatakis *et al.*, 2017; Maasakkers *et al.*, 2016) and EDGAR database for a globe (Janssens-Maenhout, *et al.*, 2017). The absence of the up to date national gridded inventory data often results in using available global data from EDGAR database, and may not be up to date for inventory reporting cycle.

6.10.2.3 SUMMARIES OF THE EMISSION ESTIMATES BY TARGET GAS

Methane

Methane (CH_4) is considered a favorable candidate to which inverse modelling techniques can be applied because of the strong atmospheric signal to noise ratio of measurements and the generally high uncertainty in emission estimates that arise from uncertainty of emission factors. Efforts to estimate national-scale methane emissions using atmospheric observations and inverse models of atmospheric transport have been made in Switzerland (see Table 6.2), the UK (see example in Box 6.3) and Ireland, the US (Miller *et al.*, 2013), and the EU-28 countries. Emission estimates for 28 EU countries (Bergamaschi *et al.*, 2017) were made with a set of several inverse models for over the period 2006-2012 using observations from a network with 18 stations. The advantage of applying several models is that the spread of individual inverse model results provides a measure of the errors and biases inherent to the transport and inverse modeling. As a summary of the study, it was mentioned that influence of natural wetland emissions over Northern Europe needs to be better quantified, transport models need to be improved, and additional observations are needed.

Carbon dioxide

[1] WMO reports (https://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html).

Uncertainties of anthropogenic emissions of carbon dioxide due to fuel combustion are usually lower than that of inverse model estimates. However, substantial effort is applied to quantify urban emissions (Lauvaux et al, 2016) that may lead to developing capability to track the emission reduction trends. High uncertainty makes carbon dioxide emissions and sinks by AFOLU one of the more challenging sectors to verify, particularly carbon stock changes and associated CO_2 fluxes for land use and management. In this case, use of atmospheric observations is obstructed by strong interference from natural fluxes. In a study by Ogle *et al.*, (2015), authors did find agreement between the results from the atmospheric CO_2 concentration data and inverse and an inventory of CO_2 emissions based on data from the US Greenhouse Gas Inventory. The study focused on a sub-region of the United States that is dominated by agricultural food production, and showed that in order to verify emissions from the AFOLU sector, compilers will need to address all sources of CO_2 uptake and release, including lateral movement of CO_2.

Nitrous oxide

Nitrous oxide emissions by agricultural soils are known to have large uncertainty because of patchy heterogeneous emission patterns and significant temporal variability, leading to uncertainty in emission factors and emission rates, which makes it useful to test the estimated emissions with inverse modeling. Inverse model estimates of the nitrous oxide emissions based on atmospheric monitoring are made for many regions of the globe (Manning *et al.*, 2011; Bergamaschi *et al.*, 2015; Miller *et al.*, 2012) and are also reported is UK inventory report (see Box 6.5). In several studies a reasonable match is found between inventory and inverse model estimates, for example N_2O inverse modeling results for Europe (Bergamaschi *et al.*, 2015) confirm the amount reported to UNFCC by 15 EU countries within the model uncertainty range.

Halogenated gases

Halogenated gases (HFCs, PFCs, SF_6) are particularly suitable for inverse modeling as they are solely of anthropogenic origin and sufficiently long-lived. In addition, bottom up inventories for halogenated gases are affected by considerable uncertainties. In the past decade, much progress has been made in the development of top-down approaches for estimating emissions of these powerful greenhouse gases. This has been made possible due to the increased capability of producing high-quality atmospheric datasets and to the rapid development of inverse modeling techniques that have been extensively applied from the global to the regional (national) scale (Stohl *et al.* 2009; Manning *et al.* 2011; Keller *et al.* 2011). Such studies are based on long-term and/or continuous observations of the atmospheric levels of halogenated gases that are carried out within international and national programmes - AGAGE (Advanced Global Atmospheric Gases Experiment, http://agage.mit.edu/), NOAA-ESRL-GMD (National Oceanic and Atmospheric Administration-Earth System Research Laboratory-Global Monitoring Division, https://www.esrl.noaa.gov/gmd/), and others. Switzerland, United Kingdom and Australia (Fraser *et al.*, 2014) included top-down estimates of halogenated gas emissions in their national inventory reports. Several regional and national scale estimates were made with available observations by Hu *et al.* (2017) for US, Keller *et al.* (2011), Graziosi *et al.*, (2017) for European countries, Kim *et al.* (2010), Fang *et al.* (2015) for East Asia (China). One of the most studied gases is HFC-134a, the most abundant HFC in the global atmosphere, mainly used as refrigerant in mobile air conditioners and stationary refrigeration. Differently to other HFCs, top-down studies suggest that bottom-up inventories are likely to be affected by an overestimate of the emission factors (Hu *et al.* 2017; Graziosi *et al.*, 2017). A more detailed analysis of UK emissions of HFC-134a (see Box 6.5) suggested a need for a reassessment of the bottom up reporting method for this refrigerant.

6.10.2.4 STRENGTHS AND WEAKNESSES OF USING ATMOSPHERIC MEASUREMENTS FOR VERIFICATION OF GHG EMISSIONS

The current level of success with the use of atmospheric monitoring for testing anthropogenic GHG emission inventories varies by target gas and region, depending on several factors, such as uncertainty of the emission inventory and of the models, number and location of available observations, contribution of the natural fluxes to the observed variability (Bergamaschi *et al.*, 2017). Table 6.1 provides an overview of where atmospheric measurements have been used for verification of GHG emissions. More details on feasibility of applying the inverse modeling estimates to comparison with emission inventories for particular target gases and emission sectors are summarized by Rypdal *et al.*, (2005) and Rypdal and Winiwarter (2001).

TABLE 6.1
OVERVIEW OF THE STRENGTHS AND WEAKNESSES OF USING ATMOSPHERIC MEASUREMENTS FOR VERIFICATION OF GHG EMISSIONS

Gas	Strengths/Successes	Problems/Weaknesses	Future Development/Possibilities
CO_2	Large amount of observations, although mostly focusing on natural fluxes.	Uncertainties of models may be significantly higher than those of inventories Not used in national reporting.	Need more developments in observations targeting anthropogenic emissions.
CO_2 city-scale	City-scale studies show some degree of success[2]. Inventory uncertainties are relatively larger than at national scale.	Even with dense observation networks, errors in emission estimates are large, due to interference from vegetation fluxes. Not used in national reporting.	Large efforts are ongoing to develop observation networks, pilot projects for tracking urban emissions, trends. Satellite observations expected to contribute.
CH_4	Large anthropogenic emission fraction National reporting: UK, Switzerland National emission estimates: EU-28[3], USA[4], India[5]	Few countries have observations, transport and inverse models have uncertainties, interference from natural emissions (wetlands) cited.	Reginal observation networks and satellite observations are available and expanding.
N_2O	National reporting: UK National emission estimates: EU-28, US	Observation sites are few, gridded inventories are simplified, large contribution from natural sources.	Expansion of surface networks will contribute to better model estimates
HFCs	National reporting: UK, Australia National emission estimates: China, US, EU EF correction: Australia and UK	Measurements are sophisticated and expensive. Observation sites are few, gridded inventories are simplified.	Expanding the monitoring network depends on funding.

6.10.2.5 USE OF COMPLIMENTARY OBSERVATIONS AND GLOBAL MODELLING PRODUCTS

SATELLITE OBSERVATIONS

Satellite observations by GOSAT were used for national scale methane emission estimates with regional inverse models by Ganesan *et al.*, (2017) for India and Turner *et al.*, (2015) for the US. Currently several global inverse modeling products by the Copernicus atmospheric monitoring service (CAMS) (Segers and Houweling, 2017) and the GOSAT Level 4 product (Saito *et al.*, 2016) use satellite observations of methane in addition to the ground-based observations. Emission estimates with inverse models utilizing GOSAT data are included in the Global Carbon Project (GCP) CH_4 assessment (Saunois *et al.*, 2016). Use of satellite methane observations (GOSAT and SCIAMACHY) in inversion is still in the experimental stage, due to multiple technical challenges of producing the high-quality concentration retrievals from the satellite-observed spectra. On the other hand, currently available products are checked for consistency by comparing with estimates made with the use of ground-based observations, and generally do not produce alarmingly different results (Bruhwiller *et al.*, 2017). Several studies have shown the

[2] Lauvaux *et al*., (2016).

[3] Bergamaschi *et al*., (2017).

[4] Miller *et al*., (2013).

[5] Ganesan *et al*., (2017).

sensitivity of satellite sensors to concentration enhancements around emission hot spots, as summarized in the recent review (Matsunaga *et al.*, 2018). A common technique is to take the difference between satellite observations over an emission hot spot or plume and several observed points away from polluted areas. Local GHG concentration enhancements observed by the GOSAT satellite correlate well with transport model simulations, so that the anthropogenic emissions for large regions like the US or temperate Asia can be estimated using a simple regression model (Janardanan *et al*., 2016), while there was less success with country scale estimates, due lack of observations. With the expected availability of methane observations from new satellite sensors, the problem of observation numbers will be relaxed, and national scale emission estimates by hot-spot emission data analysis are expected to become possible.

GLOBAL TRENDS, ISOTOPIC COMPOSITION, AND TRACER CORRELATIONS

Year to year changes of global abundance of the long-lived atmospheric trace gases can be reliably measured at one or few background monitoring stations (Prinn *et al.*, 2000). Atmospheric measurements are useful for evaluating the global emissions of the new halogenated compounds, even before reporting and inventory procedures are well established. For example, emerging growth in atmospheric content of HFC-365mfc, HFC-245fa, HFC-227ea, HFC-236fa, and NF_3 was quantified using background concentration monitoring (Stemmler *et al.*, 2007, Vollmer *et al.*, 2011, Arnold *et al*., 2012). Measurements of the methane isotopic composition were used by Schwietzke *et al.*, (2016), Rice *et al.*, (2016) and others to propose corrections of the global emissions of methane, with implications for estimates of global methane emissions of both fossil (including oil and gas) and biogenic (wetlands and agriculture) origin. Continuous observations of multiple trace gases provide opportunity to use strong correlation observed between short term variabilities of different tracers to deduce the regional emission rate ratios (e.g. CH_4/CO, CH_4/CO_2) and their trends over time (Fraser *et al.*, 2014; Tohjima *et al.*, 2014).

COMPARING NATIONAL INVENTORY TO THE GLOBAL INVERSE MODEL PRODUCTS

For many countries where the national observing networks or national scale inverse model estimates are not available, optionally, national scale emission estimates can still be derived from regional and global inverse modelling results. Regional methane emission assessments have been made by several groups for the EU, East Asia, and North America (Bergamaschi *et al.*, 2017; Thompson *et al.*, 2015; Miller *et al.*, 2013). The data can be requested from the authors and national estimates can be extracted from those inverse modelling results. Regularly updated and publicly available inverse model estimates for CH_4 and N_2O emissions are provided by operational global and regional inverse modelling products, such as Copernicus Atmosphere Monitoring Services for CH_4 (Segers and Houweling, 2017) and N_2O (Bergamaschi *et al.*, 2013), NOAA Carbontracker-CH_4 (Bruhwiler *et al.*, 2014). The Global Carbon Project - Methane (GCP-methane) compares and makes available multiple global inverse model estimates. Several institutions, such as LSCE, MPI BGC, and Wageningen University also make regular updates of their emission estimates at the global scale and make their gridded flux data available upon request. Step-by-step instructions for using global products for comparison to national inventory are provided in Table 6.3.

6.10.2.6 PROCEDURES AND EXAMPLES

NECESSARY STEPS TO FOLLOW IN APPLYING INVERSE MODELLING FOR VERIFICATION OF A NATIONAL GHG INVENTORY

Based on several working examples (Manning *et al.*, 2011, Henne *et al.*, 2016, Fraser *et al.*, 2014) of emission estimates accepted for inclusion into national reports, several key steps can be identified that are needed for the successful use of inverse modelling in verification of a national GHG inventory. These include:

- Step1: Acquisition of GHG observations from a surface network (and optionally, from satellites) that has sufficient coverage of the country. The observation data have to be linked to the same calibration scale and be processed by the same routine across the network.
- Step 2: Preparing gridded (spatially disaggregated) prior emissions data, based on up-to-date national inventory.
- Step 3: Preparing and operating the inverse model and atmospheric transport model.
- Step 4: Quality assurance/Quality Control to the inverse model output
- Step 5: Comparison, verification, and reporting. Production of final outputs and update of the GHG inventory improvement plan.

To illustrate the content of the procedures made at each step, several examples of comparing the national inventory to the inverse model estimates are provided in the Table 6.2, while UK example is presented in more detail in the Box 6.3.

TABLE 6.2
SUMMARY OF THE KEY STEPS IMPLEMENTED IN NATIONAL EXAMPLES

Examples **Comparison steps**	**Example 1** **Methane emissions in Switzerland**[6]	**Example 2** **HFC-134a emissions in UK**[7]	**Example 3** **PFCs, HFCs emissions in Australia**[8]
Step 1: Concentration measurements on national GHGs network.	CarboCount-CH measurement network (totally 4 cites).	Advanced Global Atmospheric Gases Experiment (AGAGE) / UK DECC network, one site (Mace Head).	Background AGAGE site at Cape Grim (Tasmania), and urban site at Aspendale (Victoria).
Step 2: Gridded prior emissions data.	Swiss Greenhouse Gas Inventory (SGHGI).	UK Refrigeration and Air-Conditioning (RAC) Model.	Australian national inventory.
Step3: Inverse modelling.	Lagrangian particle dispersion model (LPDM) FLEXPART.	Numerical Atmospheric dispersion Modelling Environment (NAME), InTEM (inversion technique for emission modeling).	Interspecies correlation (ISC), forward CSIRO TAPM model, inverse model NAME-InTEM.
Step 4: Quality assurance/Quality Control to the inverse model.	Sensitivity inversion, Transport model validation.	Sensitivity analysis, Transport model validation.	Sensitivity analysis, Transport model validation.
Step 5: Comparison, verification, and reporting.	Estimated national CH_4 emissions of 196 ± 18 Gg yr^{-1}, agrees with SGHGI estimation of 206 ± 33 Gg yr^{-1}.	Based on comparison with inverse model estimates, revision of the RAC model parameters (AC servicing rate) was recommended.	Agreement found to within 2% for HFC-125, HFC-134a, HFC-143a and HFC-152a, within 15% for HFC-23, HFC-365mfc and SF6, within 35% for HFC-32.

Example of national inventory comparison (UK methane (CH_4) and nitrous oxide N_2O inverse modelling) to inverse modelling estimates is provided in Box 6.3 below.

[6] (Henne *et al.*, 2016).

[7] (Say *et al.*, 2016).

[8] (Fraser *et al.*, 2014).

BOX 6.3

UK METHANE (CH_4) AND NITROUS OXIDE (N_2O) INVERSE MODELLING

Observation and modelling: In order to provide verification of the UK Greenhouse Gas Inventory (GHGI), The UK's government BEIS (Department for Business, Energy and Industrial Strategy) maintains a high-quality remote observation station at Mace Head (MHD) (set up in 1987) on the west coast of Ireland. The station reports high-frequency concentrations of the key greenhouse gases under the supervision of the University of Bristol. UK extended the measurement programme in 2012 with three new tall tower stations across the UK: Tacolneston (TAC) near Norwich; Ridge Hill (RGL) near Hereford; Tall Tower Angus (TTA) near Dundee, Scotland (replaced by to Bilsdale (BSD) in North Yorkshire in Sept 2015). Methane, carbon dioxide, nitrous oxide and sulphur hexafluoride (SF_6) are measured across the UK network, whereas all of the other gases (e.g. HFCs and PFCs) are only measured at MHD and TAC. The UK Met Office, under contract, employs the Lagrangian dispersion model NAME (Numerical Atmospheric dispersion Modelling Environment) (Jones *et al.* 2007) driven by three-dimensional modelled meteorology to interpret the observations. By estimating the underlying baseline concentration trends (Northern Hemisphere mid-latitude atmospheric concentrations where the short-term impact of regional pollution has been removed from the data) and by modelling where the air has passed over on route to the observation stations on a regional scale, estimates of UK emissions are made. A methodology called Inversion Technique for Emission Modelling (InTEM) has been developed that uses a Bayesian minimization technique, to determine the emission map that most accurately reproduces the observations (Manning *et al.* 2003, 2011). A gridded emission inventory is developed for use in inversion by disaggregating country total emissions for each category proportionally to spatially distributed activity data (Tsagatakis *et al.*, 2017).

Output, analysis and arising actions: In the study by Manning *et al.* (2011) emission estimates made for the UK are compared to the GHGI emission estimates for the period 1990 to 2007. The results indicate reasonable agreement between the inventory and inversion results for the United Kingdom for N_2O over the entire period. For CH_4 the agreement is poor in the 1990s but good in the 2000s. The UK CH_4 inventory reported reduction from 1990–1992 to 2005–2007 (over 50%) is dominated by changes to landfill and coal mine emissions and is more than double the corresponding drop in the inversion estimated emissions (24%). The inversion results suggest that the United Kingdom has met its Kyoto commitment (−12.5%) but by a smaller margin (−14.3%) than reported (−17.3%).

Findings:

- UK GHG inventory methane estimates have fallen steadily since 1990 largely due to estimated reductions in emission from the waste disposal and energy (fugitives) sectors.
- The inverse modelling estimates show little change in methane emissions across the same time-series although the uncertainties are large in the early years, and so do not show the same significant downward trend as the GHG inventory estimates.

Actions:

- The differences between the GHGI and the inverse modelling trends are a subject of active investigation by the modelling and GHG inventory teams.
- Inventory actions – Assessment of missing / underrepresented sources:

(i) Agriculture: Consider how the yearly variability from emissions from enteric fermentation (specifically sheep) could impact emission estimates. A new agriculture model is being implemented but this is unlikely to have a significant impact;

(ii) Review fugitive emissions from offshore oil/gas and coal mines.

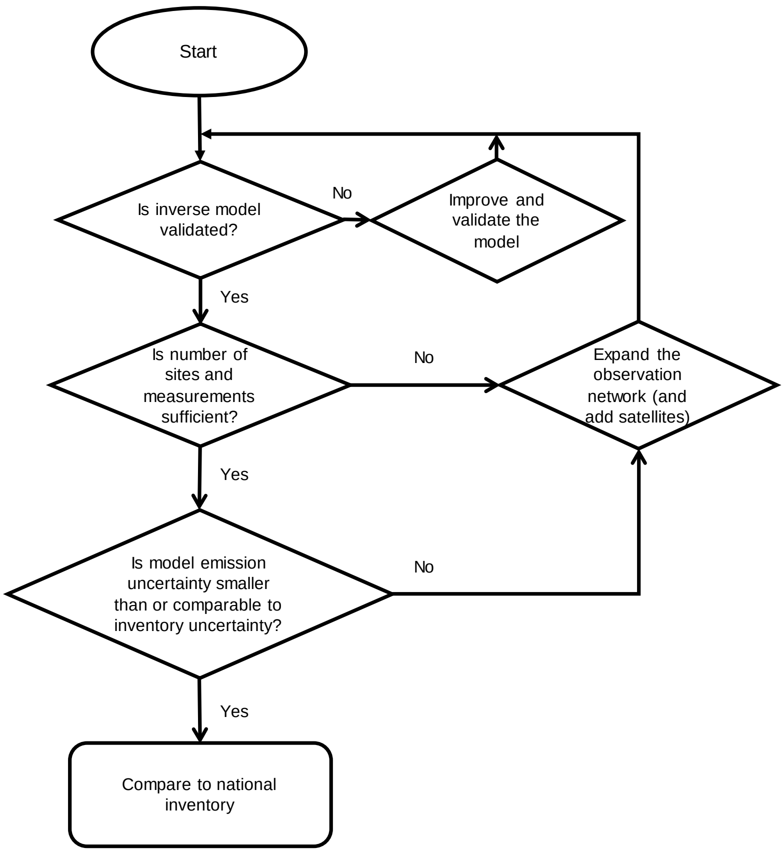
6.10.2.7 CHECKING NECESSARY CRITERIA FOR APPLYING INVERSE MODEL ESTIMATES FOR COMPARISON TO NATIONAL INVENTORY

Utility of inverse model estimates for quality checks and improving the inventory depends on the accuracy and precision of the emission estimates by inverse modeling. The inverse model estimates can be used for verification when some criteria are satisfied:

- Inverse modeling system has been tested and validated by several methods, including transport model validation with well-known tracers, inverse model validation by model comparison and sensitivity studies.
- Sufficient number of observation sites, and measurement frequency for specific gas. Three-Four tall tower sites are used for CH_4 in the Swiss and UK cases, while useful estimates for HFCs were made with one site for UK. Inverse modelers use emission uncertainty reduction in Bayesian modeling framework (targeting no less than 50% reduction) to ensure that the inverse model estimates are decided by observations rather than prior emission rates.
- Uncertainties of the inverse model estimates are comparable to or lower than GHG inventory. For example, high emission inventory uncertainty is known for HFC emissions and many other fugitive emissions, while uncertainty of carbon dioxide emissions from fuel use is low. This check is applied to avoid comparison of inventories with significantly lower uncertainty (such as carbon dioxide from fossil fuel) to the inverse model estimates.

Based on these three criteria listed above, a model decision tree for evaluating feasibility of using inverse modelling estimates for inventory verification is shown in Figure 6.1:

Figure 6.1 A decision tree for checking the necessary criteria for using the inverse model estimates in the National Inventory verification



6.10.2.8 NECESSARY STEPS FOR COMPARING NATIONAL INVENTORY TO THE INVERSE MODELLING PRODUCTS

An outline of the necessary steps for comparing national inventory to the global inverse model products is given in Table 6.3.

TABLE 6.3
GENERAL OUTLINE OF NATIONAL INVENTORY COMPARISON TO GLOBAL/REGIONAL INVERSE MODELLING PRODUCTS

Defining target gases and time periods	• Based on inverse modelling data available at the time of report preparation, select available gases (CH_4, N_2O, HFCs) and time periods overlapping between inventory data and inverse model results. Use advice from the modelers on a degree of uncertainty the product is providing for particular country's emissions.
Data acquisition	• Download, receive gridded emission data files, file format descriptions and release notes. Check if the data can be read with available software.
Remapping to make national total	• Prepare remapping table. Calculate area fraction of the national land in each grid cell of the emission data grid. • Calculate national total emission for each time step, by summing grid emissions multiplied by fraction of national land. Make national total for each year. • If available with inverse modelling results, remap emission uncertainty in a same way as emissions.
Using multiple products	• When the number of available inverse modelling products is more than one, remapping to make national total can be made for all the available products. It is recommended to include in the report national total estimates for each inverse modelling product, along with average and standard deviation of the emissions across the set of inverse modelling products.
Report preparation	• Outline the dataset (datasets) used in the report, cite the product release version, reference the release date, and version of the release note. Provide a description of the remapping procedure used in the remapping. Prepare comparison table showing the national emissions for all gases and years by inventory and emissions, emission uncertainties estimated with inverse models, average value and standard deviation across a set of inverse modelling products.

6.11 USE AND REPORTING OF MODELS

New guidance in section 6.11 of the *2019 Refinement*.

6.11.1 Use of models

The *2006 IPCC Guidelines* provide some guidance on how to ensure that data from models can comply with good practice when used in National Greenhouse Gas Inventories. For example, Table 6.4 indicates some of the specific reference in the *2006 IPCC Guidelines* related to the development and use of models. However, this guidance is not complete or systematic: this section addresses this gap.

TABLE 6.4
GENERAL GUIDANCE RELATED TO MODELS IN VOLUMES 1 & 4 OF THE 2006 IPCC GUIDELINES

Section in 2006 IPCC Guidelines	Guidance
Chapter 3, Volume 1: Uncertainties	
3.2.1 Sources of data and information (p 3.14).	Guidance on uncertainties associated with models.
Chapter 5, Volume 1: Time Series Consistency	
5.2.1 Recalculations due to methodological changes.	The calculation of emission factors and other parameters and refinements (Box 5.1, p 5.6) in AFOLU may require a combination of sampling and modelling work. Time series consistency must apply to the modelling work as well. Models can be viewed as a way of transforming input data to produce output results. In most cases where changes are made to the data inputs or mathematical relationships in a model, the entire time series of estimates should be recalculated. In circumstances where this is not feasible due to available data, variations of the overlap method could be applied.
Chapter 6, Volume 1: Quality Assurance/Quality Control and Verification	
6.7.1 Emissions factor QC (p 6.12)	Guidance on QC checks on models
Chapter 2, Volume 4: Generic Methodologies Applicable to Multiple Land-Use Categories	
2.5.2 Model-based Tier 3 inventories (p 2.52)	Guidance on developing model based Tier 3 inventories for AFOLU sector

6.11.2 Why use more complex methods?

Simple approaches to estimating greenhouse gas emissions and removals are often unsatisfactory for certain categories because they fail to capture the complexity and diversity of systems and practices, and the resulting greenhouse gas emissions and removals. Hence, a greater number of inventories rely on more sophisticated approaches, using models or direct measurements to improve the accuracy and the resolution (both spatial and temporal) of inventory estimates.

Model development relies on data from direct measurements. In general, models are used to estimate those emissions or removals that cannot be easily otherwise obtained, and to extend limited information to cover national emissions and removals, both spatially and temporally. Models use measured data for calibration and evaluation.

6.11.3 Models

Models aim to transform input data into outputs in a way that replicates the real world. For example, with inputs of the distance driven by road vehicles an appropriate model can estimate emissions of greenhouse gases. Thus, models add value to original data. Models are frequently used to assess complex systems and can be used to generate data; however, models are means of data transformation and do not remove the need for the original data to drive them.

Every act of data interpretation has an underlying model. Even a simple calculation assumes that units of activity, individually or on the average, carry the same emissions burden:

$$Emission = (Emission\ Factor)\ x\ (Activity\ Data).$$

This assumption is the underlying model. More complex models are called for where this simple calculation seems inadequate e.g., the sigmoid growth of a stand of trees means that one cannot simply multiply the removal rate by the stand area to get a removal from the atmosphere: the age of the stand also matters. Linkages between processes can be much more complicated than this. This situation can be captured by more complex models, but the greater complexity can lead to reduced transparency. This guidance aims to achieve greater transparency in these situations.

There are many benefits in using complex models in national greenhouse gas inventories. These may include:

- models may improve coverage and completeness as those can extend existing data to improve geographic coverage/distribution and coverage of source/sink categories by filling in gaps in data;
- models may increase spatial and temporal resolution of estimates;
- generally, models may increase the accuracy of results and usually improve uncertainty assessment by providing a system with an improved structure and more systematic treatment of data;
- models can provide an opportunity to test our understanding of cause-and-effect relationships, hence to assess the impacts of mitigation efforts;
- models may provide comparability with other countries and systems;
- models may improve transparency through stratification by making differences between strata (subcategories) explicit;
- models may improve time series consistency of inventory, for example, by providing annual estimates even where only occasional measurements exist;
- models may be a cost effective and in many cases, the only possible option to estimate emissions and removals compared to extensive data collection;
- models can enable better projections by matching past estimates and future projections and treatment of nationally specific circumstances, technologies and practices and mitigation efforts;
- models can represent non-linear and dynamic systems better compared to the linear averaging done in most Tier 1 and 2 methods;
- models can be adapted to national circumstances;
- models can provide frameworks for uncertainty analyses and identification of research priorities to improve greenhouse gas inventories as far as is practicable;

However, using models may have some adverse effects in such cases where:

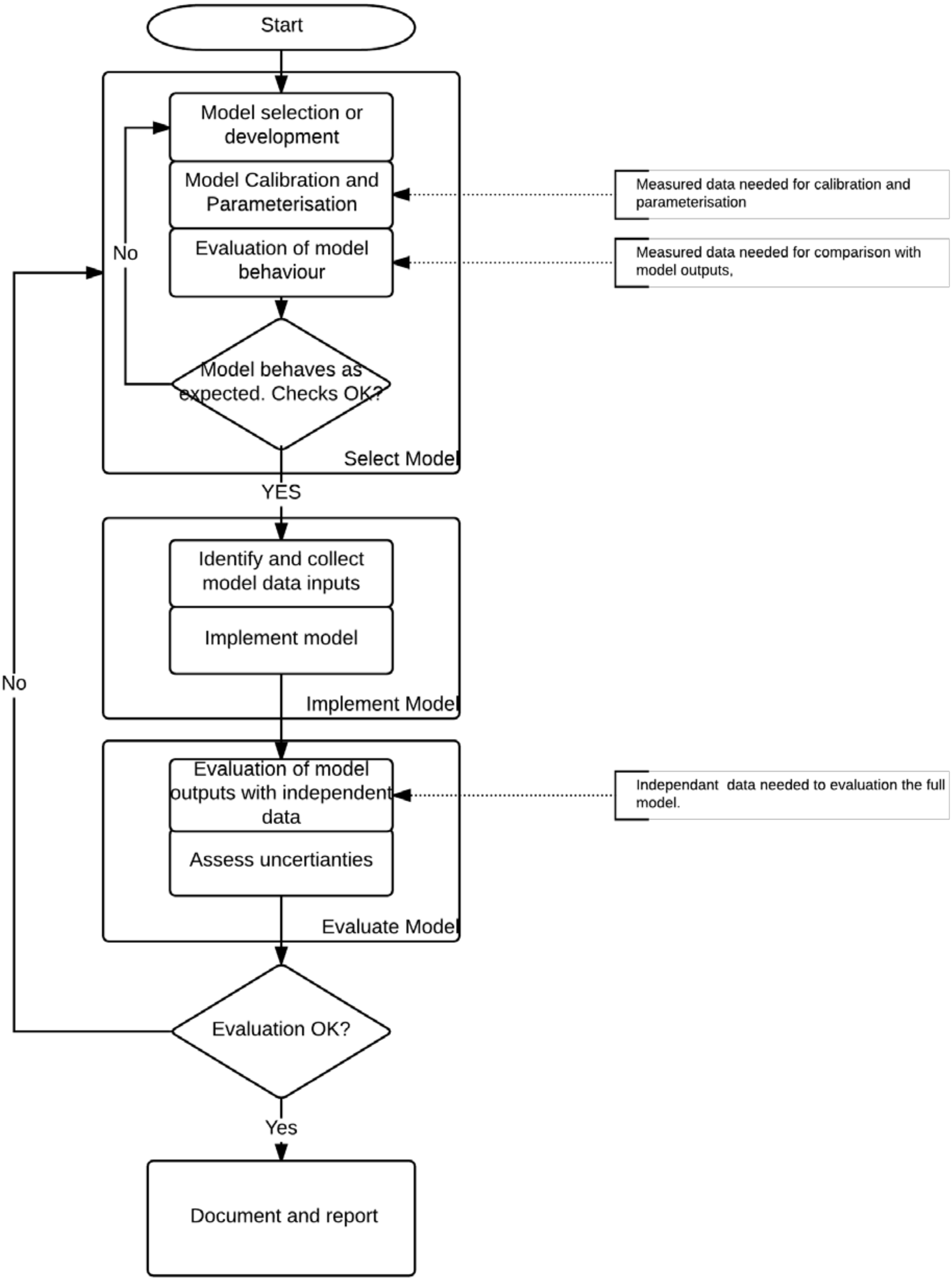
- the model is incorrectly used (e.g., applied outside the domain of application without appropriate adaptation);
- the key assumptions are not correct;
- there are errors in the model;
- inappropriate data are fed into the model.

6.11.4 Use of Models in Good Practice National Greenhouse Gas Inventories

In the application of models in National Greenhouse Gas Inventories, a critical issue is suitability. Suitability describes how well the model reflects the national circumstances: It may have been specifically developed or adapted from an existing model. A model should be correctly parameterized and calibrated, and this will be demonstrated through the model evaluation and the uncertainty assessment. Previously, lack of transparency and inconsistent documentation has been identified as a major concern (IPCC 2010). While these general guidelines will not specify how to choose, build, calibrate or evaluate a model it is crucial that they are all reported and documented transparently in order for the model results to be understandable, assessable and credible and the guidelines concentrate on these issues. It is good practice to follow the approach given here.

Most complex models should be well-documented covering model description, suitability, calibration, model evaluation and uncertainty and where this exists the existing documentation should be referenced: there is no need to reproduce it.

Figure 6.2 Schematic of typical model development/selection process



6.11.4.1 IDENTIFY MODEL: SELECT OR ADAPT EXISTING MODEL OR DEVELOP NEW MODEL

A model must be suitable for its intended use. Suitability is the applicability of the model and any adaptation to the specific national situation in which the model is used for greenhouse gas inventory purposes. A model could be developed for the specific situation or could be a development or adaptation of an existing model. Where an existing model is selected inventory, compilers need to consider and document the following questions:

- Is the model designed for, or portable to, the current national circumstances?
- Are the other conditions for which the model is applied different from those for which the model originally was developed (e.g. ecological or management)?

It is good practice to document the suitability of the model. The documentation should include:

- The reason for choosing or designing the model (applicability);
- How the differences in local conditions compared to those for which the model was constructed were treated (e.g. ecological or management)? What are the effects these differences might have on the accuracy of model estimates?

Is the model used outside the parameter space for which the model was developed? If yes, what might the consequences be?

DEVELOPING OR ADAPTING A MODEL: PARAMETERISATION, CALIBRATION AND EVALUATION OF MODEL BEHAVIOUR[9]

In order to set up, calibrate and parameterise the model real data ("calibration data") is needed. The data used and outcome of this should be documented.

Following the establishment of the model and its calibration and parameterisation, it is good practice to compare model outputs with calibration data (e.g. evaluation of model behaviour). This will check the model behaves as expected and indicates the extent to which the model reproduces the variation in the data that were used to establish its parameter values.

It is good practice to ensure that the model responds appropriately to variations in activity data and that the model is able to report results by the required categories. Re-calibration of the model or modifications to the structure (i.e., algorithms) may be necessary if the model does not capture general trends or there are large systematic biases. In some cases, a new model may be selected or developed based on this evaluation. Evaluation results are an important component of the reporting documentation, justifying the use of a particular model for quantifying emissions in a source category.

The results of these checks should be documented and reported. It is good practice to document the input data needed, the model structure and material assumptions.

6.11.4.2 IMPLEMENTING AND EVALUATING THE MODEL

Following the selection of the model, it needs to be implemented. This involves the identification and collection of all the relevant input data and the refinement of the software implementation. Following this, the next step in model development is model results evaluation: comparing model results with independent measurements.

This is an important step in the use of models as it involves testing the fully implemented model, as it will be used in practice with independent data. Evaluation with independent data is done with a completely independent set of data from model calibration, providing a more rigorous assessment of model components and results. Optimally, independent evaluation should be based on measurements from a monitoring network or from research sites that were not used to calibrate model parameters. The sampling does not need to be as dense as needed for measurement-based estimates.

[9] The terms, "*validation*" and "*verification*" are sometimes misunderstood by the inventory compilers and model developers due to their different connotations to different user groups. Therefore, these terms are not used in this document and *model evaluation* is used.

If this independent evaluation demonstrates that the model-based estimation system produces large differences between model results and the measurements this may not indicate the model is wrong. Problems may stem from two other possibilities: errors in the implementation step or poor input data. Implementation problems typically arise from computer programming errors, while model inputs may generate erroneous results if these data are not representative of the activity, management or environmental conditions. These possibilities need to be excluded before the model is revised or discarded.

It is good practice for the results of this evaluation to be documented and reported.

The evaluation should cover the following points:

- Testing should cover different conditions, circumstances and spatial scales.
- Partial or component tests for the measurable parts should be performed.
- Evaluation of the model output through model inter-comparison, if possible. This will show which models best represent local conditions.
- Evaluation of the model through comparison with Tier 1/2 results. Differences between a complex model and lower tier approaches may be due to the model better representing the real world (e.g. temporal variability), by including effects not represented in the lower tier. Therefore, it is important to explain significant differences in terms of the physical processes represented in the model. Uncertainty assessment results from the lower tier approaches should be compared and findings documented.

In addition, it may be possible to produce some indicators that show the model is performing correctly. Reporting such indicators and showing they are correctly conserved will demonstrate model robustness. Examples include:

- AFOLU sector models should conserve mass and land area.
- Energy sector models should be consistent with the energy balance.
- In some industrial sectors, a mass balance is possible (e.g. carbon in refineries and iron and steel plant).

In addition, some intermediate outputs of the model at an adequately disaggregated level may greatly help users of reported information to assess the final outputs of the models.

UNCERTAINTY AND SENSITIVITY ANALYSIS

While an understanding of likely model uncertainty may be produced based on the model structure and algorithms, uncertainty and sensitivity analysis should also be performed as part of model evaluation. This is important so that a rigorous measure of model confidence, based on model inputs and structure, can be reported. It is good practice to report:

- the error distribution of key parameters;
- the covariance matrix of the model parameters (if it is a parametric model);
- results of either error propagation or Monte-Carlo analysis;
- the results of an evaluation of uncertainties from the comparison of model outputs with the independent data;
- the results of a sensitivity analysis or identification of key parameters/inputs to which the model outputs are more sensitive.

INTERPRETATION OF MODEL RESULTS

In order to assist the correct interpretation of the model results, experience suggests that it would be useful to also supply, as part of the model and inventory documentation:

- A comparison of implied emission factors with either country-specific factors or, if not available, IPCC default values. This comparison should also provide an explanation for any significant differences.
- An explanation of any unusual input values and results (i.e. outliers with respect to some reference data).

The distribution of input and output values.

6.11.5 QA/QC for selecting, adapting and using models

It is good practice for the selection, development and use of models to be part of the inventory QA/QC plan. The elements described in section 6.3 are all relevant. There should be clear roles and responsibilities. The inventory QA/QC plan should include the checking and evaluation steps described and should check that documentation is available. References to appropriate documents and publications are acceptable. Do not replicate existing documents.

Regular use of the model should include checks on the input of data and the reasonableness of outputs.

It is good practice to include external experts (those not involved in the model development) in the evaluation of the inventories. Publication of the model in peer-reviewed literature is desirable.

6.11.6 Reporting on the use of models in emission inventories

To ensure transparency in the use of models it is good practice to report the following items (noting that references should be made to existing model documentation should be made wherever possible):

- Basis and type of model (statistical, deterministic, process-based, empirical, etc.).
- Reasons for selecting the particular model.
- If an existing model is being used and adapted: Area of application of original model and adaptation of the model (description of why and how the model was adapted for conditions outside the originally intended domain of application).
- Main equations/processes.
- Material assumptions (important assumptions made in developing and applying the model).
- Domain of application (Description of the range of conditions for which the model has been developed to apply)[10].
- How the model parameters were estimated.
- Description of key inputs and outputs.
- Details of calibration and evaluation with calibration data and independent data (showing intermediate outputs at an adequately disaggregated level).
- Description of the approach taken to the uncertainty analysis and to the sensitivity analysis, and the results of these analyses.
- QA/QC procedures adopted.
- Findings of QA by experts not involved in the model development.
- Interpretation of model results.
- Comparison of model results with lower tier approaches[11].
- References to peer-reviewed literature (where details of the research on the model can be found).

[10] Model outputs should match the definitions and requirements of the IPCC Guidelines.

[11] It is not necessary to do this every year, but in establishing a model as part of a national inventory system, the impact of the model results compared with the lower tier approach should be considered. For example, a model may be able to better describe annual temporal changes and so better describe larger year-to-year variability: this would be averaged out in lower tiers through the use of fixed emission factors.

6.11.7 Checklist for ensuring good practice in the use of complex, higher tier models in national greenhouse gas inventories

Model Identification (covering selection, development or adaption of existing models):

- Selection and applicability of model and adaptation to the situation in which the model is used for GHG inventory purposes:
  - (i) Document choice of model based on published studies using the model for the conditions in your country and/or how the model has been adapted to represent the conditions in your country.
  - (ii) Supplemental documentation may be needed to describe the adaptation of the model to the conditions in a country if publications are not available with this information.
- Basis and type of model (statistical, deterministic, process-based, empirical, top-down, bottom-up etc.):
  - (i) Document the conceptual approach (e.g. model represents statistical relationships or processes), and the mathematical formulation in general terms, such as the model is process-based with a bottom-up approach to estimate emissions.
- Identify main processes and equations:
  - (i) Document the main processes and describe the driving variables for those processes.
  - (ii) List the main equations if feasible (may not be feasible with highly complex models or not necessary with simple bookkeeping models).
  - (iii) Also, cite publications that describe the model in detail if they exist. It may be necessary to develop supplemental information documents if the model description has not been published or to provide regional parameter values that are too detailed to be publishable in a scientific journal.
- Material assumptions in model:
  - (i) Document material assumptions. E.g., first order approximation was assumed to represent soil organic matter decomposition for three kinetically defined pools with a short, medium and long turnover time.
- Domain of application:
  - (i) Provide information about the extent of the model application to systems in the country, e.g., all agricultural lands with arable crops grown on upland soils.
- Model Calibration and Checks:
  - (i) Briefly describe the calibration of the model (i.e., parameterization) which may include tuning individual algorithms or the model in a single operation using informal (manual) adjustments to parameters or an automated optimization that at empts to derive a set of parameters based on minimizing the error in the predictions relative to a set of measurements.
- Document the model checks:
  - (i) Provide graphs or other summaries of the evaluation of calibrated model to measured emissions data. Evaluation data should be from sites that were not used in calibration or data from the calibration sites that were collected at different time periods than the data used in the calibration step.
  - (ii) Other key predictions from the model may also be evaluated e.g. net primary production and respiration, litterfall, harvest transfers, or stock sizes that may be predicted in AFOLU sector models.
  - (iii) May also compare performance to other models if other models were evaluated.
  - (iv) Include references to published articles with more detail on the calibration and/or evaluation if available. Supplemental documentation may be needed if this information is not published.
- Model Implementation and Model Evaluation:
  - (i) Identify Model Inputs:
    - i. Describe type of data inputs to the model. e.g., *weather data were based on analysis of long-term precipitation and temperature data from the national weather service* or *transportation*

data were based a national scale monitoring of miles travelled by vehicle type, engine, condition and age.

ii. Include references to publications of the input data or online publication of the data.

iii. List any key assumptions that were necessary to use these data, such as representativeness of management data.

iv. Describe any special considerations with regards to the domain of the inventory application using the model given input data. e.g., were different input data sets used in different parts of the domain, or was the application of the model limited to specific parts of the country due to the domain of the input data.

(ii) Implementation of Model:

i. Briefly describe computing framework including the hardware, databases and programs that were used to execute the inventory.

ii. Provide a description of output variables from the model and any conversions or modifications made to derive the final emissions and removal estimates.

iii. Summarise QA/QC procedures adopted to ensure the modelling systems performed appropriately, e.g. checking that of land area is conserved through the analysis; unit conversions are correct; and review of the procedures, inputs and/or outputs by experts not involved with the inventory. List any critical errors identified and corrective actions taken.

iv. Optionally provide examples of simple model calculations, such as emissions and removals by forest stands or landscapes in response to different forest management, natural disturbance, or mitigation scenarios. Examples of model performance may be easier to understand than lengthy and complex descriptions of intended model behaviour.

(iii) Evaluation of inventory results:

i. Describe checks on emission results. This may include:

a) Estimating implied emissions factors and comparing to lower tier emission factors and/or expected ranges. Further explanation may be needed for differences.

b) Compare to lower tier methods if inventory also estimated with lower tiers.

c) Compare to independent measurements that were not used for calibration and evaluation of the model, such as data from a monitoring network in the country.

ii. Where conservation of mass is expected (e.g. carbon form fuel combustion, storage and leakage of fluorinated gases, carbon form land use and land use change, nitrogen in waste) check that the mass entering the system in combination with the existing storage, is accounted for through emissions and/or storage in the system. Note that losses of mass that may not all be related to greenhouse gas emissions (e.g., nitrate leaching from soils which does not contribute to direct soil nitrous oxide emissions).

(iv) Assess Uncertainties

i. Provide a description of any sensitivity analysis conducted and a summary of findings in terms of key parameters influencing the model results.

ii. Describe the derivation of uncertainties in the model inputs and model structure, as well as any other key uncertainties.

iii. Provide references to articles that provide additional detail on sensitivity or uncertainty analysis from your application. Supplemental documentation may be needed if this information is not published.

6.12 DOCUMENTATION, ARCHIVING AND REPORTING

6.12.1 Internal documentation and archiving

No refinement.

6.12.2 Reporting

No refinement.

References

Andrews, A. E., Kofler, J. D., Trudeau, M. E., Williams, J. C., Neff, D. H., Masarie, K. A., Chao, D. Y., Kitzis, D. R., Novelli, P. C., Zhao, C. L., Dlugokencky, E. J., Lang, P. M., Crotwell, M. J., Fischer, M. L., Parker, M. J., Lee, J. T., Baumann, D. D., Desai, A. R., Stanier, C. O., De Wekker, S. F. J., Wolfe, D. E., Munger, J. W. & Tans, P. P. (2014) CO_2, CO, and CH_4 measurements from tall towers in the NOAA Earth System Research Laboratory's Global Greenhouse Gas Reference Network: instrumentation, uncertainty analysis, and recommendations for future high-accuracy greenhouse gas monitoring efforts. *Atmospheric Measurement Techniques* **7**(2): 647-687.

Bergamaschi, P., Corazza, M., Karstens, U., Athanassiadou, M., Thompson, R. L., Pison, I., Manning, A. J., Bousquet, P., Segers, A., Vermeulen, A. T., Janssens-Maenhout, G., Schmidt, M., Ramonet, M., Meinhardt, F., Aalto, T., Haszpra, L., Moncrieff, J., Popa, M. E., Lowry, D., Steinbacher, M., Jordan, A., O'Doherty, S., Piacentino, S. & Dlugokencky, E. (2015) Top-down estimates of European CH_4 and N_2O emissions based on four different inverse models. *Atmospheric Chemistry and Physics* **15**(2): 715-736.

Bergamaschi, P., Houweling, S., Segers, A., Krol, M., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Wofsy, S. C., Kort, E. A., Sweeney, C., Schuck, T., Brenninkmeijer, C., Chen, H., Beck, V. & Gerbig, C. (2013) Atmospheric CH4in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. *Journal of Geophysical Research: Atmospheres* **118**(13): 7350-7369.

Bergamaschi, P., Karstens, U., Manning, A. J., Saunois, M., Tsuruta, A., Berchet, A., Vermeulen, A. T., Arnold, T., Janssens-Maenhout, G., Hammer, S., Levin, I., Schmidt , M., Ramonet, M., Lopez, M., Lavric, J., Aalto, T., Chen, H., Feist, D. G., Gerbig, C., Haszpra, L., Hermansen, O., Manca, G., Moncrieff, J., Meinhardt, F., Necki, J., Galkowski, M., Doherty, S., Paramonova, N., Scheeren, H. A., Steinbacher, M. & Dlugokencky, E. (2017) Inverse modelling of European CH_4 emissions during 2006-2012 using different inverse models and reassessed atmospheric observations. *Atmospheric Chemistry and Physics Discussions*: 1-23.

Bruhwiler, L., Dlugokencky, E., Masarie, K., Ishizawa, M., Andrews, A., Miller, J., Sweeney, C., Tans, P. & Worthy, D. (2014) CarbonTracker-CH_4: an assimilation system for estimating emissions of atmospheric methane. *Atmospheric Chemistry and Physics* **14**(16): 8269-8293.

Bruhwiler, L. M., Basu, S., Bergamaschi, P., Bousquet, P., Dlugokencky, E., Houweling, S., Ishizawa, M., Kim, H. S., Locatelli, R., Maksyutov, S., Montzka, S., Pandey, S., Patra, P. K., Petron, G., Saunois, M., Sweeney, C., Schwietzke, S., Tans, P. & Weatherhead, E. C. (2017) U.S. CH4 emissions from oil and gas production: Have recent large increases been detected? *Journal of Geophysical Research: Atmospheres* **122**(7): 4070-4083.

Ciais, P., Paris, J. D., Marland, G., Peylin, P., Piao, S. L., Levin, I., Pregger, T., Scholz, Y., Friedrich, R., Rivier, L., Houwelling, S. & Schulze, E. D. (2010) The European carbon balance. Part 1: fossil fuel emissions. *Global Change Biology* **16**(5): 1395-1408.

DeCola, P., and WMO secretariat. (2017) An Integrated Global Greenhouse Gas Information System (IG3IS). *WMO Bulletin* **66**: 38-45.

EDGAR. Emission Database for Global Atmospheric Research (EDGAR). RIVM-MNP, Bilthoven, TNO-MEP, Apeldoorn, JRC-IES, Ispra and MPIC-AC, URL: http://www.mnp.nl/edgar/.

Fang, X., Stohl, A., Yokouchi, Y., Kim, J., Li, S., Saito, T., Park, S. & Hu, J. (2015) Multiannual top-down estimate of HFC-23 emissions in East Asia. *Environ Sci Technol* **49**(7): 4345-4353.

Fraser, P., Dunse, B., Krummel, P., Steele, P., and Derek, N.: (2014) Australian HFC, PFC, Sulfur Hexafluoride and Sulfuryl Fluoride emissions. *Centre for Australian Weather and Climate Research*: 1-27.

Ganesan, A. L., Rigby, M., Lunt, M. F., Parker, R. J., Boesch, H., Goulding, N., Umezawa, T., Zahn, A., Chatterjee, A., Prinn, R. G., Tiwari, Y. K., van der Schoot, M. & Krummel, P. B. (2017) Atmospheric observations show accurate reporting and little growth in India's methane emissions. *Nat Commun* **8**(1): 836.

Graziosi, F., Arduini, J., Furlani, F., Giostra, U., Cristofanelli, P., Fang, X., Hermanssen, O., Lunder, C., Maenhout, G., O'Doherty, S., Reimann, S., Schmidbauer, N., Vollmer, M. K., Young, D. & Maione, M. (2017) European emissions of the powerful greenhouse gases hydrofluorocarbons inferred from atmospheric measurements and their comparison with annual national reports to UNFCCC. *Atmospheric Environment* **158**: 85-97.

Henne, S., Brunner, D., Oney, B., Leuenberger, M., Eugster, W., Bamberger, I., Meinhardt, F., Steinbacher, M. & Emmenegger, L. (2016) Validation of the Swiss methane emission inventory by atmospheric observations and inverse modelling. *Atmospheric Chemistry and Physics* **16**(6): 3683-3710.

Hu, L., Montzka, S. A., Miller, J. B., Andrews, A. E., Lehman, S. J., Miller, B. R., Thoning, K., Sweeney, C., Chen, H., Godwin, D. S., Masarie, K., Bruhwiler, L., Fischer, M. L., Biraud, S. C., Torn, M. S., Mountain, M., Nehrkorn, T., Eluszkiewicz, J., Miller, S., Draxler, R. R., Stein, A. F., Hall, B. D., Elkins, J. W. & Tans, P. P. (2015) U.S. emissions of HFC-134a derived for 2008-2012 from an extensive flask-air sampling network. *Journal of Geophysical Research: Atmospheres* **120**(2): 801-825.

IPCC (2011). Use of Models and Facility-Level Data in Greenhouse Gas Inventories (Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia) eds: Eggleston, H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M., Pub. IGES, Japan 2011.[12].

Jacob, D. J., Turner, A. J., Maasakkers, J. D., Sheng, J., Sun, K., Liu, X., Chance, K., Aben, I., McKeever, J. & Frankenberg, C. (2016) Satellite observations of atmospheric methane and their value for quantifying methane emissions. *Atmospheric Chemistry and Physics* **16**(22): 14371-14396.

Janardanan, R., Maksyutov, S., Oda, T., Saito, M., Kaiser, J. W., Ganshin, A., Stohl, A., Matsunaga, T., Yoshida, Y. & Yokota, T. (2016) Comparing GOSAT observations of localized CO_2 enhancements by large emitters with inventory-based estimates. *Geophysical Research Letters* **43**(7): 3486-3493.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J. G. J., Peters, J. A. H. W., van Aardenne, J. A., Monni, S., Doering, U. & Petrescu, A. M. R. (2017) EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970-2012. *Earth System Science Data Discussions*: 1-55.

Jones, A., Thomson, D., Hort, M., and Devenish, B. (2007) The U.K. Met Office's Next-Generation Atmospheric Dispersion Model, NAME III. *in: Air Pollution Modeling and Its Application XVII, edited by: Borrego, C., and Norman, A.-L., Springer US, Boston, MA*: 580-589.

Keller, C. A., Brunner, D., Henne, S., Vollmer, M. K., O'Doherty, S. & Reimann, S. (2011) Evidence for under-reported western European emissions of the potent greenhouse gas HFC-23. *Geophysical Research Letters* **38**(15): 1944-8007.

Kim, J., Li, S., Kim, K.-R., Stohl, A., Mühle, J., Kim, S.-K., Park, M.-K., Kang, D.-J., Lee, G., Harth, C. M., Salameh, P. K. & Weiss, R. F. (2010) Regional atmospheric emissions determined from measurements at Jeju Island, Korea: Halogenated compounds from China. *Geophysical Research Letters* **37**(12): L12801.

Lauvaux, T., Miles, N. L., Deng, A., Richardson, S. J., Cambaliza, M. O., Davis, K. J., Gaudet, B., Gurney, K. R., Huang, J., O'Keefe, D., Song, Y., Karion, A., Oda, T., Patarasuk, R., Razlivanov, I., Sarmiento, D., Shepson, P., Sweeney, C., Turnbull, J. & Wu, K. (2016) High-resolution atmospheric inversion of urban CO2 emissions during the dormant season of the Indianapolis Flux Experiment (INFLUX). *Journal of Geophysical Research: Atmospheres* **121**(10): 5213-5236.

Lin, J., Gerbig, C., Wofsy, S., Andrews, A., Daube, B., Davis, K., and Grainger, C. (2003) A near-field tool for simulating the upstream influence of atmospheric observations: The Stochastic Time-Inverted Lagrangian Transport (STILT) model. *Journal of Geophysical Research-Atmospheres* **108**.

Lopez-Coto, I., Ghosh, S., Prasad, K. & Whetstone, J. (2017) Tower-based greenhouse gas measurement network design—The National Institute of Standards and Technology North East Corridor Testbed. *Advances in Atmospheric Sciences* **34**(9): 1095-1105.

Maasakkers, J. D., Jacob, D. J., Sulprizio, M. P., Turner, A. J., Weitz, M., Wirth, T., Hight, C., DeFigueiredo, M., Desai, M., Schmeltz, R., Hockstad, L., Bloom, A. A., Bowman, K. W., Jeong, S. & Fischer, M. L. (2016) Gridded National Inventory of U.S. Methane Emissions. *Environ Sci Technol* **50**(23): 13123-13133.

Manning, A. J., O'Doherty, S., Jones, A. R., Simmonds, P. G. & Derwent, R. G. (2011) Estimating UK methane and nitrous oxide emissions from 1990 to 2007 using an inversion modeling approach. *Journal of Geophysical Research* **116**(D2).

Manning, A.J., Ryall, D.B., Derwent, R.G., Simmonds, P.G. and O'Doherty S. (2003). Estimating European emissions of ozone-depleting and greenhouse gases using observations and a modelling back-attribution technique, *J. Geophys*. Res. Vol. 108, No. D14, 4405, 10.1029/2002JD002312, 17 July 2003.

McKain, K., Down, A., Raciti, S. M., Budney, J., Hutyra, L. R., Floerchinger, C., Herndon, S. C., Nehrkorn, T., Zahniser, M. S., Jackson, R. B., Phillips, N. & Wofsy, S. C. (2015) Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proc Natl Acad Sci U S A* **112**(7): 1941-1946.

Miller, S. M., Kort, E. A., Hirsch, A. I., Dlugokencky, E. J., Andrews, A. E., Xu, X., Tian, H., Nehrkorn, T., Eluszkiewicz, J., Michalak, A. M. & Wofsy, S. C. (2012) Regional sources of nitrous oxide over the United States: Seasonal variation and spatial distribution. *Journal of Geophysical Research: Atmospheres* **117**(6): D06310.

Miller, S. M. & Michalak, A. M. (2017) Constraining sector-specific CO_2 and CH_4 emissions in the US. *Atmospheric Chemistry and Physics* **17**(6): 3963-3985.

Miller, S. M., Wofsy, S. C., Michalak, A. M., Kort, E. A., Andrews, A. E., Biraud, S. C., Dlugokencky, E. J., Eluszkiewicz, J., Fischer, M. L., Janssens-Maenhout, G., Miller, B. R., Miller, J. B., Montzka, S. A., Nehrkorn, T. & Sweeney, C. (2013) Anthropogenic emissions of methane in the United States. *Proc Natl Acad Sci U S A* **110**(50): 20018-20022.

[12] Accesible at: http://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/1008_Model_and_Facility_Level_Data_Report.pdf.

Nickless, A., Ziehn, T., Rayner, P. J., Scholes, R. J. & Engelbrecht, F. (2015) Greenhouse gas network design using backward Lagrangian particle dispersion modelling - Part 2: Sensitivity analyses and South African test case. *Atmospheric Chemistry and Physics* **15**(4): 2051-2069.

Ogle, S. M., Davis, K., Lauvaux, T., Schuh, A., Cooley, D., West, T. O., Heath, L. S., Miles, N. L., Richardson, S., Breidt, F. J., Smith, J. E., McCarty, J. L., Gurney, K. R., Tans, P. & Denning, A. S. (2015) An approach for verifying biogenic greenhouse gas emissions inventories with atmospheric CO_2 concentration data. *Environmental Research Letters* **10**(3).

Pison, I., Berchet, A., Saunois, M., Bousquet, P., Broquet, G., Conil, S., Delmotte, M., Ganesan, A. L., Laurent, O., Martin, D., amp, apos, Doherty, S., Ramonet, M., Spain, T. G., Vermeulen, A. & Yver Kwok, C. (2017) How a European network may help estimating methane emissions at the French national scale. *Atmospheric Chemistry and Physics Discussions* **2017**: 1-35.

Prinn, R. G., Weiss, R. F., Fraser, P. J., Simmonds, P. G., Cunnold, D. M., Alyea, F. N., O'Doherty, S., Salameh, P., Miller, B. R., Huang, J., Wang, R. H. J., Hartley, D. E., Harth, C., Steele, L. P., Sturrock, G., Midgley, P. M. & McCulloch, A. (2000) A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE. *Journal of Geophysical Research: Atmospheres* **105**(D14): 17751-17792.

Rice, A. L., Butenhoff, C. L., Teama, D. G., Roger, F. H., Khalil, M. A. & Rasmussen, R. A. (2016) Atmospheric methane isotopic record favors fossil sources flat in 1980s and 1990s with recent increase. *Proc Natl Acad Sci U S A* **113**(39): 10791-10796.

Rypdal, K., Stordal, F., Fuglestvedt, J.S. and Berntsen, T. (2005). Bottom-up vs. top-down methods in assessing compliance with the Kyoto Protocol, *Climate Policy* 5, 393-405.

Rypdal, K., and Winiwarter, W (2001). Uncertainties in greenhouse gas emission inventories — evaluation, comparability and implications, *Environmental Science & Policy*, **4**, 107-116, https://doi.org/10.1016/S1462-9011(00)00113.

Saito, M., Kim, H. S., Ito, A., Yokota, T. & Maksyutov, S. (2016) Enhanced Methane Emissions during Amazonian Drought by Biomass Burning. *PLoS One* **11**(11): e0166039.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J., Dlugokencky, E., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F., Castaldi, S., Jackson, R., Alexe, M., Arora, V., Beerling, D., Bergamaschi, P., Blake, D., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Hoglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H., Kleinen, T., Krummel, P., Lamarque, J., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K., Marshall, J., Melton, J., Morino, I., Naik, V., O'Doherty, S., Parmentier, F., Patra, P., Peng, C., Peng, S., Peters, G., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W., Saito, M., Santini, M., Schroeder, R., Simpson, I., Spahni, R., Steele, P., Takizawa, A., Thornton, B., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., van Weele, M., van der Werf, G., Weiss, R., Wiedinmyer, C., Wilton, D., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z., and Zhu, Q (2016) The global methane budget 2000-2012, *Earth System Science Data*, **8**, 697-751, 10.5194/essd-8-697-2016, 2016.

Say, D., Manning, A., O'Doherty, S., Rigby, M., Young, D., and Grant, A (2016). Re-Evaluation of the UK's HFC-134a Emissions Inventory Based on Atmospheric Observations, *Environmental Science & Technology*, **50**, 11129-11136, 10.1021/acs.est.6b03630, 2016.

Schwietzke, S., Sherwood, O., Ruhwiler, L., Miller, J., Etiope, G., Dlugokencky, E., Michel, S., Arling, V., Vaughn, B., White, J., and Tans, P(2016). Upward revision of global fossil fuel methane emissions based on isotope database, *Nature*, **538**, 88-91, 10.1038/nature19797.

Segers, A., and Houweling, S.: Description of the CH4 Inversion Production Chain, 27, 2017. (http://atmosphere.copernicus.eu/sites/default/files/FileRepository/Resources/Documentation/Fluxes/CAMS73_2015SC1_D73.2.4_201702_production_chain_v2.pdf).

Stohl, A., Seibert, P., Arduini, J., Eckhardt, S., Fraser, P., Greally, B. R., Lunder, C., Maione, M., Mühle, J., O'Doherty, S., Prinn, R. G., Reimann, S., Saito, T., Schmidbauer, N., Simmonds, P. G., Vollmer, M. K., Weiss, R. F. & Yokouchi, Y. (2009) An analytical inversion method for determining regional and global emissions of greenhouse gases: Sensitivity studies and application to halocarbons. *Atmospheric Chemistry and Physics* **9**(5): 1597-1620.

Stohl, A., Forster, C., Frank, A., Seibert, P. & Wotawa, G. (2005) Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2. *Atmospheric Chemistry and Physics* **5**(9): 2461-2474.

Thompson, R., and Stohl, A (2014). FLEXINVERT: an atmospheric Bayesian inversion framework for determining surface fluxes of trace species using an optimized grid, *Geoscientific Model Development*, **7**, 2223-2242, 10.5194/gmd-7-2223-2014.

Thompson, R., Stohl, A., Zhou, L., Dlugokencky, E., Fukuyama, Y., Tohjima, Y., Kim, S., Lee, H., Nisbet, E., Fisher, R., Lowry, D., Weiss, R., Prinn, R., O'Doherty, S., Young, D., and White, J (2015). Methane emissions in East Asia for 2000-2011 estimated using an atmospheric Bayesian inversion, *Journal of Geophysical Research-Atmospheres*, **120**, 4352-4369, 10.1002/2014JD022394.

Tohjima, Y., Kubo, M., Minejima, C., Mukai, H., Tanimoto, H., Ganshin, A., Maksyutov, S., Katsumata, K., Machida, T., and Kita, K.: Temporal changes in the emissions of CH_4 and CO from China estimated from CH_4/CO_2 and CO/CO_2 correlations observed at Hateruma Island, Atmospheric Chemistry and Physics, 14, 1663-1677, 10.5194/acp-14-1663-2014, 2014.

Tsagatakis, I., Brace, S., Passant, N., Pearson, B., Kiff, B., Richardson, J., and Ruddy, M (2017) UK Emission Mapping Methodology - A report of the National Atmospheric Emission Inventory 2015, Ricardo Energy & Environment, London, 1-63.

Turner, A., Jacob, D., Wecht, K., Maasakkers, J., Lundgren, E., Andrews, A., Biraud, S., Boesch, H., Bowman, K., Deutscher, N., Dubey, M., Griffith, D., Hase, F., Kuze, A., Notholt, J., Ohyama, H., Parker, R., Payne, V., Sussmann, R., Sweeney, C., Velazco, V., Warneke, T., Wennberg, P., and Wunch, D (2015): Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data, *Atmospheric Chemistry and Physics*, **15**, 7049-7069, 10.5194/acp-15-7049-2015.

van der Laan-Luijkx, I. T., van der Velde, I. R., van der Veen, E., Tsuruta, A., Stanislawska, K., Babenhauserheide, A., Zhang, H. F., Liu, Y., He, W., Chen, H., Masarie, K. A., Krol, M. C., and Peters, W (2017). The CarbonTracker Data Assimilation Shell (CTDAS) v1.0: implementation and global carbon balance 2001–2015, *Geosci. Model Dev.*, **10**, 2785-2800, 10.5194/gmd-10-2785-2017.

Viatte, C., Lauvaux, T., Hedelius, J. K., Parker, H., Chen, J., Jones, T., Franklin, J. E., Deng, A. J., Gaudet, B., Verhulst, K., Duren, R., Wunch, D., Roehl, C., Dubey, M. K., Wofsy, S., and Wennberg, P. O (2017). Methane emissions from dairies in the Los Angeles Basin, *Atmos. Chem. Phys*., **17**, 7509-7528, 10.5194/acp-17-7509-2017.

Vollmer, M., Miller, B., Rigby, M., Reimann, S., Muhle, J., Krummel, P., O'Doherty, S., Kim, J., Rhee, T., Weiss, R., Fraser, P., Simmonds, P., Salameh, P., Harth, C., Wang, R., Steele, L., Young, D., Lunder, C., Hermansen, O., Ivy, D., Arnold, T., Schmidbauer, N., Kim, K., Greally, B., Hill, M., Leist, M., Wenger, A., and Prinn, R (2011)Atmospheric histories and global emissions of the anthropogenic hydrofluorocarbons HFC-365mfc, HFC-245fa, HFC-227ea, and HFC-236fa, *Journal of Geophysical Research-Atmospheres*, **116**, 10.1029/2010JD015309.

Zavala-Araiza, D., Lyon, D., Alvarez, R., Davis, K., Harriss, R., Herndon, S., Karion, A., Kort, E., Lamb, B., Lan, X., Marchese, A., Pacala, S., Robinson, A., Shepson, P., Sweeney, C., Talbot, R., Townsend-Small, A., Yacovitch, T., Zimmerle, D., and Hamburg, S (2015) Reconciling divergent estimates of oil and gas methane emissions, *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 15597-15602, 10.1073/pnas.1522126112.

Annex 6A.1 QC checklists

FORMS AND CHECKLISTS FOR QUALITY CONTROL FOR SPECIFIC SOURCE CATEGORIES

This annex contains a number of example forms that provide means to record both general and category-specific QC activities. These forms are only examples, and inventory compilers may find other means to effectively record their QA/QC activities (to be defined in the QA/QC plan). Refer to the *2006 IPCC Guidelines* chapters on QA/QC and Verification, Data Collection, and for each category as described in Volume 2-5 for more detailed guidance on developing QC checks.

A1. GENERAL QC CHECKLIST

(to be completed for each category and for each inventory)

A2. CATEGORY-SPECIFIC QC CHECKLIST (CHECKS TO BE DESIGNED FOR EACH CATEGORY)

Part A: Data Gathering and Selection

Part B: Secondary Data and Direct Emission Measurement

A1. GENERAL QC CHECKLIST

Inventory Report: ____________ Source/Sink Category[13]: ____

Title(s) and Date(s) of Inventory Spreadsheet(s): ____

Source (sink) category estimates prepared by (name/affiliation): ____

INSTRUCTIONS FOR COMPLETING THIS FORM:

This form is to be completed for each source/sink category, and provides a record of the checks performed and any corrective actions taken. The form may be completed by hand or electronically. The form should be distributed and filed according as specified in the QA/QC plan. If appropriate actions to correct any errors that are found are not immediately apparent, the QC staff performing the check should discuss the results according to the procedures predefined in the QA/QC plan.

The first page of this form summarises the results of the checks (once completed) and highlights any significant findings or actions. The remaining pages in this form list categories of checks to be performed. The analyst has discretion over how the checks are implemented. Not all checks will be applicable to every category. Checks/rows that are not relevant or not available should indicate ‘n/r’ (not relevant) or ‘n/a’ (not available) so that no check and no row is left blank or deleted. Rows for additional checks that are relevant to the source/sink category should be added to the form.

The column for supporting documentation should be used to reference any relevant Supplemental Reports or Contact Reports providing additional information.

Summary of general QC checks and corrective action	
Summary of results of checks and corrective actions taken:	
Suggested checks to be performed in the future:	Any residual problems after corrective actions have been taken:

[13] Use IPCC recognized source/sink category names. See Table 8.2 of Chapter 8.

Checklist for general QC checks (complete table for each category):

Item	**Check completed**			**Corrective action**		**Supporting documents (provide reference)**
	Date	**Individual (first initial, last name)**	**Errors (Y/N)**	**Date**	**Individual (first initial, last name)**	
DATA GATHERING, INPUT, AND HANDLING ACTIVITIES: QUALITY CHECKS						
1. Check a sample of input data for transcription errors						
2. Review spreadsheets with computerised checks and/or quality check reports						
3. Identify spreadsheet modifications that could provide additional controls or checks on quality						
4. Other (specify):						
DATA DOCUMENTATION: QUALITY CHECKS						
5. Check project file for completeness						
6. Confirm that bibliographical data references are included (in spreadsheet) for every primary data element						
7. Check that all appropriate citations from the spreadsheets appear in the inventory document						
8. Check that all citations in spreadsheets and inventory are complete (i.e., include all relevant information)						
9. Randomly check bibliographical citations for transcription errors						
10. Check that originals of new citations are in current docket submittal						
11. Randomly check that the originals of citations (including Contact Reports) contain the material & content referenced						
12. Check that assumptions and criteria for selection of activity data, emission factors and other estimation parameters are documented						
13. Check that changes in data or methodology are documented						
14. Check that citations in spreadsheets and inventory document conform to acceptable style guidelines						
15. Other (specify):						

Checklist for general QC checks (complete table for each category) (Continued):

Item	Check completed			Corrective action		Supporting documents (provide reference)
	Date	Individual (first initial, last name)	Errors (Y/N)	Date	Individual (first initial, last name)	
CALCULATING EMISSIONS AND CHECKING CALCULATIONS						
16. Check that all calculations are included (instead of presenting results only)						
17. Check whether units, parameters, and conversion factors are presented appropriately						
18. Check if units are properly labelled and correctly carried through from beginning to end of calculation						
19. Check that conversion factors are correct						
20. Check that temporal and spatial adjustment factors are used correctly						
21. Check the data relationships (comparability) and data processing steps (e.g., equations) in the spreadsheets						
22. Check that spreadsheet input data and calculated data are clearly differentiated						
23. Check a representative sample of calculations, by hand or electronically						
24. Check some calculations with abbreviated calculations						
25. Check the aggregation of data within a category						
26. When methods or data have changed, check consistency of time series inputs and calculations						
27. Check current year estimates against previous years (if available) and investigate unexplained departures from trend						
28. Check value of implied emission/removal factors across time series and investigate unexplained outliers						
29. Check for any unexplained or unusual trends for activity data or other calculation parameters in time series						
27. Check for consistency with IPCC inventory guidelines and good practices, particularly if changes occur						
28. Other (specify):						

A2. CATEGORY-SPECIFIC QC CHECKLIST

Inventory Report: ___________ Source/sink Category[14]: ____

Key category (or includes a key subcategory): (Y / N): ____

Title(s) and Date(s) of Inventory Spreadsheet(s): ____

Category estimates prepared by (name/affiliation): ____

GENERAL INSTRUCTIONS FOR COMPLETING THIS FORM:

Category-specific checks focus on the particular data and methodology used for an individual source or sink category. The specificity and frequency of these checks will vary across source categories. The form may be completed by hand or electronically. Once completed, the form should be saved and included as part of the inventory archive, as defined in the QA/QC plan.

The first table on this form summarises generally the results of the category-specific checks and highlights any significant findings or corrective actions. The remaining pages in this form list categories of checks to be performed or types of questions to be asked. Part A checks are designed to identify potential problems in the estimates, factors, and activity data. Part B checks focus on the quality of secondary data and direct emission measurement. The analyst has discretion over how the checks are implemented. Checks/rows that are not relevant or not available should indicate 'n/r' (not relevant) or 'n/a' (not available) so that no check and no row is left blank or deleted. Rows for additional checks that are relevant to the category should be added to the form.

The column for supporting documentation should be used to reference any relevant Supplemental Reports or Contact Reports that provide additional information. Other sources may be included here, if they can be clearly referenced. Any documents associated with the category specific plan should be clearly referenced in the column for supporting documentation.

Summary of category-specific QC activities	
Summary of results of checks and corrective actions taken:	
Suggested checks to be performed in the future:	Any residual problems after corrective actions have been taken:

ADDITIONAL INSTRUCTIONS FOR PART A:

The checklist below indicates the types of checks and comparisons that can be performed and is not intended to be exhaustive. Supplemental Reports, Contact Reports, or other documents may be used to report detailed information on the checks conducted. For example, a Supplemental Report could provide information on the

[14] Use IPCC recognized source/sink category names.

variables or sub-variables checked, comparisons made, conclusions that were drawn and rationale for conclusions, sources of information (published, unpublished, meetings, etc.) consulted, and corrective actions required.

Category-specific checklist - Part A: Data gathering and selection						
Item	**Check completed**			**Corrective action**		**Supporting documents (provide reference)**
	Date	**Individual (first initial, last name)**	**Errors (Y/N)**	**Date**	**Individual (first initial, last name)**	
EMISSION DATA QUALITY CHECKS						
1. Emission comparisons: historical data for source, significant sub-source categories						
2. Checks against independent estimates or estimates based on alternative methods						
3. Reference calculations						
4. Completeness						
5. Other (detailed checks)						
EMISSION FACTOR QUALITY CHECK						
6. Assess representativeness of emission factors, given national circumstances and analogous emissions data						
7. Compare to alternative factors (e.g., IPCC default, cross-country, literature)						
8. Search for options for more representative data						
9. Other (detailed checks)						
ACTIVITY DATA QUALITY CHECK: NATIONAL LEVEL ACTIVITY DATA						
10. Check historical trends						
11. Compare multiple reference sources						
12. Check applicability of data						
13. Check methodology for filling in time series for data that are not available annually						
14. Other (detailed checks)						
ACTIVITY DATA QUALITY CHECK: SITE-SPECIFIC ACTIVITY DATA						
15. Check for inconsistencies across sites						
16. Compare aggregated and national data						
17. Other (detailed checks)						

ADDITIONAL INSTRUCTIONS FOR PART B:

Completing the QC checks on secondary data and direct emission measurement may require consulting the primary data sources or authors. The checklist below is intended to be indicative, not exhaustive. Additional information on appropriate checks can be found in the QA/QC, Data Collection, and sectoral chapters of the *2006 IPCC Guidelines*.

Additional documentation is likely to be necessary to record the specific actions taken to check the data underlying the category estimates. For example, Supplemental Reports may be needed to record the data or variables that were checked, and the published references and individuals or organisations consulted as part of the investigation. Contact Reports should be used to report the details of personal communications. Supplemental Reports may also be used to explain the rationale for a finding reported in the summary, the results of research into the QC procedures associated with a survey, or checks of site measurement procedures. Be sure to provide references to all supporting documentation.

Category-specific checklist - Part B: Secondary data and direct emission measurement

Item	**Check completed**			**Corrective action**		**Supporting documents (provide reference)**
	Date	**Individual (first initial, last name)**	**Errors (Y/N)**	**Date**	**Individual (first initial, last name)**	
SECONDARY DATA: SAMPLE QUESTIONS REGARDING THE QUALITY OF INPUT DATA						
1. Are QC activities conducted during the original preparation of the data (either as reported in published literature or as indicated by personal communications) consistent with and adequate when compared against (as a minimum), general QC activities?						
2. Does the statistical agency have a QA/QC plan that covers the preparation of the data?						
3. For surveys, what sampling protocols were used and how recently were they reviewed?						
4. For site-specific activity data, are any national or international standards applicable to the measurement of the data? If so, have they been employed?						
5. Have uncertainties in the data been estimated and documented?						
6. Have any limitations of the secondary data been identified and documented, such as biases or incomplete estimates? Have errors been found?						
7. Have the secondary data undergone peer review and, if so, of what nature?						
8. Other (detailed checks)						
DIRECT EMISSION MEASUREMENT: CHECKS ON PROCEDURES TO MEASURE EMISSIONS						
9. Identify which variables rely on direct emission measurement						
10. Check procedures used to measure emissions, including sampling procedures, equipment calibration and maintenance.						
11. Identify whether standard procedures have been used, where they exist (such as IPCC methods or ISO standards).						
12. Other (detailed checks)						