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Assessing compliance with the Kyoto Protocol: Expert reviews, inverse modelling, or both?

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Tittel: Vurdering av innfrielse av forpliktelsene i Kyoto-protokollen: revisjoner, invers-modellering, eller begge deler?
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Sammendrag: Kyoto-protokollen har etablert et ambisiøst system for rapportering og revisjon av utslippsdata som skal brukes for å vurdere om forpliktelsene blir innfridd. Det vil kreve betydelige ressurser å forsikre seg om at partene rapporterer nøyaktige utslippsdata. Til tross for dette er det en fare for at partene bevisst eller ubevisst rapporterer feilaktige data. Systemet for revisjoner under Kyoto-protokollen vil sannsynligvis bare avdekke større avvik. Fordi et mer omfattende system for revisjon vil være mer kostbart er det behov for en vurdering av hvor sikkert man trenger å vite om forpliktelsene er innfridd. Utslipp kan også beregnes basert på målte konsentrasjoner i atmosfæren og meteorologiske modeller. Disse metodene er imidlertid foreløpig ikke nøyaktige nok for å kunne være et uavhengig alternativ til tradisjonelle utslippsoversikter. Allikevel vil de kunne bidra til å evaluere om totale utslipp endrer seg slik som angitt i Kyoto-protokollen. De kan også til en viss grad være et tillegg til tradisjonelle utslippsoversikter, særlig for fluorgassene, og på denne måten bidra til å forbedre metoder og retningslinjer.

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Abstract: The Kyoto Protocol has an ambitious reporting and review system to assess nations' compliance with their emission commitments. This system requires considerable resources to assure that the Parties report accurate emission inventory data. In spite of this, there is a danger that Parties consciously or unconsciously report erroneous data. The agreed upon review process will likely only detect large discrepancies. Because a more stringent review system would be more costly, there is a need to establish more precisely the needed accuracy to assess compliance. Emissions can alternatively be monitored by independent "top-down" methods; by measuring concentrations of gases in the atmosphere and employing meteorological models. However, all these means are as yet too imprecise to serve as independent alternatives to the emission inventories reported by the Parties to the Kyoto Protocol. Still, they could be useful to monitor the success of the protocol. The top-down approaches might serve to some extent as useful supplements to the traditional emission inventories, in particular those dealing with fluorinated gases, and thereby provide input for improving the methods and guidelines of the emission inventories.

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Contents

1 Introduction

The signatories of the Kyoto Protocol have agreed on specific targets to reduce or limit their emissions of greenhouse gases (GHG) relative to a base year (usually 1990) during the first commitment period (2008-2012). The protocol's compliance and verification system is more stringent than similar systems under other international environmental agreements The major reasons for this include the high economic cost of reducing the emissions, the conflicting interests of the Parties to the protocol, and the difficulties in measuring or estimating the emissions (Fischer, 1995; Hovi et al. (ed.), 2003; Anderson, 2001; Anderson, 2002a; Anderson, 2002b). Furthermore, non-compliance will have economic consequences for the next commitment period which may give incentives for reporting biased data. If the emission reductions reported by the Parties are not real, the integrity of the agreement will be undermined. Moreover, the protocol's effect on reducing man-made climate impact will be even smaller than a correct implementation of the protocol would lead to.

According to the Marrakech Accords, the protocol's Compliance Committee will assess compliance based on emission inventories reported by the Parties. Proper reporting of emission inventories will be required in order for Parties to use the flexible mechanisms (i.e., emissions trading, joint implementation (JI), and the Clean Development Mechanism (CDM)). GHG emissions are, however, not directly measurable. The emission estimates are often derived from calculations based on estimation parameters. Emission data can be intrinsically uncertain (Rypdal and Winiwarter, 2001) and, in addition, some inventories may be of poor quality. The United Nations Framework Convention on Climate Change (UNFCCC) has established a system for reporting and reviewing GHG inventories that is probably the most ambitious in history. This system forms the basis for assessing compliance under the Kyoto Protocol.

Despite the emphasis on a reporting and review system, some observers have questioned whether it will function as intended. It has been claimed that the importance of verification has been neglected in the negotiations (Nilsson et al., 2001). Verification is especially important to ensure the integrity of the emission trading system (*ibid*). States and non-state participants in JI and CDM projects may have incentives to withhold information, and thereby exaggerate their reductions or sequestrations (Mitchell, 2003). Gupta et al. (2003) assert that there will be significant uncertainty about the emission reductions claimed by the parties.

The term "verification" has been used inconsistently, depending on the context and discipline (Hovi, 1992), see Box 1. In political science "verification" refers to the whole system and processes. This meaning is slightly different from its meaning in the context of emission inventories, where the term mainly refers to activities undertaken by the inventory agency (IPCC, 2000). In the emission inventory community also the term *validation* is used: "The establishment of a sound approach and foundation. This involves checking to ensure that the inventory has been compiled correctly in line with reporting instructions and guidelines. The legal use of validation is to give an official confirmation or approval of an act or product" (IPCC, 2000). Most political science definitions of verification encompass both the term verification and validation in IPCC (2000).

The aim of verification (and validation) is to increase confidence in the data reported. This can be ensured through internal systems (the inventory agency itself) and external systems (an independent entity). In this paper we will focus on external systems to ensure the accuracy of reported emissions and emission reductions. We build on the definition of verification in IPCC (2000), this is included in verification as defined by Tenner (2000) in Box 1.

Box 1. Definitions of "verification"

"Verification is a political process of 'confirmation' by means of which the states party to the treaty wish to make 'certain' that the contractually agreed standards, rules and goals are complied with or achieved by all the states involved" (Fischer et al., 1995).

"Verification is the process of gathering, processing and using information to make a judgement about compliance or non-compliance by parties to an agreement. The aim of verification is to establish or increase confidence that a treaty is being implemented fairly and effectively by all parties. In the case of the Kyoto Protocol, the verification system should provide assurance to governments that all parties are taking action to reduce greenhouse gas emissions" (Tenner, 2000).

"Verification is the assessment of the completeness and accuracy of compliance-related information such as data on greenhouse gas emissions or emission reductions, and its conformity with pre-established standards for reporting (assess whether performance matches commitments)." (Hovi et al., 2003).

"Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended application of that inventory." (IPCC, 2000).

The IPCC good practice guidance and uncertainty management in national greenhouse gas inventories (IPCC, 2000), to be applied for reporting under the Kyoto protocol, regards verification as a part of the quality assurance/quality control (QA/QC). Verification should involve data that are independent from those used to compile the inventory. Thus, atmospheric measurements combined with modelling might be regarded as a tool for independent verification of reported emissions.

The Kyoto Protocol's review system is costly to implement but more stringent systems would imply even higher costs. Consequently, it is important to assess to what extent the ambition level is appropriate and whether there are alternative ways to verify that the commitments are fulfilled. This paper will attempt to determine the following: 1) Whether the reporting and review system under the Kyoto Protocol is likely to detect all cases of non-compliance (Section two); 2) The relative strengths and weaknesses of independent verification methods; and (Section three) 3) Whether such independent verification methods in the future should replace or complement the traditional emission inventories as a basis for assessing compliance (Section four). The discussions that follow will focus on the verification of data reported at the national level, and is thus relevant primarily for Parties with specific emissions targets (Annex I Parties). Data reported on the use of flexible mechanisms may have to take into account additional factors that are not addressed here.

2 Compliance based on inventories of emissions and removals

2.1 Overview of the current reporting and control system

To be in compliance with the Kyoto Protocol, the Annex I Parties must do the following:

- Establish a national inventory system and meet reporting requirements (articles 5 and 7)
- Keep net emissions (corrected in accordance with the flexible mechanisms) below their assigned amounts[1] (Article 3)
- Comply with the requirements for use of the flexible mechanisms (articles 6, 12 and 17)

The system for reporting and review was agreed on by the Parties in 2002. Parties must report, in a specific format, detailed annual data on emissions and removals consistent with the base year. A comprehensive document explaining both the methods used and the data must accompany each submission (the National Inventory Report). There are also requirements under the national inventory system for institutional arrangements and data management; for example, the Parties must have in place a formal quality assurance/quality control system. The system's reporting requirements are more stringent than those of other environmental agreements.

The data submitted by the Annex I Parties will be reviewed by an Expert Review Team (ERT) (Article 8 of the Kyoto Protocol). The review team will conclude, by means of a technical process, whether the reported data were prepared in accordance with the agreed guidelines (IPCC, 1997) as set forth by the "good practice guidance" (IPCC, 2000). Inventories will be reviewed annually. There are three types of reviews: 1) desk reviews which take place in the office of each reviewer, 2) centralised reviews which take place at the UNFCCC secretariat, and 3) in-country reviews which take place in the country being reviewed. In-country reviews have proven most successful in detecting inconsistencies. However, such reviews also demand the most resources, and are therefore planned to occur only every fifth year for each inventory (UNFCCC, 2002).

If the reporting Party does not implement the recommendations of the ERT, for example by changing a methodology that does not follow guidelines, the ERT could make adjustments in the reported data,[2] i.e., replace the estimate reported by the Party with their own preliminary estimate. The threat of such adjustments, and the difficulties they would cause to a Party in meeting its commitments are meant to give Parties an incentive to improve their reporting[3].

The Enforcement Branch of the Compliance Committee, using the reports of the review team, will decide on compliance. They will also resolve any disagreements between the

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[1] The amount of emissions in carbon dioxide equivalents that a Party is allowed to emit over the first commitment period.

[2] Addressed in Article 5.2 of the Kyoto Protocol and further elaborated in the UNFCCC document FCCC/CP/2001/13/Add.3.

[3] Technical guidance on methodologies for adjustments can be found in the UNFCCC document FCCC/SBSTA/2003/L.6/Add.3.

review team and the Party regarding the application of adjustments. While the technical experts on the ERT are appointed by the UNFCCC Secretariat on a personal basis, the members of the Compliance Committee are appointed at the political level by the COP/MOP (Conference of the Parties to the UNFCCC and Members of the Parties to the Kyoto Protocol).

Figure 1 gives an overview of the reporting and review system under the Kyoto Protocol.

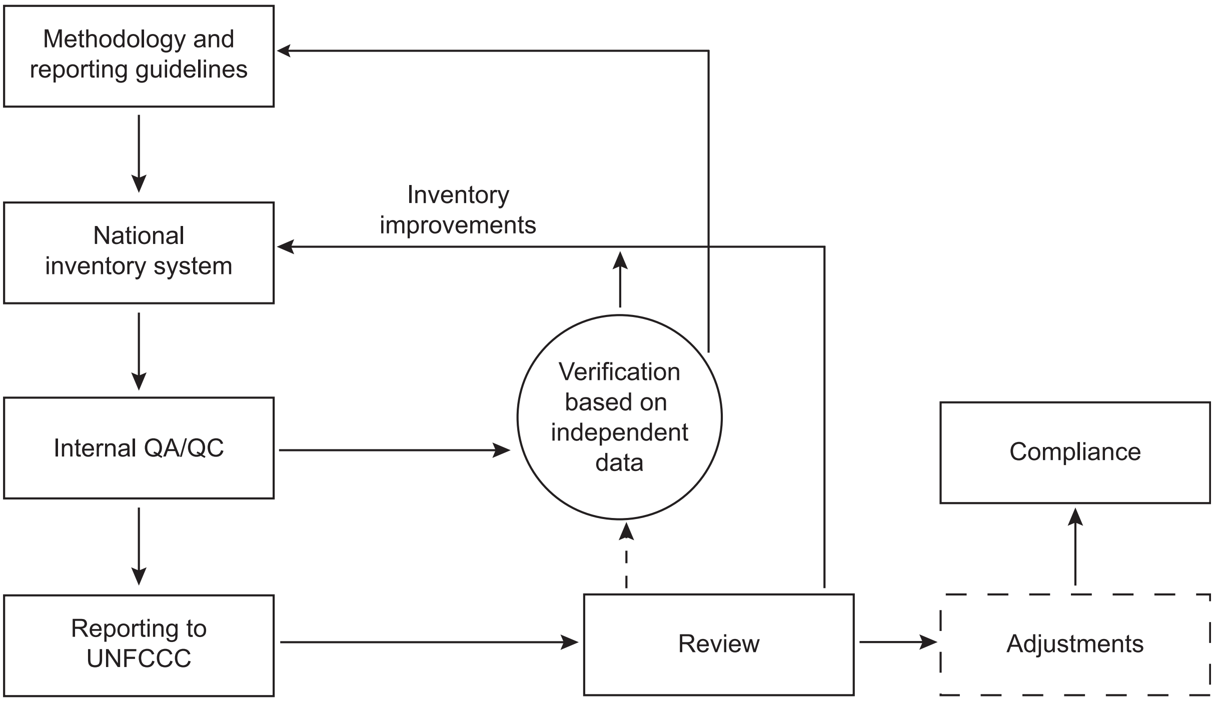

Figure 1. Overview of the reporting and review system under the Kyoto protocol

The importance of uncertainties in the system Assessing compliance can appear to be straightforward if one thinks of it as simply checking that reporting is complete and that emissions do not exceed specified limits (adjusted for the use of the flexible mechanisms). There are, however, several reasons why the reported emission data need further examination, including the following:

i) Scientific uncertainty of the emission data
ii) Deficient reporting (for example due to low capacity)
iii) Intentional reporting of erroneous emission data

The uncertainty in the emission data can be 15-20% in total CO_2 equivalent emissions, depending on the source and gas composition. The average uncertainty of the trend is 4 percentage points (Rypdal and Winiwarter, 2000). This scientific uncertainty is inherently present because most emission processes (CO_2 from fuel combustion is an exception) are complex. Furthermore, adequate models and data to estimate emissions accurately do not always exist. Because the exact levels of emissions cannot be known, there is a danger that Parties appearing to be in compliance would in fact be missing their emission reduction targets by a wide margin. It can be argued that scientific uncertainty is irrelevant in the assessment of legal compliance, because compliance will be based on the best estimates according to the IPCC (1997) guidelines. On the other hand, the high uncertainty makes it difficult to evaluate weaknesses in the reporting (points ii and iii above) because there will be a larger range of acceptable values of a parameter. Indeed, a Party could in principle manipulate data in order to meet their emission target. The role of the review system is to reveal weaknesses in the reporting, but this can be complicated when emission sources that are difficult to estimate are involved. Consequently, the basis for assessing compliance must be a well-functioning review system as described in the next section.

2.2 The importance of uncertainties in the system

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2.3 The review system

The Expert Review Team (ERT) will have to deal with a large number of complex categories of emissions and removals that have been estimated using an even larger number of parameters and statistical data from different sources. Even though a comprehensive national inventory report explaining all data and methodologies is required, it will in practice be difficult to evaluate the quality of data and methodologies due to the large volume of each involved. The national inventory reports also frequently have to refer to technical background reports. But these may be difficult to evaluate because they are often written in technical language, or in a foreign language. The ERT will face time constraints, being limited to only one week for an in-country review. They will consequently not be able to fulfil its duties unless i) the review is focused and ii) it is given the necessary resources, including sufficient time for advance work, and sufficiently qualified personnel and leadership.

Can a review identify deficiencies?

What is the appropriate information to focus on in an inventory review? Only a small number of emission sources might be responsible for the majority of emissions[4]. These should therefore be the focus of reviews since reviews of such key sources are most likely to uncover weaknesses that are important for assessing compliance.

As mentioned, Parties have considerable flexibility to choose methods and emission parameters, and could *in principle* manipulate these parameters to make it easier to meet their emission targets. However there are built-in checks in the review process:[5]

- Methods and emission factors that deviate from guidelines in IPCC (1997) and IPCC (2000) have to be explained and documented.
- Data that deviates from that reported to international organisations (for example energy data reported to the International Energy Agency (IEA) and agricultural data reported to UN Food and Agriculture Organisation (FAO))[6] have to be explained and documented.
- Emission factors (or implied emission factors[7]) that deviate from those used in other countries have to be explained and documented.
- Large changes in year-to-year emissions must be explained to exclude the possibility of inconsistencies in time series.
- Changes in emission factors over time must be documented and explained (for example, by changes in technology, installation of abatement technologies), and linked to the reporting of policies and measures.
- Recalculations (changes in methodologies and data) must be explained[8].

On the other hand, there are many factors that could make it difficult for an ERT to detect weaknesses:

- Complete and fully transparent inventory reporting by all Parties might be lacking.
- New or complex methodologies might have utilized by Parties in their reporting.
- A Party's statistical data might be inaccurate, making the review process very difficult, e.g., energy data or consumption of HFCs.
- Parties might claim that certain data is confidential, e.g., data concerning private enterprises.
- Data for base year emissions are distant in time and consistent data may be lacking and is difficult to review

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[4] The "key sources" according to IPCC (2001) and Rypdal and Flugsrud (2000).

[5] UNFCCC document FCCC/CP/2002/8 includes guidelines for review.

[6] This does not mean that it is assumed that data reported to international organisations always are correct, but these data are reported independently from the data in the inventory.

[7] Implied emission factors are reported emissions within a source category divided by an activity rate for that source category.

[8] Recalculations will not be allowed during the commitment period, except for Land Use Land Use Change and Forestry.

- Land Use Land use Change and Forestry (LULUCF) where final estimates might not be available until after the commitment period while uncertainties can be high

Expert review team

The ERT will identify questions of implementation and possible cases of non-compliance to the Compliance Committee. The efficacy of the review system will depend on the ERT's being staffed and lead by highly qualified personnel able to comprehend a large number of complex technical issues. This includes[9]:

- Knowledge of specific emission processes
- Knowledge of cross-cutting issues in inventories (quality assurance/quality control (QA/QC) systems, completeness, double-counting issues)
- Knowledge of the language of the country being reviewed

The composition of the teams shall secure a balance between Annex I and non-Annex I Parties. Normally the members of the ERT are technical experts involved in the inventory preparation in their home country. None are professional reviewers. The competence of the ERT has been a concern of the SBSTA[10]. UNFCCC has prepared a training course for reviewers. The expenses of experts from Annex I countries (except countries with economies in transition) will normally be funded by their respective governments. Therefore, the review system will rely heavily on funding by the home governments of the experts. Another COP 8 decision calls for the rotation of ERTs, i.e. that the inventory will be reviewed by different teams in subsequent years. It is hoped that rotating ERTs will compensate for any deficiencies in the work of some ERTs. It is also expected that the qualifications of the team members will be improved over time.

Alternative emission inventory based reporting and review systems

More stringent review systems, involving private sector auditors, have been proposed as a means of increasing the certainty with respect to compliance (Hargrave et al., 1999). Hargrave et al. (1999) suggest that private auditors should either participate in the review by the UNFCCC Secretariat or in a pre-certification of the inventory.

There are several options, building on the proposals of Hargrave, to improve the level of uncertainty about compliance, including the following:

1. There could be more stringent requirements for methodologies and documentation in the current reporting and review system. The volume of monitoring could be increased and more advanced estimation methodologies implemented
2. There could be more time allotted for the preparation and conduct of reviews. The reviewers could then go into more detail with respect to the inventory preparation, data sources and methodologies.
3. A system with certified and professional reviewers could be implemented by the UNFCCC.
4. Independent audits by professional reviewers could be conducted.
5. Independent verification methods and measurements (see Section 3) could be more heavily relied upon.

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[9] Decision at COP 8, UNFCCC document FCCC/CP/2002/8.

[10] Subsidiary Body for Scientific and Technological Advice established under the UNFCCC to advice on scientific and technological matters relating to the convention

6. The ERT could focus on reviewing low-quality inventories, rather allotting a about an equal amount of time to each inventory.
7. Peer reviews of data and methodologies could be implemented to a larger extent.

All these options (except 6) will require more resources than current system as described in the previous sections. It is not evident that options 3 and 4 would lead to a greater certainty of compliance. Option 3 and 4 would rely on the expertise of professional auditors, but expertise in auditing might not be sufficient to review the highly technical aspects of emission inventories. Option 6 might be efficient, but might conflict with the current system under which all Parties are treated equally. This could have the effect of making the review process more political.

3 Indirect methods for quantification and verification of emissions

Despite the commitment of significant resources to the review system under the Kyoto Protocol, uncertainties might still prevail; therefore, it is tempting to consider other approaches. Emissions cannot be measured directly, but atmospheric concentrations of gases can be, and therefore useful information can be derived from such measurements. Most of the GHGs covered by the Kyoto Protocol are currently measurable in the atmosphere. The use of models to estimate the amounts and locations of emissions is possible, provided that enough is known about the atmospheric transport of the gases, and about sinks and loss processes. The issue is, however, whether the resulting calculations will have the necessary levels of certainty and geographical resolution to serve as alternatives to traditional emission inventories.

Figure 2 shows an example of measured time series, at four European sites, of one of the Kyoto GHG gases, HFC-125, which is used as a substitute for ozone depleting CFC gases[11]. The results reflect that different air masses arriving at the measurement sites are polluted with HFC-125 to a varying degree. HFC-125 is removed from the atmosphere very slowly (its lifetime is 29 years). Once emitted into the atmosphere it will accumulate and mix globally as it is transported by winds. The measurements show a baseline representing air masses that have not been influenced be emissions recently, reflecting a global average background level. Because HFC-125 is currently emitted at a rate that is higher than the rate of removal from the atmosphere, the background concentration is increasing.

Superimposed on the baseline is a series of spikes, representing air masses that have more recently been exposed to emissions. The air masses arrive at the four stations at different times, according to variations in the winds. Typically the spikes are higher at the locations that are closer to the high emission regions (higher at Jungfraujoch, Switzerland and Monte Cimone, Italy than at Mace Head, Ireland and Ny-Ålesund, Spitzbergen) because the high concentrations near the emission points are diluted during transport to more remote areas.

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[11] Part of the network SOGE, System for Observation of halogenated Greenhouse gases in Europe

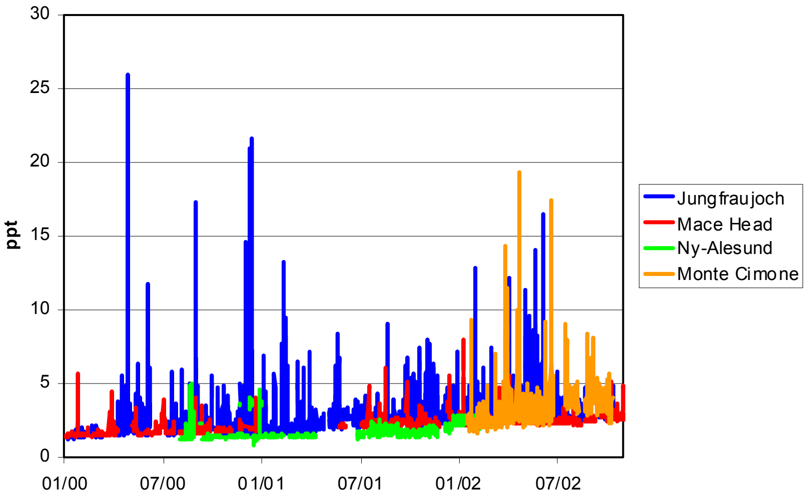

Figure 2: Data series of HFC-125 at four observational sites in the European SOGE network.

In general and in principle, the results depicted in Figure 2 can be used to deduce information on emissions in two ways. First, the baseline can be used to deduce global emissions because it represents a global background concentration. This only requires information about the lifetime of the gas. Second, the spikes can be used to deduce the location of the emissions. Combining this with other information, such as meteorological data, assists in determining the history of the air masses arriving at the stations. A discussion follows about various tools and approaches used to study emissions of GHGs based on atmospheric concentrations of the gases.

3.1 General approach

Estimating GHG emissions from measured concentrations requires knowledge about the processes governing the distribution of GHGs in the atmosphere. A combination of measurements and modelling results is needed to estimate the emissions[12]. There are two processes that have to be taken into account in order to make estimates of the geographical distribution of anthropogenic emissions. The first such process is losses of the GHG in route from the site of the emissions to the site of the measurement; for example, chemical decomposition and surface deposition. The second process is the natural emissions that can be substantial for some gases. Because such natural emissions are not caused by human activities, they are not covered by the Kyoto Protocol reporting system described in Section 2.

Losses of SF_6, PFC, most HFCs, CH_4 and N_2O can be considered insignificant because such losses occur very slowly, and to a large extent take place at high altitudes in the atmosphere. Much more complicated to measure are losses of atmospheric CO_2, because this gas has a strong natural cycle; e.g., it is exchanged with the ocean as well as the biosphere. A complicating factor is that some of the exchange processes are quite fast, which cause spikes in the observed atmospheric concentrations that are not related to anthropogenic emissions (which can be both positive from emissions to the atmosphere and negative from uptake in the ocean or the biosphere).

The fluorinated gases (SF_6, PFC and HFCs) only have anthropogenic sources of emissions that are fully covered by the Kyoto Protocol. CH_4 and N_2O, however have significant natural

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[12] Also initial *a priori* values of emissions are needed to derive *a posteriori* values based on observations of concentrations. Better *a priori* values will in some cases speed up the calculations and reduce uncertainties in *a posteriori* values.

sources. Again, CO_2 emissions stand out as the most complicated component, because the gas has large oceanic and biospheric sources.

Finally, meteorological data are used to calculate the way emissions are transported in the atmosphere. Estimating emissions through measurements also sets certain requirements for the measurements, such as spatial and temporal resolutions. Simple analyses can be made with only a few measurement sites and sampling that is relatively infrequent (e.g. weekly so-called grab sampling, which was common for many GHGs in the 1970s and 1980s). However, more detailed analyses require a time resolution of only a few hours or better to resolve the variations in wind systems bringing air masses towards the measurement stations. The spatial density of the observations is also important. This will restrict the spatial scale on which one can resolve the derived emissions, as will be discussed in the following section.

3.2 Emissions on a global scale

The simplest approach is the global one. In global models the atmosphere is treated as a single entity ("box"). Thus, uncertainties related to the transport of the gases would not influence the results, which would therefore be more accurate. From measurements, globally averaged concentrations could be used. This method is most suitable in measuring long-lived gases that would be well mixed in the atmosphere, and that would have negligible or well characterized natural sources and sinks. Most Kyoto Protocol GHGs meet these criteria. The most problematic gas is CO_2, due to its large natural sources and sinks. Perhaps some very short-lived HFCs could also be problematic. The global approach can only be used to estimate total global emissions. However, estimating global emissions can be useful in evaluating whether the emissions reported by the Parties are in agreement with the Kyoto Protocol on a global scale, i.e., such estimates can be used to assess the effectiveness of the climate regime as a whole. The global approach provides useful information about whether the total budget is correct, and is thus useful in determining whether further control of national inventories or improvement in the guidelines for reporting emissions is necessary.

As mentioned above, a simple global box model is useful in estimating global emissions. The basis for this model is that the observed atmospheric trend equals the atmospheric sources minus losses. This can be restated as follows: the atmospheric sources equal the trend plus the atmospheric losses. For gases with anthropogenic emissions this could be stated as follows: the global emission equals the observed trend plus the atmospheric losses. The atmospheric loss is large (small) for a species with a short (long) lifetime, and can be expressed as the global atmospheric concentration divided by the lifetime. For species with a negligible loss (a very long lifetime), the uncertainty in the estimated emission is the same as the uncertainty in the observed trend, for most species only a few percent. When the losses are large (short lifetimes) the uncertainty will approach that of the lifetime, which is typically 10% or more.

Below we present an example of a study taking a global approach. This approach is well suited to the two fluorinated gases, HFC-134a (a CFC replacement gas) and SF_6 (Höhne and Harnisch, 2002). The results are depicted in Figures 3 and 4. The shaded areas in the figures show the reported emissions from the main emitting countries. Only emissions from the countries included in Annex I of the Kyoto Protocol have been taken into account. The lines represent global emissions based on measurements of atmospheric concentrations and estimates of losses, as calculated in a simple global box model. Whereas the loss for HFC-134a is large on the timescale of the 10 years studied (lifetime 13.8 years, yielding a loss of slightly above 50% in 10 years) it is negligible for SF_6 (lifetime 3200 years, 0.3% loss over 10 years).

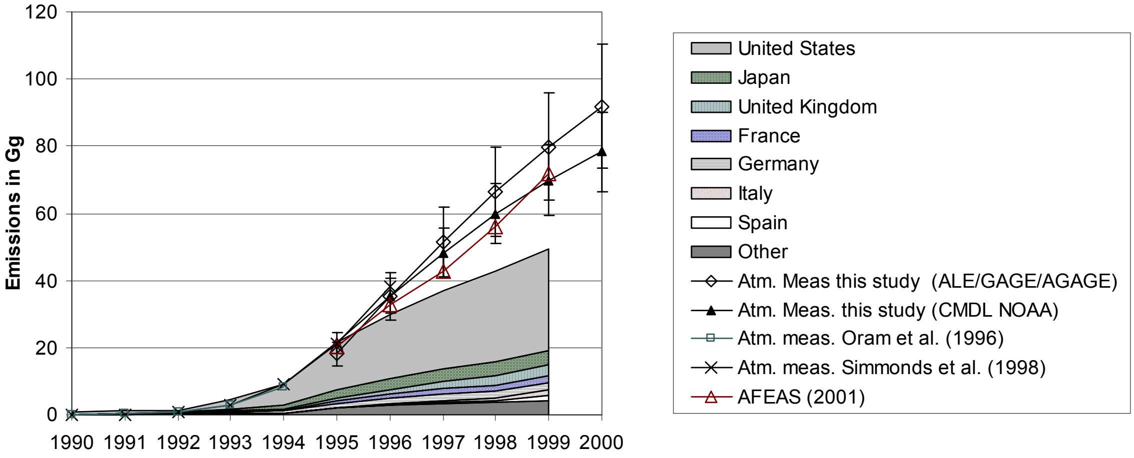

Figure 3: Emission estimates of HFC-134a (Höhne and Harnisch, 2002).

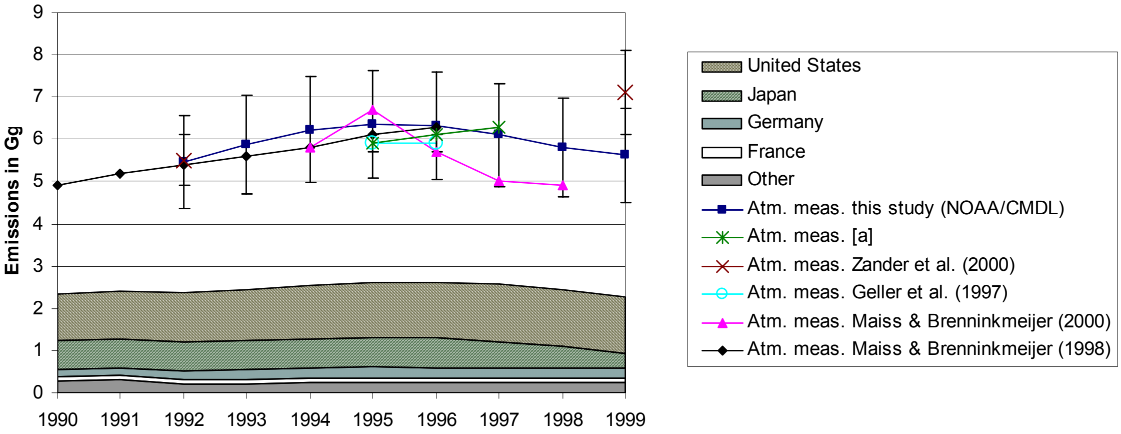

Figure 4: Emission estimates of SF_6 as estimated by Höhne and Harnisch (2002) (see their paper for references to the various observations upon which the estimated have been based).

The use of HFC-134a is growing rapidly. It was first produced in 1980, and its production has greatly increased since the early 1990s. Figure 3 shows that the emissions of HFC-134a derived from atmospheric observations are in line with the reported emissions during the period 1990-1995. After 1995 the emissions reported by the Annex I countries are significantly lower than the measurements, possibly due to increasing emissions in the developing countries (non-Annex I countries). There are uncertainties in the estimates, which reflect uncertainties in the measurements. The calculations have thus been performed with several measurement datasets (see legend in Figure 3 and references therein).

In the case of emissions of SF_6 (Figure 4), there is agreement in the reported data and the indirectly derived data: In the beginning of the 1990s there was a slight increase in emissions, followed by stabilization in the mid 1990s, and then a gradual decline thereafter. However, the estimates of SF_6 emissions were twice as large as the actual emissions reported. This could be due to emissions in Russia, China, and other developing countries, although Höhne and

Harnisch (2002) doubt this explanation. This is an example of how the simple global approach can indicate weaknesses in the reported emission inventory data.

3.3 Emissions on regional and country scales

Models on a smaller scale than global models utilize analytical approaches that have varying degrees of sophistication. But such models introduce increasing uncertainties in the calculations. The results depend on what we know about natural sources and sinks, meteorological data we have to derive wind speed and direction, and on the accuracy of the analytical method that is used – in addition to the uncertainty and geographical density of the measurements. Again, the most difficult task is to estimate anthropogenic emissions of CO_2. As explained above, there are large natural sources and sinks of CO_2, overwhelming the signals that the anthropogenic emissions cause in the short-term variability in the observed atmospheric concentrations. In fact, the techniques explained below are used to study and constrain the distribution and strengths of natural sources and sinks (e.g. Kaminski and Heimann, 1999b). Therefore, the following discussion is limited to considering estimates of emissions of GHG other than CO_2.

Currently the main limitation in estimating emissions of GHGs is the lack of measurements. Ground-based stations making continuous measurements are few in number. More such stations are needed to form the backbone of a measurement program. There are now 10-20 stations measuring CH_4 emissions in Europe, including measurements made in a network of 7 tall towers. There are fewer than 10 stations measuring emissions of N_2O, and only 4 stations measuring emissions of the fluorinated gases (PFC, HFC and SF_6). This severely limits spatial resolution and the degree of accuracy in emission estimates conducted on a regional scale. Measurements conducted in sporadic campaigns could complement the long-term measurements from the network of ground stations in order to estimate certain emission sources. Such campaigns, using aircraft to take measurements, are ongoing. Further, satellite measurements have the potential to offer good geographical resolution and coverage. However, currently only vertically integrated concentrations, with sparse time resolution, can be discerned from satellite measurements.

In order to derive emissions from measurements of atmospheric concentrations, it is necessary to measure the spikes above a baseline, as discussed above. Determination of the spikes requires an accuracy in the measurements that is high compared to the magnitude of the spikes. This requirement applies to the measurement of most GHGs discussed here. Perhaps the most problematic gas in this respect is N_2O, which has both large natural sources and widespread anthropogenic sources. This was pointed out in an early study by Prather (1985), who found that the instrumental noise was significant compared to the magnitude of the spikes. This phenomenon was also discussed by Ryall et al. (2001). Nevertheless, both studies reported emissions of N_2O from European sources.

A very simple approach adopted at an early stage in support of the Convention on Long-Range Transboundary Air Pollution (LRTAP) was wind sector allocation, which was pioneered by Schaug et al. (1987). They allocated sectors to arriving air masses according to their history over the last few days of arrival, by calculating air trajectories from analysed winds. This method was later adopted to study emissions of CH_4 and N_2O (Derwent et al., 1998a) and emissions of several other gases under the Montreal Protocol (Derwent et al., 1998b). These two studies were based on measurements taken at Mace Head, Ireland, contrasting concentrations of CH_4 and N_2O originating in Europe to those originating from the sea.

Stohl (1996) applied this trajectory-based approach to identifying possible sources of particulate sulphate pollution. His method was tested with a large set of trajectories at 14 measurement sites in Europe. A first guess concentration field was computed showing possible sources of the pollutant. In an iterative procedure, the concentrations were redistributed along the trajectories, thereby improving the concentration field. In this case it was possible to identify sources with a higher resolution than where measurements were obtained from only a single station. Reimann et al. (2002) employed a similar technique, using measurements from the four SOGE stations, to identify potential source regions of a range of halogenated gases under the Montreal and Kyoto Protocols.

The trajectories used in the above-mentioned papers represent a simplification of the transport of the pollutants, as they neglect the facts that the measurements are performed over a range in time (of the order of one hour, during which time the winds and trajectories change) and also small-scale disturbances in the winds (giving rise to dispersion). These effects have been accounted for in Derwent et al. (1998a) and Stohl et al. (2002), by replacing calculations of single trajectories associated with each measurement with a Lagrangian particle dispersion model, based upon a large number of particle trajectories. Whereas Stohl et al. (2002) start their trajectories at the measurement station and establish them backward in time, Derwent et al. (1998b) calculate their trajectories forward in time, by following particles that are labelled with their location and time of origin, so it is possible to identify the various sources that contribute to a defined receptor and quantify their relative contributions. Using atmospheric measurements at Mace Head, Ireland, the method has been applied to derive emissions of CH_4 and N_2O (Derwent et al., 1998a) as well as emissions of HFCs 134a and 152a (in addition to a range of Montreal Protocol gases; Derwent et al., 1998b; Ryall et al., 2001). Emissions derived by this modelling technique for the period 1995 to 1999 have been compared to conventional inventory emission estimates. The results are shown in Figure 5, which contains direct comparisons of the pairs of estimates for six separate years (including a range of Montreal Protocol gases) to increase the number of species and thus improve the analysis. The relationship between the two sets of results is robust; it appears that the model based emissions estimates are consistently lower than those calculated by consumption data by a factor of about 1.7. This is most likely due to the way in which the model calculates emissions from outlying regions. The difference is a reflection of the accuracy of this method. This is considered as a good starting point, because the method has a large potential for improvement, especially by including measurements from stations receiving air masses with origins different from those of the air masses arriving at Mace Head.

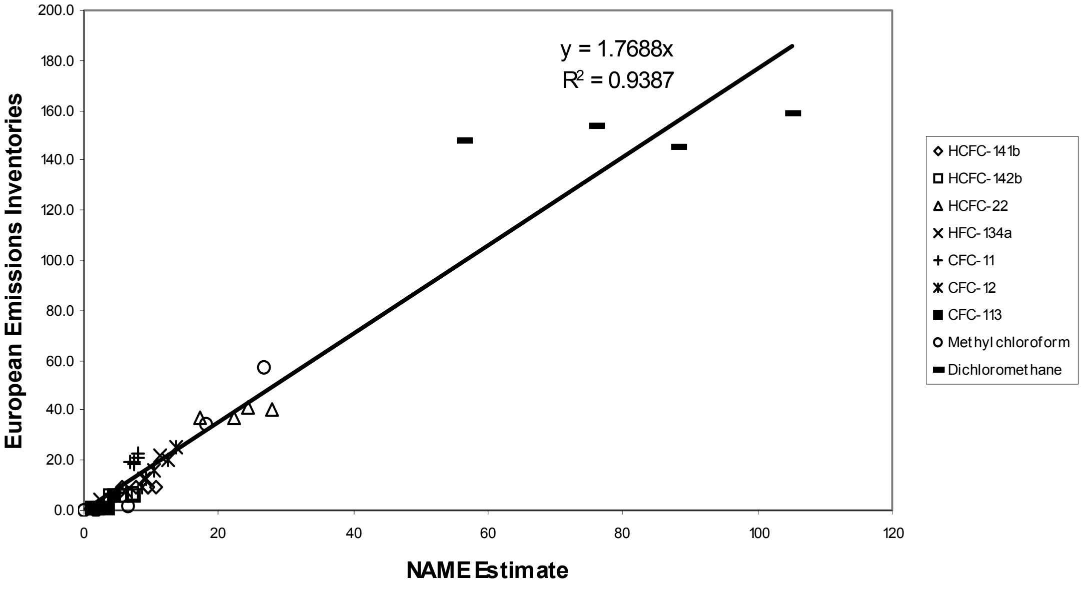

Figure 5. Comparison of estimated European emissions of halocarbons (Gg) by conventional use-plus-emission-function methodology and dispersion modelling by NAME.

In the approaches discussed above, the problem of using observed atmospheric concentrations of GHGs has been solved in a direct manner from emissions to concentrations, followed by an iteration to work back to the emissions required to explain the observations. Formally, using GHG observations to determine regional emissions is an inverse problem. Some studies are performed treating the problem in this way, using observations to constrain regional sources or sinks by inverse models. This is a rigorous and computationally expensive procedure.

Inverse models have been used to study emissions of CO_2 (e.g. Bousquet et al., 1999a; b; Kaminski et al., 1999a; b), and CH_4 (e.g. Houweling et al., 1999) on a global scale. Inverse modelling of CO_2 has been successful in estimating emissions on a continental scale, helping greatly in constraining the total budget of CO_2. Several models have been developed. Results from 8 different models were compared and interpreted in IPCC (2001). In a more recent study, Gurney et al. (2002) reported emissions from sources and sinks of CO_2 in 22 different regions based on 16 different models employing two different inversion techniques. Although the study significantly improve the estimates of natural oceanic and terrestrial sources and sinks, they have not proven useful in constraining anthropogenic emissions. As discussed above, this is because the natural sources and sinks are much larger than the anthropogenic emissions, and because uncertainties are still large in the natural CO_2 budget components (see discussion in Kaminski and Heimann, 1999). A huge reduction in uncertainties of natural sources and sinks is needed, a factor 20, for current inverse models to be able to estimate anthropogenic emissions accurately enough to resolve the reductions in emissions required by the Kyoto Protocol (5.2% overall globally; Gurney et al., 2002). Thus it is clear that for CO_2 there is a long way to go before inverse models can be of practical use in the emission work within the UNFCCC.

Høst et al. (1999) used an inverse modelling approach in studies of SO_2 emissions in Europe. Their analysis benefited from the high density of sites from which measurements were available. They used 42 stations located across Europe (mainly western, central and northern Europe), allowing a more detailed estimate of emissions in European regions. Estimates of emissions were possible down to the level of individual countries in Europe. As they pointed out, the precision of their method depended on the number and location of the monitoring stations.

As discussed above, there are a only a very small number of stations to measure GHGs included in the Kyoto Protocol, because of the high cost of building the necessary instrumentation and measurement infrastructure. Furthermore, the infrastructure that has been built has been designed mostly for monitoring global trends. There is probably a large potential for using dispersion model based methods (either direct or inverse methods) to derive emissions of GHGs under the Kyoto Protocol if the number of stations is increased. Increasing the number of stations would allow estimates to be conducted on a decreasing spatial scale.

Other measurements of atmospheric concentrations of gases can be used to enhance the possibilities of deriving emissions of GHGs. This can be done in many of the approaches already discussed above. Such observations include isotopes (isotopes of carbon for CO_2 and CH_4, isotopes of nitrogen for N_2O) that can be used to distinguish between molecules of different origin, or other trace gases (e.g. CO) for which the strength and distribution of its anthropogenic emission are assumed to better known than that of the GHG.

4 Discussion

In this paper we have described the system for reporting and reviewing emission inventory data under the Kyoto Protocol. We have also described how emission data can be derived from measurements of atmospheric concentrations of GHGs. The three key questions are: 1) To what extent will the reporting and review system be sufficient for determining compliance?; 2) Can emissions estimated through atmospheric measurements be used to complement traditional emission inventories?; and 3) Can uncertainties be reduced, and if so, at what cost?

At present top-down estimates of emissions have a role in the reporting system under the Kyoto Protocol as a part of the verification system included in the QA/QC procedures (IPCC, 2000), see Figure 1. Such estimates, however, do not have any specific role in the review system (as indicated by the dashed line). It is important to bear in mind that the assessment of data for compliance purposes is not related to real emissions (which are unknown anyway) but to the reporting guidelines. Reported emission data might differ from real emissions not only due to compilation errors, but also due to the intrinsic uncertainty in the data and the methodologies. The Parties might have established the guidelines using inaccurate information. The fact that the guidelines form the basis for assessing compliance is an important point, since it implies that under the Kyoto Protocol it is possible for a Party to be in “legal compliance” although scientifically emissions have not been reduced accordingly.

Wettestad (2003) argues that experience from other protocols with self-reporting (for example the LRTAP) has shown that identification of non-complying countries may very well often take place on the basis of self-reporting. The weakness of this argument is that it only takes into account the fact that non-compliance *may* be revealed by self-reporting, not that there might be undiscovered cases. Furthermore, the compliance regime under LRTAP and other environmental protocols has been less strict, so the argument may not be true for the climate regime. Large deficiencies in reporting will very likely be discovered by the agreed reporting and review system. The reason is the rather detailed and systematic system agreed under the Kyoto Protocol as described in Section 2. However, it is not likely that the system will identify all smaller inconsistencies. Problematic areas are sources with a large natural uncertainty in emission factors and countries with a weak statistical system. More stringent review processes, for example using professional reviewers (auditing) would require more resources, and it is not evident that it will be more efficient than the proposed system. The current review system with participation from all Parties (Parties reviewing each other) may also in the long run be beneficial through mutual learning, and increase the inventory quality in both the country under review and the country of the reviewer.

The Enforcement Branch of the Compliance Committee will decide whether each Party is in compliance. This decision will build on the technical assessment by the ERT. If emission targets are met with large margins, it is very likely that the reported emissions reductions are real, but with smaller margins compliance might be questioned. Consequently, there is a need to develop rules for when a country is in non-compliance. Gupta et al. (2003) have proposed to reduce the uncertainty with respect to compliance by setting minimum requirements for the probability of being in compliance, for example 66 % (using a single standard deviation). This proposal might, however, not be politically feasible. First, because it is difficult to reduce uncertainties, in practice this would mean that a Party would have to reduce emissions more than the targets to be in compliance from a statistical point of view. Second, inventory uncertainty is to a large extend determined by pollutant and source composition and not quality (Rypdal and Winiwarter, 2000). Third, inventory uncertainties are at present very subjective (*ibid*). A more practical way forward would be to address whether non-compliance with small margins actually matters given the high uncertainty in emission data. Furthermore, inventories from countries where compliance is met with small margins could be examined more closely in a review.

To reduce the risk of conscious reporting of biased data, also the nature of punishment is essential. Obersteiner (2000) suggests that the successful implementation of the Kyoto Protocol is unlikely unless Parties in non-compliance are subject to severe penalties. One could suggest that this punishment should be far higher than immediately reporting non-compliance. One problem with penalty is that it is extremely difficult to assess the motivation for reporting of biased emission data. Neither the expert review team nor the enforcement branch will likely be capable or willing to undertake such a task. Consequently, such possible punishment is not likely to be used in practice. In the agreed systems, adjustments can be seen as an incentive to report correct data, although they are meant to be temporary, giving the Party a chance to correct their estimates.

The independent top-down methods for estimating emissions based on measured atmospheric concentrations of, described in Section 3, rely on data from sources other than the inventories, and are independent of the reporting by the Parties. Emission data derived from measurements of atmospheric concentrations and inverse modelling may differ from real emissions for several reasons:

i) Due to errors in accounting for uncertainties in natural emissions and loss processes in the modelling
ii) Due to errors in the representations of uncertainties in meteorological data and modelling of transport
iii) Due to lack of representativity of measurement stations

Table 1. Overview of uncertainties emission data derived from inverse modelling (IM) and traditional emission inventories

	Inverse modelling (IM)				**Traditional inventories**	
	Man-made fraction of total emissions	Knowledge of natural sources to contribute to atmospheric gradients	Knowledge of loss processes sources to contribute to atmospheric gradients		Emission factors	Activity data
CO_2	4-5%	Low	Low		Well known, except for land use change and forestry	Well known, except for land use change and forestry
CH_4	55-70%	Low	Medium		Are rather uncertain for some sources	Is well known for some sources, uncertain for other
N_2O	About 45 % (large uncertainty range)	Low	High*		Are very uncertain for some sources	Is well known for some sources, uncertain for other
HFCs	100%	No natural sources	High**		Leakage rates are uncertain for some sources	Can be unavailable or uncertain
PFC/SF_6	100% [13]	No natural sources, except an extremely weak source of CF_4	High*		Leakage rates are uncertain for both, emission factors are rather uncertain for PFCs from aluminium manufacture	Can be unavailable or uncertain

Source IPCC (2001) and Rypdal and Winiwarter (2001)
* Mainly loss in the stratosphere or above
** Partly loss in the stratosphere

As discussed in Section 3, the uncertainties are currently high when emission estimates are derived from atmospheric concentrations. Table 1 gives a qualitative overview of the contribution to uncertainties for each gas. The observed spikes in the atmospheric GHG concentrations that are the basis for the model estimation of anthropogenic sources are generated from emissions that are made in certain regions, stemming from the fact that the anthropogenic emissions are not evenly distributed geographically. Natural sources or sinks that also exhibit geographical variation will similarly give rise to geographical variation in the

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[13] Harnisch and Eisenhauer (1998) have shown that CF_4 and SF_6 are naturally present in flourites, and out-gassing from these materials leads to natural background abundances of 40 ppt for CF_4 and 0.01 for SF_6. At present the man-made emissions of CF_4 exceed the natural emissions by a factor of 1000 or more and are responsible for the rapid increase in atmospheric levels of this gas (IPCC, 2001).

concentration of the GHG that will result in spikes (positive for sources, negative for sinks) in the observations, after transport of air from the source or sink region to the observing station. The status of the knowledge of the impact of such sources and sinks on the model estimates of anthropogenic emissions are assessed in Table 1.

The uncertainties with respect to inverse modelling are smallest for the halogenated gases that do not have natural sources, but that have long lifetimes in the atmosphere. For the two most important GHGs, CO_2 and CH_4, and to some extent also N_2O, uncertainties are considerable due to natural emission sources and complex removal processes. Furthermore, for CO_2 from LULUCF and N_2O from soils, the distinction between natural and man-made sources and sinks is complex and the distinction in the Kyoto Protocol has been derived based on practical and political considerations and is not purely scientific. With the present monitoring network independent methods are most suitable to monitor global emissions, uncertainties in emissions at a regional, and in particular country level, is considerable. Uncertainties in traditional emission inventories are lowest for CO_2 from combustion and highest for N_2O.

The independent verification techniques will be useful:

a) On a global scale

i) For monitoring the protocol as a whole (i.e., regime effectiveness, determining whether total emissions are actually reduced)
ii) For detecting major weaknesses in the reporting guidelines for some gases (missing sources or biased emission factors)

b) On a regional/country scale

iii) For verifying emissions in certain regions, currently only on a coarse spatial resolution, based on a long-term, surface-based measurement network
iv) For identifying unrecognised emission sources
v) In the future, for verifying emissions on a finer resolution, down to the scale of individual countries, assuming the ground-based networks will be denser and targeted campaigns are conducted (e.g., aircraft observations), or based on remote sensing (e.g., satellite observations)
vi) In the future, for focusing the control system on inventories with particular deficiencies

It is also important to bear in mind that verification should focus not only on absolute emission levels, but also on the general emission trend because the targets are based more on trends than absolute levels. For example, although the fluorinated gases constitute a very small percentage of total global emissions, they are important for compliance in many countries because levels of emissions of these gases are changing rapidly. To some extent the top-down method may be more suitable to verify trends because some “systematic errors” related to natural emissions and sinks are rather constant over time.

The uncertainty in the top-down method could be reduced if more accurate estimates of natural emissions and removals were available. In general, including more stations improves emission estimates by giving a finer spatial scale (resolving e.g. large countries). Alternatively one can still concentrate on emissions in larger regions (e.g. Europe) and then achieve more accurate emission estimates. A key issue is thus to establish a higher number of stations for measurements of GHGs in regions where emissions are to be determined. Observations can be established at a relatively low cost at stations with existing infrastructure. Most suitable are stations with other atmospheric measurement programs (e.g. tropospheric ozone and precursors, acid deposition, toxic components, particles) as other atmospheric observations can support and improve the estimates of emissions of GHG. But in regions where new stations have to be established, costs are increased substantially.

5 Conclusion

The review system established at COP 8 for the Kyoto Protocol will likely detect major deficiencies in reporting. Furthermore, the Parties will have strong incentives to improve their reporting in order both to avoid adjustments and to be allowed to participate in the flexible mechanisms. More experience is needed to conclude whether the current ambition level is appropriate given higher costs of performing more ambitious reviews and the incentives Parties may have to report inaccurate data. In the end, the key questions are how accurately compliance must be assessed and how much we are willing to pay for higher certainty. For some sources (namely agriculture and LULUCF), strict demands for certainty could be very costly. Thus the need for verifiable data can be in conflict with the wish to adopt a multi-gas approach and including all anthropogenic sources in the protocol. In the end there will be a need to define some margins of what constitute non-compliance given the high uncertainty in emission data for some pollutants.

In order for top-down emission data derived from monitoring of atmospheric concentrations to be a real alternative to traditional emission inventories it would have to be both cheaper and better. Uncertainties are lowest for the halogenated gases; at the global scale the uncertainties are in fact lower than for traditional emission inventories. On the other hand, the uncertainties are considerable for N_2O and CH_4 and in particular CO_2 due to important sinks and high natural emissions. Reductions in uncertainties are not anticipated in the short run as this would require a better measurement network. While the uncertainties are too high for inverse modelling to be applicable for compliance purposes for individual countries, discrepancies with global estimates can be used as an indication of weaknesses in the guidelines for estimating emissions, for example missing sources or too high or too low emission factors.

Coincidentally, the estimates based on emission inventories are considered to be most certain for CO_2 while reporting of emissions of the fluorinated gases can be difficult for some countries due to lack of consumption data. Consequently, the approaches may to some extent give complimentary information. However, N_2O is a gas where currently none of the approaches can give accurate data. Emission data reported from the Parties will consequently have to be used also for the next commitment period and can’t be substituted by emission data derived from atmospheric concentrations.

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