Practical applications of uncertainty analysis for national greenhouse gas inventories*

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Abstract

International policy-makers and climate researchers use greenhouse gas emissions inventory estimates in a variety of ways. Because of the varied uses of the inventory data, as well as the high uncertainty surrounding some of the source category estimates, considerable effort has been devoted to understanding the causes and magnitude of uncertainty in national emission inventories. In this paper we focus on two aspects of the rationale for quantifying uncertainty: (a) the direct benefits of the process of investigating uncertainty in terms of improvements in inventory methods and quality, and (b) the uses of the quantified uncertainty estimates in policy as a means of adjusting inventories used to determine compliance. We find that it is difficult to develop uncertainty estimates for a national inventory that account for significant types of uncertainty, are objective, and will be comparable across countries. Consequently, the quality of quantitative uncertainty data associated with national inventories is insufficient to warrant its use for policy purposes. While statistically valid methods for adjusting inventories to account for uncertainty exist, there is no unique method for adjusting inventory estimates to account for uncertainty, further complicating the issue of adjustments, and of reaching consensus on a method. The best use of uncertainty analysis may be in extracting lessons for improving the quality of inventory methods and data. In other words, the richest use of uncertainty estimates may come from the process of investigating data quality, which is instructive concerning the sources of uncertainty and means by which uncertainty can be reduced.

1 Introduction

Policy-makers and climate researchers use greenhouse gas emissions inventory information in a variety of ways. Internationally, national inventory estimates provide a basis for gauging global progress in meeting emissions targets and,

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more specifically, measuring compliance with commitments to reduce emissions under the Kyoto Protocol. Emission inventories can also assist national or sub-national policy makers to assess the need for, and track the success of, measures or policies to reduce greenhouse gas emissions. In the research arena, inventory estimates are one input into global models projecting atmospheric levels of greenhouse gases and consequent warming and other climatic changes. Inventories are also a component of simplified decision-analytic models and integrated assessments that combine several types of models and help evaluate the impacts of alternative policies or emission paths. In all these contexts, inventory estimates are used to identify differences or changes across countries, source categories, regions, time, or other dimensions. In other words, the fundamental use of inventory data is for comparison purposes.

In financial accounting, it is standard practice to report individual point estimates (i.e., single value versus a range of possible values). In contrast, the standard practice for most scientific studies of greenhouse gas and other emissions is to report their quantitative data with estimated error bounds or in terms of significant digits, both of which are simply quantitative ways of expressing uncertainty in an estimate. In general, emission inventories under the United Nations Framework Convention on Climate Change (UNFCCC) have been treated more as accounting reports than scientific studies, with a focus on point estimates and changes in those point estimates. However, it is impossible to escape the fact that preparing an emission inventory is also a scientific exercise that involves real uncertainty. The question is then how and whether to bring information regarding uncertainty into the policy process.

In this paper we will examine some of the reasons for investigating uncertainty, the limitations in using uncertainty estimates, and the potential benefits from the process of estimating uncertainty on the scale of a national greenhouse gas inventory.

2 The Uncertainty in Uncertainty Estimates

In the context of national greenhouse gas inventories, it is safe to say that "the uncertainty in national uncertainty estimates is likely to be far greater than the uncertainty in the emission estimate itself." This statement can be supported through a careful examination of the types of uncertainty associated with greenhouse gas inventories and the options available to estimate each type of uncertainty.

Uncertainties associated with greenhouse gas inventories can be broadly categorized into scientific uncertainty and estimation uncertainty. Scientific uncertainty arises when the science of the actual emission and/or removal process is not completely understood. For example, the process of indirect N_2O emissions associated with nitrogen containing compounds that are first emitted to the atmosphere and then deposited on soils involves significant scientific uncertainty. Evaluating and quantifying such scientific uncertainty is extremely problematic.

Estimation uncertainty arises any time greenhouse gas emissions are quantified. Therefore all emission or removal estimates are associated with estimation uncertainty. Estimation uncertainty can be further classified into two types: model uncertainty and parameter uncertainty.

Model uncertainty refers to the uncertainty associated with the mathematical equations (i.e., models) used to characterize the relationships between various parameters and emission processes. For example, model uncertainty may arise either due to the use of an incorrect mathematical model or inappropriate input in the model. Like scientific uncertainty, model uncertainty is problematic to quantify because it requires knowing exactly how the formulation of the relationships in the model biases the resulting estimate.

Parameter uncertainty refers to the uncertainty associated with quantifying the parameters used as inputs (e.g., activity data and emission factors) to estimation models. Parameter uncertainties can be evaluated through statistical analysis, measurement equipment precision determinations, and expert judgment. Quantifying parameter uncertainties and then estimating source category uncertainties based on these parameter uncertainties is typically the primary focus of most national inventory agencies.

Given that the only type of uncertainty that it is practical for an inventory agency to attempt to quantify in a comprehensive manner, uncertainty estimates for national greenhouse gas inventories will in all cases be severely limited. In an attempt to address this limitation, it is often assumed that scientific and model uncertainties are constant across all national inventories by nature of the use of the Intergovernmental Panel on Climate Change (IPCC) inventory guidelines. However, this assumption ignores the actual flexibility given to Parties by the UNFCCC in their selection of methods and the ability of the methods themselves to be equally applicable to all national circumstances. Clearly, this assumption that scientific and model uncertainties are identical across countries and across time is one of convenience and not empirical fact.

While for many scientific exercises, it is possible to collect rigorous statistical data that can be used to estimate statistical uncertainty[1] in a parameter, it is often not possible to collect similar sample data for many of the national statistics used in inventories. Often only a single data point will be available for most parameters (e.g., tons of coal purchased). It is not practical to repeatedly collect independent sets of national statistics. On a smaller than national scale, information on the precision and calibration error of measurement instrumentation can be used an objective estimate of statistical uncertainty. How one could practically collect and aggregate such data on a national scale is unclear.

However, assuming that objective statistical uncertainty estimates for the parameters used in a country's inventory could be obtained, there is still the problem of identifying and quantifying systematic uncertainties[2]. For many source or sink categories, systematic biases may be the primary cause of uncertainty (e.g., under reporting by companies or black market activities)[3]. There-

[1] Statistical uncertainty results from natural variations (e.g. random human errors in the measurement process and fluctuations in measurement equipment). Statistical uncertainty can be detected through repeated experiments or sampling of data.

[2] Systematic parameter uncertainty occurs if data are systematically biased. In other words, the average of the measured or estimated value is always less or greater than the true value. Biases arise, for example, because emission factors are constructed from non-representative samples, all relevant source activities or categories have not been identified, or incorrect or incomplete estimation methods or faulty measurement equipment have been used. Because the true value is unknown, such systematic biases cannot be detected through repeated experiments and, therefore, cannot be quantified through statistical analysis. However, it is possible to identify biases and, sometimes, quantify them through data quality investigations and expert judgments.

[3] There are cases where cause and direction of a specific systematic biases may be known for a national statistical dataset, but for reasons of resource and time limitations or political

fore, countries will usually have to rely on expert judgment for the majority of their parameter uncertainty estimates[4]. The problem with expert judgment, however, is that even with the most rigorous expert elicitation protocol, it is difficult to obtain judgments in a comparable (i.e., unbiased) and consistent manner across parameters, source categories, countries, and inventory reporting years. Some experts will inherently tend to be optimistic about the quality of data and others will tend to be pessimistic[5].

For these reasons, almost all comprehensive estimates of uncertainty for national greenhouse gas inventories will be not only be limited to addressing parameter uncertainty but also have a subjective component. In other words, national inventory uncertainty estimates cannot be interpreted as an objective measure of the inventory's quality. Nor can they be used to compare the quality of emission estimates between source categories, countries, or even reporting years in many cases.

If uncertainty estimates for national inventories are not comparable then, as argued below, it is highly questionable whether they should be used as a basis for adjusting inventory estimates for compliance purposes. Moreover, because of opportunities for gaming the system that subjective uncertainty assessment would provide, an extensive system for policing uncertainty estimates would be required internationally. Such a system would significantly add to the burden on the UNFCCC review process.

3 Lessons from the Process of Estimating Uncertainty

In the context of national greenhouse gas inventories, the process of producing an uncertainty analysis can be divided into two parts: (1) the investigation of data uncertainty and quality and the collection of quantitative uncertainty inputs and (2) the mathematical combination of these inputs through the use of some statistical model (e.g., first order error propagation or Monte Carlo method). There has been a tendency in much uncertainty work associated with greenhouse gas inventories to focus excessively on the second part. Such a focus can be distraction-or worse be a replacement for-efforts to sincerely investigate data quality and the causes of uncertainty.

Given the limitations discussed above, the process of estimating uncertainty can still be, in and of itself, instructive. If the mechanics of combining quantitative parameter uncertainty estimates can be kept in perspective, then the

constraints it cannot be quantified or corrected for in the official national statitics. Therefore, arguing that known systematic biases can be corrected for ignores the real complexities of collecting national statistical data.

[4]The role of expert judgment can be twofold: Firstly, expert judgment can be the source of the data that are necessary to estimate the parameter. Secondly, expert judgment can help (in combination with data quality investigations) identify, explain, and quantify both statistical and systematic uncertainties. It is also important to recognize that it is difficult for experts to distinguish between statistical uncertainty and systematic biases. Therfore, elicited estimates of uncertinty tend to incorporate both.

[5]For example, in the United States an early estimate of the uncertainty in CH4 emissions from manure managment based on expert judgment was 15%. The following year, improvements were made to the methdology to account for more regional differences and corrections were made to some activity data. The resulting change in the overall emission estimate was 60%.

process of estimating uncertainty can provide a systematic approach and impetus for thorough investigation of the data underlying the inventory and a basis for a deeper understanding of data quality. Inventory practitioners and data collection agencies can then in turn facilitate the generation of "political will" to push for specific and well-argued investments in data quality improvements (e.g., data collection).

This process of implementing an uncertainty analysis effort that is investigation focused has been found to be helpful to the authors in the process of preparing inventories at an individual facility (i.e., project), and at the corporate and national levels. One of the key conclusions from this experience is that it is not necessary to invest in the full process of actually quantifying the uncertainty in all parameters or mathematically combining those uncertainties in order to reap most of the benefits of the process. These benefits can be summarized as:

- Promoting a broader learning and quality feedback process within the national inventory process.
- Supporting efforts to qualitatively understand and document the causes of uncertainty and help identify ways of improving inventory quality. For example, collecting the information needed to determine the statistical properties of activity data and emission factors forces researchers to ask hard questions, and to carefully and systematically investigate data quality.
- Establishing lines of communication and feedback with national statistical agencies, researchers, and other data suppliers, in order to identify specific opportunities to improve the quality of the data and methods used.
- Providing valuable information to reviewers, stakeholders, and policy makers for setting priorities for investments into improving data sources and methodologies.

4 Inventory Uncertainty and Climate Policy

National emission inventories are the yardsticks by which progress in reducing national greenhouse gas emissions and compliance with international commitments (such as the requirements of the Kyoto Protocol) are measured. Emission inventories have levels of uncertainty that vary significantly by source, subsource, and country, and uncertainty in inventory estimates has been used to justify a number of adjustments or approaches. For example, some analysts have proposed adjusting emission inventories upwards for countries that have less certain inventories, or that do not use best practice methods[6]. Some have also proposed adjusting trading ratios between countries to reflect inventories that have different levels of uncertainty, or even excluding highly uncertain sources from trading regimes.

[6]The current adjustment approach under the Kyoto Protocol is based on the judgments of an expert review team and default uncertainty estimates (i.e., conservative factors). These default uncertainty estimates are based on expert judgement and are not specific to a Party's inventory or related to the actual quality of a Party's inventory. They are instead used as a justification for a conservative (i.e., punitive) adjustment to a Party's inventory estimate. Expert review teams are also given flexibility to apply adjustments and conservative factors. (See FCCC/SBSTA/2003/L.6/Add.3)

In this section we explore how statistically valid adjustments might be made to inventory estimates, taking into account uncertainty. We do not advocate any of the approaches here, or claim to have presented all reasonable approaches, but rather propose two approaches as examples of how uncertainty could be used concretely to adjust inventory estimates. This exploration has several implications. First, more than one type of adjustment can be analytically justified, and so there is no unique, statistically valid, approach to adjusting emission inventories. Second, the magnitude of the adjustment will be very sensitive to the magnitude of the uncertainty estimate. Third, because of the sensitivity of the adjustment to the magnitude of the uncertainty estimate, the uncertainty surrounding the uncertainty estimates themselves will make it problematic to use the uncertainty estimates, and further politicize the process of adjusting inventories based on country-level uncertainty estimates.

4.1 Potential Adjustments Based on the Uncertainty of Emissions

We start from the premise that any adjustments to inventory estimates that are made (or other actions that are taken) should be designed to maintain the environmental integrity of the system. In the current context, environmental integrity can be broadly interpreted to mean ensuring that actions-including the estimation process for national emission inventories, the level of emission commitments, compliance requirements, and any adjustments made or enforcement actions-tend to further, and not erode, the goals of the UNFCCC and Kyoto Protocol in protecting the environment. We might choose to define environmental integrity broadly as follows: we want to be confident that our policies have met our global climate change goals (i.e., that when we say that emissions have fallen globally, we can have confidence in that statement). Put differently, we care about increasing the confidence that we can have in our global emissions estimates and the confidence that we have met our goals or are in compliance.[7]

This type of definition is consistent with the views of a number of countries that are Parties to the Kyoto Protocol, and who have stressed that maintaining environmental integrity requires a conservative approach[8].In turn, they offer a number of different interpretations of adopting a conservative approach (e.g., that commitment period emission estimates should be conservatively high rather than too low and that estimates and any adjustments overestimate rather than underestimate emissions), or that the emissions baseline estimate should be conservatively low[9]. By extension, another interpretation could be that estimated reductions should be conservatively lesser rather than too great.

To develop an adjustment factor we must, however, develop a more specific definition of environmental integrity. A reasonable place to start the analysis

[7]Additional discussion of potential adjustments, particularly under a trading regime, can be found in [1].

[8]See, for example, submissions from Canada, Australia, New Zealand, China, Portugal, and the United States to the UNFCCC. Views from Parties on national systems, adjustments and guidelines under Articles 5, 7 and 8 of the Kyoto Protocol. FCCC/SBSTA/2000/MISC.1, 24 February 2000.

[9]For ease in exposition, in this paper we sometimes refer to commitment years and sometimes to commitment periods. The analysis is appropriate for either, but is easier to conceptualize in terms of years. The Kyoto Protocol uses commitment periods, which are summed over 5 years.

is the targets set by the Kyoto Protocol (Annex B of the Protocol) for each participating developed country for the first commitment period. Suppose we start by defining a goal that we want to be confident that, when countries report emissions inventories that nominally are in agreement with their commitments under the Protocol, the countries are truly-if not in compliance-at least within a given tolerance of complying with their commitments. Thus, we might consider an adjustment based on uncertainty as described in Definition 1.

Definition 1 *Compliance with Emissions Targets: Attain a reasonable level of confidence that countries have actually achieved the emissions levels stated in their commitments under the Kyoto Protocol and are in compliance.*

To implement this definition we ask three questions: (a) would we consider it acceptable if actual emissions exceeded the target emissions commitment by some fractional or percentage amount; (b) how much is that amount; and (c) how confident do we want to be in our result? If we assume that we know the magnitude of uncertainty surrounding the inventory estimate, this definition suggests that inventory emission estimates would be adjusted upward to take into account the uncertainty of the estimate. In particular, the assumption would be that we want to ensure that, given a reasonable level of confidence, actual emissions do not exceed estimated emissions by more than a specified amount (which could be zero)[10].

Table 1 illustrates the types of adjustments that this definition might imply, based on the quantified level of uncertainty of the inventory estimate, on the amount of confidence we want to have in our results, and on the percentage amount by which actual emissions could exceed the emission commitment (i.e., the target level of emissions) before we were uncomfortable with the result[11]. Thus, for example, if emission estimates are 50% uncertain, and we want to be 90% certain we have not exceeded our emission target by more than 10%, we need to adjust the emission inventory estimate upward by 20%, and compare the adjusted emission estimated with the target level to determine compliance. This adjustment provides a margin of safety, i.e., a country would effectively need to reduce emissions by that much more than its commitment in the Kyoto Protocol to remain in compliance with commitments[12]. The higher the level of uncertainty surrounding the emissions inventory, the greater the increase in

[10]Throughout this discussion we assume that probability distributions for estimated emissions or emission reductions are normal, and that the shape of the probability distribution of emissions for each country or source does not change significantly as emissions are reduced. This entire analysis also ignores the possibility that we might underestimate actual emission reductions, i.e., that is, this analysis assumes that the purpose of investigating uncertainty is to ensure that we do not overestimate actual emission reductions.

[11]Given the uncertainty (u%) range (assumed to be the end points of a 95% confidence interval) around estimated emissions (E), and assuming a normal distribution, the standard deviation of the distribution equals approximately: u% E / (1.96). If we are willing to accept that our emissions that could be up to p% higher than the nominal emissions commitment or, then the probability that the actual value lies below an upper bound of [E (100 + p)] can be calculated from the table for a normal error integral found in standard statistics textbooks or using standard statistical software (including Excel). See, for example, Appendix A of Taylor [6].

[12]Another way of thinking about this is what the estimated emissions inventory would need to be to in order to ensure that commitments were likely met by actual emissions, i.e., how the emission targets would need to be adjusted downward in order to ensure that we are confident that we meet the emissions limits in the Kyoto Protocol

	Uncertainty of Emissions Inventory		
Confidence*	20%	60%	80%
95%	1.06	1.30	1.52
90%	1.03	1.20	1.39
85%	1.01	1.15	1.30
80%	n/a	1.10	1.22

*Confidence that actual emissions will not exceed emission estimate by more than 10%. Source: [4] and [5].

Table 1: Ratio of Adjusted Emissions to Estimated Emissions

estimated emissions that would be required. Similarly, the greater the degree of confidence we require, the greater the adjustment.

The definition of environmental integrity proposed above focuses on only one aspect of emissions uncertainty: the uncertainty of current year emission estimates as they are reported for compliance purposes. However, the emissions estimate for the base yearfrom which the commitment level for a country is calculated under the Kyoto Protocolis subject to uncertainty that is likely to be similar or greater in magnitude to the uncertainty of the emissions estimate for a commitment period[13]. Thus, we can broaden the definition to take into account the influence of uncertainty in both the base year and the current inventory year, by focusing on estimated emission reductions. In particular, we can argue that it is more important to ask whether or not we have reduced emissions (and in the case of the Kyoto Protocol achieved the emissions reductions to which countries have committed) than to ask whether emissions are actually what we think they are. Moreover, since the uncertainty surrounding the level of emissions is not identical to the uncertainty surrounding the absolute (or relative) level of emission reductions, we can develop a second definition.

Suppose that a country has agreed to reduce emissions to a target level in a given year (or set of years). If estimated emissions in that year(s) equal the target level, how confident can we be that emissions have actually been reduced by an amount equal to the difference between base year emissions and estimated emissions in the target year? Put another way, how confident can we be that estimated emission reductions are not smaller than we think they are or, at least, that they are not "off" by more than a certain amount. Following this line of reasoning, we might choose to define environmental integrity along the lines of Definition 2.

Definition 2 *Achieving Emission Reductions: Achieve a reasonable level of confidence that countries have actually achieved the emission reductions, measured relative to base year emissions, stated in their commitments under the Kyoto Protocol and are in compliance.*

To implement this definition, we need to ask (a) would we consider it acceptable if actual emission reductions fall below the committed level of reductions by some fractional or percentage amount; (b) how much is that amount; and (c) how confident to we want to be in our result? If we assume that we know

[13]The uncertainty in the base year emission estimates would be greater in cases where data quality and methods have improved over time.

	Uncertainty of Emissions Reductions*		
Confidence**	20%	50%	80%
95%	1.01	1.04	1.15
90%	1.00	1.03	1.08
85%	1.00	1.02	1.04

*Emissions reductions for compliance assumed to be 7% below baseline level.
**Confidence that actual emission reductions equal at least 90% of estimated reductions. Source: [5].

Table 2: Ratio of Adjusted Emissions to Estimated Emissions

the magnitude of uncertainty surrounding the estimated emissions reductions, this definition suggests that estimated emission reductions would be adjusted downward to take into account the uncertainty of the estimate. However, the result can be compared more easily to the results in Table 1 if we ask how the emissions estimate for the commitment period would have to be adjusted upward in order to ensure that, given a reasonable level of confidence, actual emissions reductions do not fall below estimated reductions by more than a specified amount (which could be zero). Again, the conclusion is that emissions estimates would be more heavily increased for more uncertain inventories.

We can construct Table 2 in a manner analogous to Table 1, but this time begin by looking at uncertainty in emission reductions. Our goal is to provide a level of confidence that our emission reductions have actually been achieved. Given that goal, we can ask what adjustment should be made to the nominal emission inventory for the commitment period in order to compensate for the uncertainty of emission reductions. Suppose that emissions in a commitment year must be 7% below emissions in the base year for compliance (a number that translates into a target absolute quantity of emission reductions). Then, if quantified emission reductions are 50% uncertain, and we want to be 90% confident that we have achieved at least 90% of the target quantity of emission reductions, the emission inventory estimate should be adjusted upward by 3%. The adjusted emission estimate is then compared with the target level to determine compliance[14].

4.2 A Comparison of the Alternative Adjustments

In some respects, the two approaches are similar[15]. Both approaches focus on increasing the certainty with which we achieve externally defined goals, i.e., quantified emissions or emission reductions for a target year or period, such as the first commitment period under the Kyoto Protocol. By adjusting emissions estimates to account for uncertainty, both approaches provide a concrete

[14]Constructing Table 2 requires two steps: (a) making necessary assumptions (e.g., about the uncertainty of emission reductions and required level of confidence) and calculating the necessary adjustment in emission reductions to provide that level of confidence; and (b) translating the adjustment to emission reductions into an adjustment to emissions.

[15]Another, related approach would be to focus on the commitment level-i.e., what would estimated emissions need to be in order to ensure that, given uncertainty, actual emissions do not exceed commitments.

incentive for countries to reduce estimated emissions below nominal emissions requirements. Thus, both approaches increase the confidence that we can have in our global emissions estimates, by adjusting the estimated emissions to account for uncertainty[16]. They also provide an incentive for countries to improve the precision of their emission estimates over time, in order to reduce the magnitude of the adjustment and so move estimated emissions closer to the nominal commitment level[17].

Which approach is more stringent? If the uncertainty surrounding the emissions estimate is identical to that surrounding estimated emission reductions, then the second definition is less onerous; i.e., a comparison of Tables 1 and 2 suggests that requiring certainty in emission reductions implies much less of an adjustment to the emissions estimate than does requiring certainty in emissions. But is this a reasonable assumption?

If we assume that the emission estimates in two different years-year B (the base year) and year i (the commitment year) are normally distributed and independent, then the uncertainty of the difference in the estimates for the two years is implicitly given by the relationship:

$$(E_B - E_i)u_{B-i} = \sqrt{(u_B E_B)^2 + (u_i E_i)^2} \tag{1}$$

In this equation, u_B and u_i represent the fractional (or percent) uncertainty of the emission estimate (E_B and E_i) in the baseline and compliance years, respectively; u_{B-i} is the uncertainty of the calculated difference between E_B and E_i. Squaring both sides, it follows that

$$(E_B - E_i)u_{B-i} \leqslant u_B E_B + u_i E_i \tag{2}$$

Put differently, the standard deviation of the difference in emissions between the two years (the fractional uncertainty times the difference in emissions) is always less than or equal to the sum of the standard deviations in the two years[18]. In fact the same inequality holds more generally, i.e. even if the emissions in the two years are not independent[19].

[16] The upper bound on estimated emissions would be lower under a system where targets were less than commitments. Note that this would actually give us a higher level of confidence that we have met our goal than we currently have, i.e. we would be more confident that actual emissions are equal to or less than our emissions goal than we currently have confidence that actual emissions are equal to or less than estimated emissions (as given by emissions inventories that are currently prepared).

[17] We may also want the emissions estimate to be precise because we want to have confidence in our estimated emissions for purposes of planning and forecasting future temperature rise. In this case, the emissions estimate is simply that: an estimate of the emissions that have occurred and a component of estimated global emissions, which are an input into models projecting global concentrations of greenhouse gases and the rate and extent of temperature rise and associated climatic effects. Hence, if we improve our estimates over time we can improve our ability to model global GHG concentrations and forecast future warming. To the extent that adjusting targets provides an incentive to improve emissions estimates, it will ultimately provide better information on which to base global warming projections.

[18] Strictly, uBEB and uiEi represent the respective standard deviations multiplied by a scalar. The magnitude of the scalar (which may equal 1) depends on the width of the confidence interval for which the uncertainties are estimated. The scalar would equal 1.96 for a 95% confidence interval if emissions are normally distributed.

[19] This can be shown using the formula $Var(X - Y) = Var(X) + Var(Y) - 2Cov(X, Y)$ and the bound $|Cov(X, Y)| \leqslant SD(X)SD(Y)$, where X and Y are the emission estimates in the two years, and Var, Cov and SD are the variance, covariance, and standard deviation, respectively.

What does this imply for the uncertainty of the estimated emission reductions[20]? Suppose that the uncertainty of annual estimated emissions is the same from year to year for this source or country, and equals "u," and that estimated emissions are independent from year to year. Suppose, further, that emissions in the compliance year fall to 10% below baseline emissions, i.e., that $E_i = (0.90 * E_B)$. In this case, the uncertainty of the emission reductions will be given by the equality above. In particular, because of the assumption of independence, the standard deviation of the difference will be less than the sum of the standard deviations of emissions in the two years; because of the small size of the emission reductions, however, the fractional uncertainty of the estimated emission reduction may be very high, about 13 times the uncertainty for the annual emissions estimate. This result suggests that it is difficult to know how to estimate the uncertainty of an emission reduction and use it meaningfully; nonetheless, this is the uncertainty that policy-makers may most care about.

Winiwarter and Rypdal [7] provide some evidence of trend uncertainties for the Austrian inventory[21]. Trend uncertainties are calculated using Monte Carlo analysis. Selected results, both for the uncertainty of the annual inventory and for the uncertainty in the trend between 1990 and 1997 are reported in Table 3. Mean annual emissions and trend differences are reported in Tg CO_2-equivalent per year. Their uncertainty calculations for the inventory in 1997 are reported in percentage terms. Two uncertainty calculations are reported for the trend: (1) uncertainty as a percentage of the mean difference between the base year and inventory year; and (2) uncertainty of trend (i.e., as percentage points off mean base year emissions). The table reports their results only for random uncertainty (i.e., does not include their estimates of systematic uncertainty), and for the IPCC inventory (they also provide results for full inventory).

Note that, in Table 3, the uncertainty of the trendexpressed as percentage points off the base yearis generally smaller than the percent uncertainty associated with the inventory. However, uncertainty stated as a percentage of the absolute difference in emissions between the two years is considerably higher-ranging from 17% to over 137%than either uncertainty when expressed relative to base year emissions.

A cursory comparison of Tables 1, 2, and 3 above suggests the highly tentative conclusion that adjustments based on the goal of maintaining confidence in emission reductions rather than confidence in actual emissions may result in larger adjustments. For example, compare the adjustments that would be made for N_2O. In Table 3, the uncertainty around the emission estimate for N_2O is approximately 20%; at a 90% confidence limit, Table 1 indicates an adjustment of about 3%in the inventory. In Table 3 the uncertainty around the trend estimate (which we take as a proxy for the emission reduction estimate) is approximately 80%; at a 90% confidence limit, Table 2 indicates an adjustment of about 8%. Considerably more research, however, into the relationship between trend and level uncertainties in the inventory would be needed to confirm this

[20] If emission reductions are measured directly, rather than calculated from emissions data, this discussion does not hold. For the most part, however, emission reductions are likely to be calculated in this fashion.

[21] They make two critical assumptions: (1) the uncertainty of an emission factor does not change over time, (i.e., 100% covariance among emission factor uncertainty over time); and (2) activity data over time are fully independent (i.e., random uncertainty is the only important uncertainty for known activity data and so covariance = 0).

	CO_2	CH_4	N_2O	GHG-eq
Trend: 1990 - 1997				
Difference	4.51	-1.40	0.28	3.39
Uncertainty of difference (%)	17.4	137.4	82.4	67.1
Uncertainty of trend (% points)	1.2	16.8	11.4	3.0
Annual Inventory: 1997				
Emissions	68.05	10.02	2.27	80.34
Uncertainty (%)	1.0	28.5	23.9	3.8

Source: Tables 3 and 4 in [7].

Table 3: . Uncertainties in 1997 Inventory and Trend Based on Differences between 1990 and 1997 for the Austrian Inventory

result.

4.3 Implications

The above discussion has several implications. First, if we were to undertake adjustments to inventory estimates based on uncertainty, several different possible adjustments could be reasonable, and no unique, statistically valid, adjustment exists. The choice of approach makes a difference in the magnitude of the adjustment, which itself is not small in magnitude. Thus, a rationale would be required for choosing one method over another. It is likely that the discussion would become highly politicized, since the relative impact on different countries is likely to vary with the adjustment mechanism.

Second, however, even given a consensus method for adjusting inventories, it is unclear that uncertainty estimates are sufficiently comparable across countries and sources to warrant performing an adjustment in a practical and equitable manner. As discussed above, expert judgment is a significant component of uncertainty estimates for the inventory, since the measurements needed to produce probability distributions rarely exist for the emission factors and activity data used for greenhouse gas emissions inventories. In addition to the uncertainties that reliance on experts produces, it also produces variability in the uncertainty estimates across countries and source categories using different experts. Rypdal and Winiwarter [3] report that, for N_2O, uncertainty estimates range dramaticallyby two orders of magnitudeacross existing country estimates. While differences in data and methods account for a portion of the difference, a large part of the difference is attributable to differences in the subjective assessments provided by expert judgment [2].

As a result of these difficulties with estimating uncertainty reliably across source categories (and source category experts) and countries, there is considerable question about the reliability of the uncertainty estimates, and there is also likely to be considerable variation in the estimates. Consequently, it is questionable whether the uncertainty estimates are sufficiently objective or accurate as to base adjustments to inventory estimates (which could result in potentially very costly incremental reductions) on these uncertainty estimates, for purposes of compliance.

Moreover, because of opportunities for gaming the system that subjective uncertainty assessment would provide, and because of the huge stakes involved in terms of the cost implications for countries if compliance requirements are altered by adjustments to the inventory, an extensive system for policing uncertainty estimates would be required internationally.

5 Conclusion

Because of concerns regarding the quality of national inventory data for compliance and other purposes, as well as the likely high uncertainty surrounding emissions from some source categories, researchers and policy makers have called for more reporting of quantitative uncertainty estimates. However, a prerequisite to this effort is understanding the uses of inventory data, and the reasons for calculating and reducing uncertainty. In turn, the uses of inventory and uncertainty data will suggest how important it is to investigate the causes of uncertainty in greenhouse gas inventories and to improve the quality of the methodologies and data used to construct inventories.

All of the applications for quantitative uncertainty data in the context of national greenhouse gas emission inventories submitted under the UNFCCC involve the comparison of uncertainty estimates across countries, time, or source categories. However, the inherent and practical limitations in quantitative uncertainty estimates in national inventories result in the uncertainty estimates being of little use for making objective comparisons or adjusting inventories to ensure environmental integrity of reduction commitments. Even in hypothetical cases where adequately objective uncertainty could be obtained, it would be politically difficult to negotiate specific approaches and confidence intervals to apply adjustments to inventory emissions estimates that are based on quantitative uncertainty estimates reported by a country. The process of investigating causes of uncertainty in an inventory, however, can have significant benefits in terms of the transparency and quality of the data used to prepare the inventory.

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