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Greenhouse Gas Inventories

Dealing With Uncertainty

Springer

Foreword

At the beginning of the 1970s, at the height of the Cold War, it was believed that the scientific community could be an important element of future détente between the main political superpowers, the Soviet Union and the United States, and their allies in the Eastern and Western political blocs. It was therefore decided to establish a scientific institution whose main aim would be to build bridges between these two competing political and economic systems. The International Institute for Applied Systems Analysis (IIASA) was founded in 1972 by 12 countries. Poland, represented by the Polish Academy of Sciences (SRI PAS), was one of the founding countries of IIASA and has continuously collaborated with the Institute ever since.

Polish scientists joined the international scientific community of IIASA with great enthusiasm. Working with leading scientists from different countries helped Poland to establish new areas of scientific activity focused on interdisciplinary research. As a result of cooperation with IIASA, Poland has initiated large research programs to address problems such as the development of rural areas and the establishment of rational water policies. The important Polish contribution to the work of IIASA has also been noteworthy, especially in the application of optimization methods for solving complex decision problems.

After the breakdown of the Communist system the role of IIASA changed. IIASA now applies its main asset—expertise in solving complex problems using rigorous scientific methodology—to tackling problems of regional and global dimensions. Polish scientists working in IIASA's multinational teams have been involved in many important research activities such as efforts against transboundary air pollution. Polish scientific expertise, especially in the area of building mathematical and computer models of complex phenomena, has contributed to important research programs at IIASA addressing problems related to climatic change. As the impact of human activities on climate, especially those related to energy generation and consumption, is of great importance to Poland, the Polish scientific community is determined to continue their research engagement in this important field.

The present book is an example of the cooperative activities of IIASA and Polish researchers. It is an outcome of the 2nd Workshop on Uncertainties of Greenhouse Gas Inventories, the second of the three triennial Workshops organized by IIASA and the Systems Research Institute, Polish Academy of Sciences. The first Workshop took place in Warsaw, Poland, in 2004, the second in Laxenburg, Austria, in 2007, and the third in Lviv, Ukraine, in 2010 with the support of the Lviv Polytechnic National University. This series of Workshops, devoted to topical investigations on the impacts of human activities on climatic changes represents an important contribution of IIASA and Polish researchers cooperation to the world community.

May I wish the IIASA and the worldwide scientific community every success in their future cooperative endeavors.

Professor Michał Kleiber
President of the Polish Academy of Sciences

Warszawa
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Benefits of dealing with uncertainty in greenhouse gas inventories: introduction

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Abstract The assessment of greenhouse gases emitted to and removed from the atmosphere is high on the international political and scientific agendas. Growing international concern and cooperation regarding the climate change problem have increased the need for policy-oriented solutions to the issue of uncertainty in, and related to, inventories of greenhouse gas (GHG) emissions. The approaches to addressing uncertainty discussed in this Special Issue reflect attempts to improve national inventories, not only for their own sake but also from a wider, systems analytical perspective—a perspective that seeks to strengthen the usefulness of national inventories under a compliance and/or global monitoring and reporting framework. These approaches demonstrate the benefits of including inventory uncertainty in policy analyses. The authors of the contributed papers show that considering uncertainty helps avoid situations that can, for example, create a false sense of certainty or lead to invalid views of subsystems. This may eventually prevent related errors from showing up in analyses. However, considering uncertainty does

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not come for free. Proper treatment of uncertainty is costly and demanding because it forces us to make the step from "simple to complex" and only then to discuss potential simplifications. Finally, comprehensive treatment of uncertainty does not offer policymakers quick and easy solutions. The authors of the papers in this Special Issue do, however, agree that uncertainty analysis must be a key component of national GHG inventory analysis. Uncertainty analysis helps to provide a greater understanding and better science helps us to reduce and deal with uncertainty. By recognizing the importance of identifying and quantifying uncertainties, great strides can be made in ongoing discussions regarding GHG inventories and accounting for climate change. The 17 papers in this Special Issue deal with many aspects of analyzing and dealing with uncertainty in emissions estimates.

1 Introduction

Accounting for greenhouse gas (GHG) emissions has emerged as an issue of considerable interest. While the scientific community is working for understanding of geochemical cycles, public policy is aiming to limit and decrease emissions and thereby to mitigate global climate change. The issues of monitoring and verification of international or subnational commitments to reducing emissions are receiving increasing attention (e.g., NRC 2010).

Markets for trading emission permits are emerging. Decision makers are very interested in understanding the risks of increasing emissions and the opportunities for mitigation. An earlier collection of papers (Lieberman et al. 2007) raised many of the issues associated with uncertainty in emissions accounting and this is the continuing concern of this special volume of research papers.

The current task under the United Nations Framework Convention on Climate Change (UNFCCC) is to agree on a climate treaty that comes into force in 2012, the year in which commitments under the Kyoto Protocol will cease (FCCC 2009a, b). Leaders of the world's major industrialized countries have formally agreed, in the wake of the 2009 UN climate change conference in Copenhagen, that the average global temperature should not increase by more than 2°C from its preindustrial level (FCCC 2009c; Schiermeier 2009; WBGU 2009a, b). Compliance with this temperature target can be expressed equivalently in terms of limiting cumulative GHG emissions, for example, up to 2050, while considering the risk of exceeding this target (Meinshausen et al. 2009). The emission reductions required are substantial: 50–80% below the 1990 level at the global scale, with even greater reductions for industrialized countries (EU 2009; Schiermeier 2009; WBGU 2009b).[1]

Given the formidable task ahead, we are confronted with the uncertainty inherent in estimating emissions and the challenges involved in monitoring commitments and supporting markets for emissions trading. What are the benefits of dealing directly with uncertainty?

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[1] Emission reductions for industrialized countries until 2050 typically range in the order of 70–90% below their 1990 levels if the cumulative GHG emissions constraint of Meinshausen et al. (2009) for a 2°C temperature increase (with a risk of 10–43% of exceeding it) is expressed on a per-capita basis, with global population projected for 2050 taken from http://www.iiasa..ac.at/Research/POP/proj07/index.html.

The answer to this question, given by the participants of the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories, held 27–28 September 2007, in Laxenburg, Austria, was unanimous: we need to make use of uncertainty analysis in developing clear understanding and informed policy. Uncertainty matters, and is key to many issues upstream and downstream of emission inventories. Dealing proactively with uncertainty allows useful knowledge to be generated that the international community of countries would wish to have at hand before negotiating international environmental agreements such as the Kyoto Protocol or its successor. Generating this knowledge and understanding should not wait until countries agree on a formula that will translate an approved global emissions constraint to the sub-global level and allocate global emission shares to countries.

This Special Issue of *Climatic Change* brings together 17 key papers presented at the 2nd Uncertainty Workshop, which was jointly organized by the Austrian-based International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/) and the Systems Research Institute of the Polish Academy of Sciences (http://www.ibspan.waw.pl/). This collection of insights and techniques captures recent thinking on why and how dealing properly with uncertainty is important as we confront the legal and technical issues of trying to mitigate global climate change. In this introduction we describe the overall setting of the Workshop and provide an introduction to the individual contributions and to the group consensus. The latter grew from the various scientific discussions and retreats during the Workshop. The participants at the 2nd Uncertainty Workshop sensed the increasing awareness of the importance of dealing with uncertainty. Moreover, methods for dealing with uncertainty are improving through research efforts such as those summarized in this volume.

2 The challenges of dealing with uncertainty are still with us

Under the UNFCCC, developed-country parties to the Convention (so-called Annex I countries) have, since the mid-1990s, published annual or periodic national inventories of GHG emissions and removals. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of those strategies and policies. Where formal commitments to limit emissions exist, regulatory agencies and corporations rely on emission inventories to establish compliance records. Scientists, businesses, other interest groups, and the public use inventories to better understand the sources and trends in emissions (see also, Lieberman et al. 2007: 1–4).

However, GHG inventories (whether at the global, national, corporate, or other level) contain uncertainties for a variety of reasons, and these uncertainties have important scientific, economic, and policy implications. The uncertainty of emissions estimates can be dealt with proactively. Proper treatment of uncertainty affects everything from our understanding of the physical system to the politics of mitigation agreements and the economics of mitigation strategies. A comprehensive and consistent understanding of, and a framework for dealing with, the uncertainty of emissions estimates has a large impact on the functioning and effectiveness of the Kyoto Protocol and its awaited successor.

Central to policy concerns and the present discussion alike is the need for a better definition of the role of uncertainty analyses in national GHG inventories, as well as in other inventories (e.g., for mitigation projects) falling under the purview of international or national regulatory schemes. At present, parties to the UNFCCC listed in Annex I (industrialized countries and countries undergoing economic transition) are obliged to include in the reporting of their annual inventories direct or alternative estimates of the uncertainty associated with these emissions and removals, consistent with the good practice guidance reports of the Intergovernmental Panel on Climate Change (IPCC) (FCCC 2006a; Penman et al. 2000, 2003). Inventory uncertainty is monitored, but not regulated, under the Kyoto Protocol. International schemes such as European Union (EU) emissions trading or that established by the Kyoto Protocol, if they are to function as binding agreements, must be able to demonstrate that estimates regarding emission changes are not only measurable but also that they outstrip the uncertainty metric with which they are associated.

3 The key arguments for dealing proactively with uncertainty are becoming increasingly relevant

It makes a big difference to the framing of policies whether or not uncertainty is considered either reactively, because there is a need to do so, or proactively, because impediments are anticipated. Uncertainty estimates are not intended to dispute the validity of national GHG inventories; however, grasping the uncertainty of emission estimates serves to underscore the lack of accuracy that characterizes many source and sink categories. There is wide agreement that the consideration of uncertainty can help to identify opportunities for improvements in data measurement, data collection, and calculation methodology. But it is only by identifying elements of high uncertainty that actual methodological changes can be introduced to address them. Currently, most countries that perform uncertainty analyses do so for the express purpose of improving their future estimates; and the rationale is generally the same at the corporate and other levels. Estimating uncertainty helps to prioritize resources and to take precautions against undesirable consequences, thus establishing a more robust foundation on which to base policy.

The issues of concern at the 2nd Uncertainty Workshop continued to be rooted in the level of confidence with which national emission inventories can be performed. The research papers presented at the Workshop demonstrate that these concerns go beyond verification, compliance, and trading of GHG emissions, which were the issues of concern covered by Lieberman et al. (2007). The topics addressed at the 2nd Uncertainty Workshop covered:

1. Achieving reliable GHG inventories at national and sector scales and reporting uncertainties reliably at, and across, these scales (see especially the papers by Winiwarter and Muik 2010; Szemesová and Gera 2010; and van Oijen and Thomson 2010)
2. Bottom-up versus top-down GHG emission analyses (see especially the papers by Ciais et al. 2010; Rivier et al. 2010; Verstraeten et al. 2010; Shvidenko et al. 2010; and Gusti and Jonas 2010)
3. Reconciling short-term emission commitments and long-term concentration targets; and detecting and analyzing GHG emission changes vis-à-vis uncertainty, and addressing compliance (see especially the papers by Jonas et al. 2010; and Bun et al. 2010a)

4. Issues of scales of GHG inventories (see especially the papers by Bun et al. 2010b; Leip 2010; and Horabik and Nahorski 2010); and
5. Trading emissions (see especially the papers by Ermolieva et al. 2010; Stańczak and Bartoszczuk 2010; Nahorski and Horabik 2010; and Pickl et al. 2010)

All five topics were discussed individually and in depth at the Workshop. However, the interlinked and interdisciplinary setting of the Workshop allowed for scientific retreats during which all topics could be reviewed in context and from a holistic perspective, which allowed insights to emerge that could be fully scrutinized. This made it possible to strike a balance in dealing with topics that were seen as controversial.

4 The topics addressed

4.1 Achieving reliable GHG inventories

The comparison of inventories across countries or regions within countries, and across sectors received wide attention. There are a number of approaches to testing the quality of our uncertainty knowledge, to putting the uncertainty estimates of countries into context, and to helping us to understand the differences in estimates. Typically, only a few emission sources dominate the overall uncertainty of national emissions inventories. While, in general, the economic structure of a country influences the emission sources that contribute to uncertainty, there is currently only one major source that is uniquely uncertain for all countries: the nitrous oxide (N_2O) emissions from soils. The dominance of one source has consequences for calculating uncertainty, especially with regard to splitting the source into direct and indirect emissions following the IPCC GHG inventory guidelines (Eggleston et al. 2006, vol. 4). Winiwarter and Muik (2010) argue, based on their in-depth study on Austria, that the split sources need to be considered as being statistically interdependent, a fact that cannot be considered by the simpler methodology recommended by IPCC for uncertainty assessment, namely, the error propagation approach. When this interdependency is covered in a more elaborate Monte Carlo algorithm, the overall national GHG inventory uncertainty increases. Results thus need to be understood in a methodology-dependent context, making it even more difficult to provide meaningful comparisons between countries unless methodologies are laid open in detail. In general, correlating uncertainty properly appears to be more important than switching from less- to more-sophisticated tiers in analyzing uncertainty.

Uncertainty is inherently higher for some GHGs and sectors of an inventory than for others. Estimates of N_2O emissions tend to be more uncertain than those of methane (CH_4) and CO_2. As another example, the landfill (see Szemesová and Gera 2010) and the land use, land use change, and forestry (LULUCF) sectors[2] have higher uncertainties than other sectors. Wetlands are a typical example of a sector with high uncertainty. The emissions from wetlands can be sizable and are highly uncertain; not least because transient environmental conditions, anthropogenic or natural, can turn wetlands from a GHG source into a GHG sink, and vice versa

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[2] Another and alternative acronym introduced by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006: vol. 4) is AFOLU (agriculture, forestry and other land use).

(Eggleston et al. 2006: vols. 4, 5; Pandey et al. 2007). It is important to recognize the existence of these higher relative uncertainties. They raise the possibility that some components of a GHG inventory could be treated differently from others in the design of future policy agreements. Furthermore, limiting the reporting of GHG emissions and removals under the current inventory framework to anthropogenic sources and sinks creates additional difficulties, including uncertainty regarding the proper designation of which particular activities are anthropogenic and which are natural (see also full GHG accounting below). Alternative *modi operandi*, could include, for example, (1) the option of not pooling subsystems, including sources and sinks, with different relative uncertainties, but treating them individually and differently; and (2) the option of not splitting the terrestrial biosphere into directly human-impacted (managed) and not-directly human-impacted (natural) parts to avoid, among other things, sacrificing bottom-up/top-down verification, as there is no atmospheric measurement that can discriminate between the two (Jonas et al. 2009).

How to approach GHGs and sectors individually and differently was certainly not explored in the framing of the Kyoto Protocol. It is essential to bear in mind that inventorying the more certain GHG emissions from a specific sector on a corporate level can be a huge challenge. Accurately inventorying the upstream and downstream emissions of globally operating oil and gas companies serves as a good example of the inventory challenges involved. During recent years, these companies have become quite aware of their need for high quality data and harmonized measurements, monitoring, and uncertainty assessment methods; they have also realized the need to develop their own, tailored guidelines that will facilitate compliance with diverse GHG regimes (API 2004; IPIECA 2003, 2009).

The LULUCF sector with its spatially distributed emissions provides by far the largest challenges for emissions accounting (e.g., N_2O from soils or from wetlands, together with CO_2 and CH_4). The LULUCF sector's list of crucial issues is unusually long—it is difficult to squeeze them into the inventory framework considered under the Kyoto Protocol. A major reason is that the mechanisms driving changes in carbon inventories reflect both natural ecosystem processes and the direct and indirect effects of human actions. The tools for quantifying impacts of the direct effects of humans and of certain ecosystem processes are quite mature. Bayesian approaches, for example, are powerful but under-utilized tools, not only for reducing parameter errors but for combining different kinds of information and integrating across different approaches to provide a single answer. Van Oijen and Thomson (2010) make use of a Bayesian approach to account for the spatial heterogeneity in soils and weather to calculate conifer forest productivity and carbon sequestration for the whole of the United Kingdom.

Except from these specific processes, however, a wide range of indirect ecosystem responses still require significantly improved characterization in order to be adequately quantified and attributed (Field 2007). Progress in attributing and projecting changes in large-scale carbon balances—their dynamics cover a wide range of time scales—will require fundamental advances in understanding and modeling the interactions between human and ecosystem processes. Inventory techniques for quantifying ecosystem carbon stocks and stock changes are improving, as they develop from being a foundation for assessing harvestable forest resources toward being a set of general tools for supporting carbon accounting. The challenges, however, in moving from timber industry statistics to general carbon accounting are daunting and far from being completely resolved. The advances required include not only the ability to quantify the carbon in soils and non-marketable components of the vegetation but also the ability to extend the analysis to ecosystem types not covered in traditional forest inventories. Remote sensing with LIDAR and RADAR are among the most promising techniques for efficiently extending inventories to poorly characterized ecosystems, including tropical forests, savannas, shrublands, and tundra (see, e.g., Stanford University's Carnegie Airborne Observatory: http://cao.stanford.edu).

Attributing changes in ecosystem carbon stocks to particular mechanisms is complicated. However, neither inventory techniques nor simulation models are well positioned to unravel the diversity of complex mechanisms and the range of possible interactions among these mechanisms.

4.2 Bottom-up versus top-down GHG emission analyses

Top-down accounting takes the atmosphere perspective. The atmosphere mixes and integrates surface fluxes that vary spatially and temporally. Top-down accounting relies on observations of atmospheric CO_2 concentrations (and those of other GHGs), changes in concentrations, atmospheric circulation, and atmospheric modeling to infer net fluxes from land and ocean sources, and their regional distributions. Bottom-up accounting takes the opposite perspective. It relies on observations of stock changes or net fluxes at the Earth's surface and infers the changes in the atmosphere. Full carbon (and GHG) accounting—estimating all land-based fluxes, whether human-induced or not—is necessary to reconcile the top-down and bottom-up approaches. However, this comparison is not straightforward and must be done with caution (see also Denman et al. 2007: Section 7.3.2.3).

Atmospheric inversions have proven to be a useful top-down approach for quantifying carbon fluxes at large scales. Inversions allow the mismatch between modeled and observed concentrations to be minimized, and thus measurement and model errors to be accounted for. In inversions, fossil fuel emissions are typically believed to be perfectly known so that their contribution to the CO_2 concentration in the atmosphere can be easily modeled and subtracted to solve for the remainder, the regional distribution of land and ocean fluxes. However, for the majority of countries the foundations of this assumption are weak (Marland 2008). The uncertainty number (6–10% for the global total of emissions, based on a 90% confidence interval) that Marland and Rotty (1984) published for global fossil-fuel CO_2 emissions in 1982 is not often considered and has never been formally reworked.

Ciais et al. (2010) review the potentials and perspectives of atmospheric inversion to anticipate its emerging limitations in terms of extending atmospheric inversion to smaller scales, for example, inadequate as well as insufficient data and resolving atmospheric transport in global models, Atmospheric inversion is seen as playing a role as one of several observing strategies for the global carbon cycle, especially in detecting carbon cycle feedbacks resulting from climate change and other large-scale signals. Atmospheric inversions are envisioned as a continuing complement to surface flux models or surface observations and inventories.

Rivier et al. (2010) demonstrate the usefulness of the atmospheric inversion approach, if used at large scales, to advance our understanding of the carbon cycle regionally and its relevance to mitigation policies at these scales. The authors perform a CO_2 monthly inversion for the years 1988–2001 to estimate the net ecosystem exchange (NEE) for the whole of Europe, revealing a small sink of −0.1 ± 0.4 Gt C/y (based on a 68% confidence interval). Their regional analysis shows a "flux dipole" with a strong annual carbon sink in the southwest and a small annual source in the northeast of Europe, while their seasonal analysis shows a shift over time in the period of maximum carbon uptake from June to July.

While remote sensing is being used more often to assess ecosystem carbon fluxes, its use is still infrequent. In their study, Verstraeten et al. (2010) illustrate how remotely sensed soil moisture data (soil water index) can be integrated into an already existing carbon balance model. Their integration exercise underlines the important impact that soil moisture has on the magnitude as well as on the spatial pattern of carbon exchange. Estimated net ecosystem production (NEP) decreases in many areas when soil moisture is fully taken into account, shifting some European countries from being an apparent sink to being an apparent source of carbon.

Full GHG accounting, meaning the full accounting of all emissions and removals, including all greenhouse gases, is a prerequisite for reducing uncertainties in our understanding of the global climate system. A verified full carbon accounting, including all sources and sinks of both the technosphere and the biosphere, considered continuously over time, would allow the research and inventory communities to:

- Present a real picture of emissions and removals at national to continental scales;
- Avoid ambiguities generated by such terms as "managed biosphere," "base-line activities," "additionality," etc.; and,
- Perhaps most importantly, provide reliable and comprehensive estimates of uncertainties that cannot necessarily be achieved using the current approach under the UNFCCC and the Kyoto Protocol, which provide for only partial accounting of GHG sources and sinks. It is virtually impossible to estimate the reliability of any system output if only part of the system is considered.

Shvidenko et al. (2010) explore the limits of employing a full carbon accounting (FCA) approach in support of the Kyoto Protocol. By integrating all available information sources, including empirical landscape-ecosystem approaches and process-based vegetation models, the authors show that the net biome production of their study region, a large boreal forest ecosystem region in Siberia, can be constrained and estimated with relative uncertainty of as little as ∼60–80% and, by way of comparison, its net ecosystem production with uncertainty of ∼35–40% (based on a 90% confidence interval). Although the authors emphasize the substantial effort needed in applying such a multiply constrained systems approach, this must be considered as a very useful way of cross checking partial carbon accounts that are reported under the UNFCCC and that follow incomplete system views. It would thus be up to policymakers to decide how the FCA is used; that is, to decide whether the results of FCA should be used for "crediting" in the sense of the Kyoto Protocol (i.e., for compliance) or only for "accounting," as under the UNFCCC currently.

This perception is strengthened by Gusti and Jonas (2010) who address the gap that still exists between bottom-up and top-down in accounting for net carbon dioxide emissions. Their study focus is on the terrestrial biosphere of Russia, a signatory state to the Kyoto Protocol, and large enough to be resolved in a bottom-up/top-down exercise. For the whole of Russia during 1988–1992, the authors estimate an atmospheric loss, or net flux to Russia's terrestrial biosphere (uptake) with uncertainty of the order of 100% (based on a 90% confidence interval).

4.3 Reconciling short-term emission commitments and long-term concentrations targets; and detecting and analyzing GHG emission changes vis-à-vis uncertainty, and addressing compliance

The consideration of uncertainty can help to identify opportunities for improvement in data measurement, data collection, and calculation methodology, for resources to be prioritized and precautions to be taken against undesirable consequences, and thus for a more robust foundation for policy to be laid.

However, this may not be the full extent of the utility of uncertainty analysis. Another still widely debated rationale for performing uncertainty analysis is to provide a policy tool, a means to adjust inventories or analyze and compare emission changes so as to be able to determine compliance or the value of a transaction. While some experts find the quality of uncertainty data associated with national inventories insufficient for these purposes, others offer justification for conducting uncertainty analyses to inform and enforce policy decisions. Some experts suggest revising the system of accounting on which current reduction schemes are based, while others seek to incorporate uncertainty measurements into emission and emission change analysis procedures. The latter could offer policymakers enhanced knowledge and additional insights on which to base GHG emission reduction measures.

In the literature on climate change policy modeling at the national and international scale, there has been virtually no treatment of uncertainty in GHG inventories (inventory uncertainty is monitored, but not regulated, under the Kyoto Protocol). The only provision under the UNFCCC is for adjustments in emissions to be made for missing or misreported data (FCCC 2006b: Decision 20/CMP.1). This raises questions as to what the benefits are of including inventory uncertainty in policy analysis, and also of accounting for it in the implementation of policy, as opposed to just controlling those emissions that can be definitely reported.

The consequence of including inventory uncertainty in policy analysis has not been quantified to date. The benefit would be both short-term and long-term, for example, an improved understanding of compliance (already a research focus) or of the sensitivity of climate stabilization goals to the range of possible emissions, given a single reported emissions inventory. That is, given that emissions paths are sensitive to starting conditions and uncertain relative to what is being mandated, what is the probability that long-term targets might be missed? Further efforts in the latter direction are critical for addressing the practical concerns of policymakers.

The current policy approach of ignoring inventory uncertainty altogether, whether at the country, sector, corporate, or other level, is problematical. Emission reductions are activity- and gas-dependent and can range widely. Biases (discrepancies between true and reported emissions) are not uniform across space and time and can discredit flux-difference schemes which tacitly assume that biases cancel out. Human impact on nature is not necessarily constant and/or negligible and can jeopardize a partial GHG accounting approach that is not a logical subset of, and safeguarded by, a full GHG accounting approach. Thus, the legitimate concern is that a policy agreement is trying to tie down a system that is considered certain but is not truly controlled. Being aware, and knowing, of the uncertainties involved will help to strengthen political decision making. Of course, uncertainties are frequently reported, even by experts, with a false sense of uncertainty. But practice will allow the expert community involved to deal with uncertainty increasingly more accurately. The logical step for policymakers would be to decide whether the post-Kyoto agreement will have good and clear rules to incorporate uncertainty and which parts of an emissions inventory will undergo stringent compliance while accounting for uncertainty, as opposed to consistent reporting under a global monitoring framework.

Such a step is overdue, as underlined by ongoing research that aims to improve our understanding of compliance under uncertainty and to make use of uncertainty at the scale of and across countries. Jonas et al. (2010) apply and compare six techniques to analyze the uncertainty in the emissions changes that countries agreed to realize by the end of the Kyoto Protocol's first commitment period, 2008–2012. The techniques all perform differently and can thus have a different impact on the design and execution of emission control policies. However, any of the techniques, if implemented, could "make or break" claims of compliance, especially in cases where countries claim fulfillment of their commitments to reduce or limit emissions. Jonas and collaborators argue that a single best technique cannot yet be identified, the main reason for this being that the techniques suffer from shortfalls that are not scientific but are related to the way the Protocol has been framed and implemented politically: (1) the overall neglect of uncertainty confronting experts with the situation that for most countries the agreed emission changes are of the same order of magnitude as the uncertainty that underlies their combined CO_2 equivalent emissions; and (2) the introduction of nonuniform emission reduction commitments from country to country. However, the two shortfalls could be easily overcome under a political regime that plans with foresight and prudence.

Bun et al. (2010a) apply one of the aforementioned techniques in an educational exercise, which allows the GHG inventories of countries under the Kyoto Protocol to be examined from the perspective of supply and demand of emission credits (allowances) in an emissions change-uncertainty context rather than in an emissions-only context. The applied boundary condition—countries balance their supply and demand among each other—facilitates the focus but does not limit the authors' conclusions. They show that, when taking uncertainty into account, not all of the countries are credible emission sellers, as the risk remains that these countries' true (but unknown) emissions exceed allowed levels. Limiting this risk considerably influences the countries' supply–demand balance. Countries can sell less, and must buy more, emission allowances if the risk is decreased that the countries' emissions exceed allowed levels. Considering uncertainty can also be seen as bringing the future closer to the present. Some countries—notably, Russia and Ukraine—can sell much of their emissions allowances, as GHG emissions in these countries are far below their agreed Kyoto targets. However, their collective GHG emissions have increased since around 2000, and appear likely to increase unabated and to exceed their Kyoto targets in the near future, which is when the supply of allowances is exhausted. This situation, the break-down of the supply side, will arise much sooner if uncertainty is considered.

4.4 Issues of scales of GHG inventories

Studying GHG inventories across spatial and temporal scales, including upscaling and downscaling, is not only carried out to achieve better insight into emissions but can also help in identifying errors in regional inventories (e.g., with regard to LULUCF) and validating inventory procedures from a consistency point of view. Operating with data across scales of heterogeneous quality, including inventory data, is becoming commonplace. Research needs seem to be understood, such as the development of spatio-temporally resolved emission factors and their dependencies. However, although it is recognized that working across scales also requires knowledge of uncertainty, the benefits of actually including uncertainty are less explored and understood, particularly the newly involved boundary conditions and forthcoming research needs. The following papers serve as examples of the benefits that can be gained from explicitly including uncertainty in spatio-temporal analyses.

To provide a basis for regionally targeted mitigation measures, Bun et al. (2010b) spatially reference GHG emissions and removals, including their uncertainties, across the territory of the Ukraine. This allows GHGs and their uncertainties to be analyzed individually by region, gas, sector, etc. and tested against approaches—including Monte Carlo analyses—that capture emission factors, activity data, etc., and uncertainties nationally in the form of single numbers or distributions. The difference in relative uncertainty (~2%, based on a 95% confidence interval) found for the energy sector of the Lviv region is noteworthy.

Leip (2010) presents a new methodology to estimate the uncertainties for the categories subsumed under the agriculture sector in the GHG inventory of the European Community (EU15). This methodology allows a more transparent comparison of the uncertainty of GHG inventories across countries and could thus be used to focus on efforts to improve GHG emission estimates at a supra-national level. Not surprisingly, N_2O emissions from agricultural soils are found to dominate the uncertainty not only of the agricultural sector, but also of the overall GHG inventory for many countries. The author's analysis also shows that differences in the countries' uncertainty data are mainly based on different input data for the calculations. Thus, the challenge is to put uncertainty estimates for activity data and emission factors on a solid and common basis, and to harmonize the concepts underlying the uncertainty assessment.

Horabik and Nahorski (2010) study spatially distributed inventory data for N_2O emissions from municipalities in southern Norway, tackling situations where inventory extensions beyond their present coverage have to be developed using, as proxy data, emission activities which are more frequently available than activity data themselves. Examining the spatial covariance in the data—the authors use a conditional autoregressive model—it is possible to compensate for the weaker explanatory power of proxy information and thus to improve inventory accuracy. Formally, the spatial extension of inventories is treated as a prediction task within a statistical framework. Compared to a non-spatial approach, a 15% reduction in the mean square prediction error was obtained.

4.5 Trading emissions

With uncertainty in GHG emissions inventories that can be quite large and can vary significantly by country, gas, sector, source and/or sink, the focus of international agreements and mitigation activities is still on achieving maximum benefit with minimum economic cost. Thus international and national programs provide for the trading of emissions "permits." Inventory uncertainty is not considered to have a bearing on emissions trading. However, if reliably and quantitatively assessed uncertainty were to be incorporated, a host of questions would arise: How can trading systems account for uncertainty and yet ensure that trading really does provide both environmental and economic benefits? Can methods for incorporating uncertainty be easily standardized? Is a price mechanism better able to deal with uncertainty than a cap and trade system? Can uncertain CO_2 emissions from fossil-fuel use in one country be credibly and economically offset with uncertain reductions in CH_4 emissions from agriculture in another country? Can trading or offset systems, or emission taxes, be designed to recognize or deal with the issues of uncertainty? The papers in this series focus largely on issues of trading emissions permits and the role of uncertainty.

Ermolieva et al. (2010) make use of a basic multi-agent, stochastic model of emissions trading to analyze the stability and robustness of carbon markets, while taking into account the uncertainty in estimates of natural and human-related emissions. The authors' concern is that trading markets do not necessarily minimize abatement costs or comply with environmental targets because the markets respond to stochastic "disequilibrium" price signals that are often driven by market speculations and bubbles. The authors' computer-based model allows emission trading to be studied from a decentralized equilibrium perspective, that is, when trading partners themselves choose, without revealing their knowledge on costs and uncertainties, the optimal level of technological abatement and the traded amount under the condition of minimized costs and compliance with long-term environmental constraints.

It is generally perceived that implementing a system of tradable emission permits will allow a seller with low abatement costs to sell permits to a buyer with high abatement costs, thus equalizing marginal abatement costs. Stańczak and Bartoszczuk (2010) simulate the trading process while accounting for the transaction prices of emission permits. With the goal of minimizing the cost of meeting emissions commitments or trading agreements, negotiated permit prices will result in trades when the cost of permits is lower than the cost of reductions for the buyer and vice versa for the seller. The aim of the paper is to simulate by taking uncertainty into account the evolution of prices on the basis of an iterative trading procedure, for which the authors make use of an evolutionary (multi-heuristic) algorithm.

The issue of compliance with emission restrictions or trading agreements is accentuated when there is high uncertainty in emission inventories. High uncertainty can lead to undershooting (i.e., keeping emissions well below the agreed target) in order to decrease the risk of non-compliance; hence, improved precision may not only mean more reliable inventories but also lower costs for compliance. In deriving new rules for checking compliance or for emissions trading, Nahorski and Horabik (2010) are particularly concerned about instances where the uncertainty is asymmetric. Right-skewed asymmetry is typically observed in uncertainty distributions that are obtained from Monte Carlo simulations when reported emission values are used. This leads to biased compliance; it is more likely that true emissions are higher than reported emissions and less likely that they are lower. The authors consider asymmetric distributions and apply fuzzy numbers to more precisely determine the required level of emission reductions necessary to yield a high likelihood of meeting reduction or trading commitments.

Trading of emission permits requires there to be some sort of cooperative behavior and trading markets. Pickl et al. (2010) discuss the problem of uncertainty in transaction relationships and note that the mere existence of formal markets reduces uncertainty by providing for a more structured relationship among economic agents. Markets permit stable expectations about the economic outcome of transactions. The authors describe a macro-economic game model for exploring interactive, cooperative resource planning, including uncertain emissions trading.

Box 1 Rationale for improving and conducting uncertainty analyses (revised)

- Calculations of greenhouse gas (GHG) emissions contain uncertainty for a variety of reasons such as the lack of availability of sufficient and appropriate data and the techniques for processing them.
- Understanding the basic science of GHG gas sources and sinks requires an understanding of the uncertainty in their estimates.
- Schemes to reduce human-induced global climate impact rely on confidence that inventories of GHG emissions allow the accurate assessment of emissions and emission changes. To ensure such confidence, it is vital that the uncertainty present in emissions estimates is transparent. Clearer communication of the forces underlying inventory uncertainty may be needed so that the implications are better understood.
- Uncertainty estimates are not necessarily intended to dispute the validity of national GHG inventories, but they can help improve them.
- Uncertainty is higher for some aspects of a GHG inventory than for others. For example, past experience shows that, in general, methods used to estimate nitrous oxide (N_2O) emissions are more uncertain than methane (CH_4) and much more uncertain than carbon dioxide (CO_2). If uncertainty analysis is to play a role in cross-sectoral or international comparison or in trading systems or compliance mechanisms, then approaches to uncertainty analysis need to be robust and standardized across sectors and gases, as well as among countries.
- Uncertainty analysis helps to understand uncertainties: better science helps to reduce them. Better science needs support, encouragement, and greater investment. Full carbon accounting (FCA), or full accounting of emissions and removals, including all GHGs, in national GHG inventories is important for advancing the science.
- FCA is a prerequisite for reducing uncertainties in our understanding of the global climate system. From a policy viewpoint, FCA could be encouraged by including it in reporting commitments, but it might be separated from negotiation of reduction targets. Future climate agreements will be made more robust, explicitly accounting for the uncertainties associated with emission estimates.

Source: IIASA (2007)

5 Conclusions

The approaches to addressing uncertainty discussed in this Special Issue attempt to improve national inventories, not only for their own sake but also from a wider, systems analytical perspective that seeks to strengthen their usefulness under a compliance and/or global monitoring and reporting framework. They thus show what the challenges and benefits are of including inventory uncertainty in policy analysis. The issues that are raised by the authors featured in this Special Issue, and the role that uncertainty analysis plays in many of their arguments and/or proposals, highlight the importance of such efforts. While the IPCC clearly stresses the value of conducting uncertainty analyses and offers guidance on executing them, the arguments made here in favor of performing these studies go well beyond any suggestions made by the IPCC to date. Several reasons for continuing to improve and standardize the research and estimation methodologies that lead to quantifiable estimates of uncertainty associated with GHG inventories are noted in the text box above (Box 1). These were identified during Workshop discussions and retreats, and are covered in detail by the expanded papers that appear in this Special Issue. The most important of the reasons compiled in Box 1 have been taken from a policy brief prepared as an immediate output of the 2nd Uncertainty Workshop (http://www.iiasa.ac.at/Admin/PUB/policy-briefs/pb01-web.pdf).

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Statistical dependence in input data of national greenhouse gas inventories: effects on the overall inventory uncertainty

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Abstract An uncertainty assessment of the Austrian greenhouse gas inventory provided the basis for this analysis. We isolated the factors that were responsible for the uncertainty observed, and compared our results with those of other countries. Uncertainties of input parameters were used to derive the uncertainty of the emission estimate. Resulting uncertainty using a Monte Carlo approach was 5.2% for the emission levels of 2005 and 2.4 percentage points for the 1990–2005 emission trend. Systematic uncertainty was not assessed. This result is in the range expected from previous experience in Austria and other countries. The determining factor for the emission level uncertainty (not the trend uncertainty) is the uncertainty associated with soil nitrous oxide N_2O emissions. Uncertainty of the soil N_2O release rate is huge, and there is no agreement even on the magnitude of the uncertainty when country comparisons are made. In other words, reporting and use of N_2O release uncertainty are also different between countries; this is important, as this single factor fully determines a country's national greenhouse gas inventory uncertainty. Inter-country comparisons of emission uncertainty are thus unable to reveal much about a country's inventory quality. For Austria, we also compared the results of the Monte Carlo approach to those obtained from a simpler error propagation approach, and find the latter to systematically provide lower uncertainty. The difference can be explained by the ability of the Monte Carlo approach to account for statistical dependency of input parameters, again regarding soil N_2O emissions. This is in contrast to the results of other countries, which focus less on statistical dependency

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when performing Monte Carlo analysis. In addition, the error propagation results depend on treatment of skewed probability distributions, which need to be translated into normal distributions. The result indicates that more attention needs to be given to identifying statistically dependent input data in uncertainty assessment.

1 Introduction

Maintaining greenhouse gas (GHG) inventories is a key requirement of international efforts to combat global climate change. We need to understand the quantities and the sources of GHG fluxes to the atmosphere to be able to devise measures to reduce them. Information about data reliability is also required; thus uncertainty estimates are an essential element of a complete emission inventory.

Uncertainty analysis is useful in many respects (Lieberman et al. 2007). It helps with analyzing and revising an inventory, provides information about the most important factors contributing to uncertainty, and thus assesses which parts of the inventory require the most urgent improvements. It is not able or intended to dispute the validity of the inventory estimates. However, comparing uncertainty across countries helps the comparability of the inventories as such to be judged, as well as the “tradability” of the respective emissions.

Ideally, emission estimates and uncertainty ranges would both be derived from source-specific measured data. In practice, estimates are often based on the known characteristics of sources taken to be representative of the data population. Sometimes, uncertainty and statistical distributions can be determined empirically, based on a large number of specific measurements. Often, however, expert judgement will be necessary to define the uncertainty ranges.

The assessment and propagation of uncertainties in emission inventories have been described in detail in IPCC (2000, 2006). The mathematical algorithms used allow information to be added up in such a way that the relative uncertainty of the parameter combination (as a percentage of the mean value) becomes lower than the relative uncertainty of any of the input parameters. A precondition for applying such algorithms is that statistically independent data should be used, that is, data whose random variation does not simultaneously affect another input parameter. One can say that such parameters need to provide additional information, or, in mathematical terms, that parameters must not be correlated.

The advantage of going into statistically independent detail is often implicitly taken advantage of when a problem is disassembled into sub-problems and the sub-results are being recombined. Such a procedure will allow the overall uncertainty to be reduced (on a relative basis). Nevertheless, it is not always the most detailed level that yields the results of lowest uncertainty. If measurements or assessments at the most detailed level are difficult, a more comprehensive level of information may provide the lower overall uncertainty.

Thus, optimizing the approach requires input information to be collected at the most detailed level at which an inventory can be prepared. Attaching uncertainty data should then be done at a level where greatest confidence can be expected regarding the data. This may be at the most detailed level; but uncertainty data will more often not be available, or an approach using balances at a more aggregate level (energy balance, solvent balance) will provide lower uncertainty. To obtain adequate results, error propagation may be performed at the most reliable level of information available.

For this paper, we use the results of a recent study on the uncertainties in the Austrian GHG inventory (Winiwarter 2008). The work is based on a previous assessment for Austria (Winiwarter and Rypdal 2001; Winiwarter and Orthofer 2000). Similar assessments, which are a reporting requirement under the United Nations Framework Convention on Climate Change (UNFCCC), have been published for a variety of countries, for example, the United Kingdom (Baggott et al. 2005), Finland (Monni et al. 2004), the Netherlands (Ramirez et al. 2008), and Luxembourg (Winiwarter and Köther 2008).

To understand how the methods chosen influence the results, and which parameters are in general (not nationally) most important for describing the overall uncertainty, we draw on the similarities and differences between the respective exercises and the numerical values that are available in detail for Austria.

2 Methodology: how to assess the uncertainty of national emission inventories

2.1 Selection of input data

We demonstrate the general principles according to a description of the system in Austria. The Austrian national inventory system ("OLI") contains a compilation of emissions of air pollutants and greenhouse gases. Results from OLI feed into national reports on air pollution emissions (required under the framework of United Nations Economic Commission for Europe [UNECE] protocols) and greenhouse gas reporting to the UNFCCC and the European Commission. To allow these quite different tasks, OLI provides emission factors and activity data for a large number of sectors and sector/fuel combinations. In this study we use OLI data for 559 individual sectors or sector/fuel combinations (activity data, emission factors for CO_2, CH_4, and N_2O). Additionally, 24 sector/gas combinations for fluorinated gases (F-gases) are evaluated. Not all, but many, of these detailed input data are relevant for the GHG inventory. We will refer to this information as the "base level" of OLI, even if some of the emission factors or activity numbers presented may derive from more detailed emission models. Starting from the "base level" enables us to perform a consistent uncertainty analysis.

Within the framework of this project we had to attribute quantitative information on uncertainty to this input data. All the details of this task have been laid out in the background report (Winiwarter 2008). Linking was performed on the OLI base level, but most uncertainty information was available at a more aggregate level. For aggregate information the same uncertainty was attributed to all input entries concerned, with this input being considered a statistically dependent entity. Uncertainty information was collected both for emission factors and for activities associated with the respective emission source. Uncertainty of total emissions was used only when this more detailed information was not available.

Uncertainty information was taken from national studies, from international information (like, for example, the reports of the Intergovernmental Panel on Climate Change [IPCC]), from data variations in the literature, and from national experts. Structured interviews were not held, but information collected previously in structured interviews (Winiwarter and Orthofer 2000) could still be made use of. As will be explained in Section 2.3, special attention was given to covering statistical dependence (correlation) of source categories.

In all input and output parameters, uncertainty has been expressed as a normal or lognormal probability density function. In line with IPCC requirements, the uncertainty range is presented as the range with 95% probability of a given value being within its boundaries. Thus the boundaries were given as the 2.5 and 97.5 percentiles of the respective distribution. For a normal distribution, this is ±2 standard deviations (SD) from the mean.

As information on uncertainty is often very sparse, we had already considered information on reasonable upper and lower limits of a value as being sufficient to describe a full distribution. Consistent with the procedure above we understand a reasonable range (lower limit to upper limit) to contain 95% of all possible values; thus the total difference is interpreted as 4 SD. As Winiwarter and Rypdal (2001) have shown that the type of distribution used does not strongly influence the results in a wide range of cases, we chose to transform distributions into normal or lognormal distributions rather than using other distribution types. Lognormal distributions were required to cover realistic cases of very large uncertainties (i.e., uncertainties higher than 100%, which were physically limited by zero as the lower end of range [strongly skewed distributions]).

2.2 Error propagation vs. Monte Carlo simulation

Error propagation is a technique that allows the uncertainty associated with the result of a mathematical function to be estimated, based on the function's input uncertainties. Explicit equations for error propagation can be set under a number of preconditions only (IPCC 2000):

- The function consists of additive and multiplicative terms only;
- Uncertainty for each input parameter is normally distributed (i.e., lognormal or other distributions are not modeled);
- Input data are not correlated; and
- Standard deviation does not exceed 30% of the mean.

IPCC (2000) provides a standard template to perform error propagation. This template has been utilized by a number of countries under their obligation to submit national greenhouse gas inventories. This approach is, in accordance with these guidelines, often also referred to as the "Tier 1" uncertainty calculation. Using the template requires assumptions to be applied on a conversion of lognormally distributed parameters to a normal distribution.

A Monte Carlo simulation is based on repeating the actual inventory calculation a number of times. For each replicate, input parameters are varied and (multiple) output is recorded. Variation of input is performed randomly, according to predefined boundary values and probability density functions. The set of individual output data will again follow its own probability density and thus provide the resulting uncertainty, strictly based on the input uncertainty.

Moreover, as correlating inputs and outputs are stored, it is possible to calculate regressions. The regression allows the sensitivity of the result toward an input parameter to be obtained, thus indicating which input is responsible for the result and to what extent.

Emission inventories are fairly easy to calculate and require only little computation time, such that even a few thousand replicates will not require more than a few minutes. Commercial software packages are available that couple with standard spreadsheet programs. This facilitates application on a standard PC. Within this project, we use the software "@RISK" from Palisade Co. (www.palisade.com). The standard tools of these software packages allow many different kinds of probability density functions to be defined and used, as well as the specification of full and even partial correlation between parameters. This also allows for coupling of inputs to a level of detail where uncertainty is assumed to be the smallest. Because of the simplicity of use, many countries have also successfully implemented the Monte Carlo approach (termed: "Tier 2" uncertainty calculation). Respective reports have been published, among others, by Charles et al. (1998), Winiwarter and Rypdal (2001), Monni et al. (2004), and Ramirez et al. (2008). In this paper we provide some specific comparisons between the results of Tier 1 vs. Tier 2 approaches. The methodologies as such are well established and do not require further specification.

2.3 Considering correlated uncertainties

In the standard methodology to estimate uncertainties of an emission inventory, uncertainties are derived for an emission factor or activity number of a specific source category, and as they are assessed independently they are treated as being statistically independent. This procedure is implemented in the IPCC template of "Tier 1" uncertainty calculation, which by its nature would not allow treatment of correlated variables to estimate the uncertainty of emission levels. We do not deem this approach to be the most appropriate representation of the situation Instead, in this study we attempt to identify indications that hint at correlation within parameters. These indications could then be used only in the "Tier 2" approach.

In the case of activities, we regard input information as correlated if derived from data originally collected at a lower level of detail. This is the case for energy balances. All energy activities related to solid fuels, whether in the industry sector or used for domestic heating, are thus considered correlated with respect to their uncertainty. Likewise, we consider liquid fuels used in transport or power plants to be statistically dependent—the same goes for gaseous fuels or biofuels. We treat solvent balances in the same way as fuel balances.

For emission factors, one indication to be used is the value of the emission factor. If two emission factors used in different areas have the same value (e.g., in combustion for different source categories but using the same fuel), there should be a suspicion that these emission factors have been derived from the same set of measurements, and thus uncertainties should be seen as correlated. This has happened in the case of Austria, as shown by an inspection of the original source of emission factors, but it need not be the case generally. Two emission factors could have been assessed fully independently, and still have arrived at the identical value.

Moreover, two emission factors could have different values, but with the uncertainty being most strongly affected by just one parameter. Such a case is visible when national Austrian emission factors for CH_4 from combustion processes are inspected. Measured quantities are emissions of total hydrocarbons and assumptions on the fraction of CH_4 in total hydrocarbons (Orthofer 1991) drive the overall uncertainty. Thus it is also clear in this case that emission factors are correlated. We also assumed this to be the case for N_2O from soil nitrogen (direct and indirect emissions), as the underlying processes are the same. When specifically considering the indirect emissions that occur because of volatilization loss of nitrogen, assumptions on subsequent N_2O formation are based on exactly the same assumptions as those used for direct nitrogen application (IPCC 2000). However, in order to account for the unknown pathways of nitrogen, which also include leaching to groundwater or runoff in surface water, uncertainty for indirect emissions was considered higher, as it also contained other components contributing to uncertainty. Thus one could also argue that those other components are independent and that only partial correlation should be considered—an argument that we do not apply here, as it seems impossible to assess the degree of such a partial correlation.

3 Results

3.1 Tasks

Estimating uncertainty does not yield just one result. Following the guidance of IPCC (2000), uncertainties have been derived for the total GHG inventory (as CO_2 equivalents) as level uncertainty for 2005 and for the base year 1990, and for the trend uncertainty between those years. Moreover, the same results are available specifically for each of the six gases in the “Kyoto basket.” Individual uncertainty estimates have been provided for the 40 key sources of the Austrian inventory (it is only for the respective gas(es) that this source category is “key”) and for the combined non-key sources (aggregated for all non-key source emissions of each gas). Key sources have been identified according to the procedures developed by IPCC (2000), which also guides which source categories should be used. A key source category is thus one that is prioritized within the national inventory system because its estimate has a significant influence on the total GHG inventory in terms of the absolute level of emissions, the trend in emissions, or both.

Separate uncertainty calculations were performed using a spreadsheet prepared specifically according to the “Tier 1” approach (IPCC 2000) and with a Monte Carlo approach fully considering statistical dependence of detailed input data as described above (“Tier 2” approach). The same input uncertainty information was used as much as possible. It should be noted that the “Monte Carlo” approach, averaging a large number of randomly varied input data, may exhibit slightly different results in total emissions as well as source category emissions in comparison with a direct calculation. The physical meaning of this difference is similar to a rounding error and may be ignored. For the present evaluation we used 10,000 iterations and standard Monte Carlo (random) sampling.

3.2 Results using the Tier 1 (error propagation) approach

The results of the error propagation approach are strictly limited to the key sources and the potential of the IPCC spreadsheet used. Table 1 presents the resulting spreadsheet. An extension to other sources than the 40 key sources is in theory

Table 1 Tier 1 (error propagation) uncertainty calculation and reporting, according to Table 6.1 of IPCC (2000) for Austria, 2005

A	B	C	D	E	F	G	H	I	J	K	L	M
IPCC source category	Gas	Base year emissions 1990	Year 2005 emissions	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in 1990	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
		Input data	Input data	Input data	Input data							
		Gg CO_2 equivalent	Gg CO_2 equivalent	%	%	%	%	%	%	%	%	%
1 A 1 a liquid: public electricity and heat production	CO_2	1,229	1,083	0.5	0.5	0.7	0.01	−0.00	0.01	−0.0024	0.0100	0.01
1 A 1 a other: public electricity and heat production	CO_2	118	490	10.0	20.0	22.4	0.12	0.00	0.01	0.0917	0.0907	0.13
1 A 1 a solid: public electricity and heat production	CO_2	6,247	5,844	0.5	0.5	0.7	0.05	−0.02	0.08	−0.0101	0.0541	0.05
1 A 1 b liquid: petroleum refining	CO_2	1,957	2,151	0.5	0.3	0.6	0.01	−0.00	0.03	−0.0006	0.0199	0.02
1 A 2 mobile-liquid: manufacturing industries and construction	CO_2	1,018	1,161	3.0	0.5	3.0	0.04	−0.00	0.02	−0.0003	0.0645	0.06
1 A 2 other: manufacturing industries and construction	CO_2	375	849	10.0	20.0	22.4	0.21	0.01	0.01	0.1061	0.1570	0.19
1 A 2 solid: manufacturing industries and construction	CO_2	5,014	5,602	1.0	0.5	1.1	0.07	−0.00	0.07	−0.0021	0.1036	0.10

Table 1 (continued)

A	B	C	D	E	F	G	H	I	J	K	L	M
IPCC source category	Gas	Base year emissions 1990	Year 2005 emissions	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in 1990	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
		Input data	Input data	Input data	Input data							
		Gg CO_2 equivalent	Gg CO_2 equivalent	%	%	%	%	%	%	%	%	%
1 A 2 stat-liquid: manufacturing industries and construction	CO_2	2,883	1,920	3.0	0.5	3.0	0.06	−0.02	0.03	−0.0097	0.1066	0.11
1 A 3 a jet kerosene: civil aviation	CO_2	24	209	3.0	3.0	4.2	0.01	0.00	0.00	0.0071	0.0116	0.01
1 A 3 b diesel oil: road transportation	CO_2	4,013	16,645	3.0	3.0	4.2	0.78	0.16	0.22	0.4668	0.9238	1.04
1 A 3 b gasoline: road transportation	CO_2	7,911	6,393	3.0	3.0	4.2	0.30	−0.04	0.08	−0.1162	0.3548	0.37
1 A 3 b gasoline: road transportation	N_2O	219	149	3.0	70.0	70.1	0.12	−0.00	0.00	−0.1013	0.0082	0.10
1 A 4 biomass: other sectors	CH_4	315	244	10.0	50.0	51.0	0.14	−0.00	0.00	−0.0842	0.0451	0.10
1 A 4 mobile-diesel: other sectors	CO_2	1,379	1,472	3.0	0.5	3.0	0.05	−0.00	0.02	−0.0010	0.0817	0.08
1 A 4 other: other sectors	CO_2	239	72	10.0	20.0	22.4	0.02	−0.00	0.00	−0.0552	0.0132	0.06
1 A 4 solid: other sectors	CO_2	2,654	562	1.0	0.5	1.1	0.01	−0.03	0.01	−0.0168	0.0104	0.02
1 A 4 stat-liquid: other sectors	CO_2	7,319	7,125	3.0	0.5	3.0	0.24	−0.02	0.09	−0.0100	0.3955	0.40

1 A gaseous: fuel combustion (stationary)	CO_2	11,169	18,510	2.0	0.5	2.1	0.42	0.07	0.24	0.0346	0.6849	0.69
1 B 2 b: natural gas	CH_4	273	552	4.2	14.1	14.7	0.09	0.00	0.01	0.0423	0.0429	0.06
2 A 1: cement production	CO_2	2,033	1,797	5.0	2.0	5.4	0.11	−0.01	0.02	−0.0159	0.1663	0.17
2 A 2: lime production	CO_2	396	579	20.0	5.0	20.6	0.13	0.00	0.01	0.0072	0.2141	0.21
2 A 3: limestone and dolomite use	CO_2	222	291	19.6	2.0	19.7	0.06	0.00	0.00	0.0007	0.1053	0.11
2 A 7 b: sinter production	CO_2	481	310	2.0	5.0	5.4	0.02	−0.00	0.00	−0.0170	0.0115	0.02
2 B 1: ammonia production	CO_2	517	503	2.0	4.6	5.0	0.03	−0.00	0.01	−0.0065	0.0186	0.02
2 B 2: nitric acid production	N_2O	912	274	3.0	20.0	20.2	0.06	−0.01	0.00	−0.2104	0.0152	0.21
2 C 1: iron and steel production	CO_2	3,546	4,995	0.5	0.5	0.7	0.04	0.01	0.07	0.0052	0.0462	0.05
2 C 3: aluminium production	CO_2	158	0	2.0	0.5	2.1	0.00	−0.00	0.00	−0.0012	–	0.00
2 C 3: aluminium production	PFCs	1,050	0	0.0	50.0	50.0	0.00	−0.02	0.00	−0.8123	–	0.81
2 C 4: SF_6 used in Al and Mg foundries	SF6	253	0	0.0	5.0	5.0	0.00	−0.00	0.00	−0.0196	–	0.02
2 F 1/2/3/4/5: ODS substitutes	HFCs	21	908	0.0	54.0	54.0	0.54	0.01	0.01	0.6237	–	0.62
2 F 7: semiconductor manufacture	FCs	133	291	0.0	11.2	11.2	0.04	0.00	0.00	0.0195	–	0.02
2 F 9: other sources of SF_6	SF6	127	82	0.0	56.0	56.0	0.05	−0.00	0.00	−0.0498	–	0.05
3: solvent and other product use	CO_2	283	177	5.0	10.0	11.2	0.02	−0.00	0.00	−0.0205	0.0164	0.03
4 A 1: cattle	CH_4	3,561	3,029	10.0	20.0	22.4	0.75	−0.02	0.04	−0.3091	0.5605	0.64
4 B 1: cattle	N_2O	908	789	10.0	100.0	100.5	0.88	−0.00	0.01	−0.3727	0.1460	0.40

Table 1 (continued)

A	B	C	D	E	F	G	H	I	J	K	L	M
IPCC source category	Gas	Base year emissions 1990	Year 2005 emissions	Activity data uncertainty	Emission factor uncertainty	Combined uncertainty	Combined uncertainty as % of total national emissions in 1990	Type A sensitivity	Type B sensitivity	Uncertainty in trend in national emissions introduced by emission factor uncertainty	Uncertainty in trend in national emissions introduced by activity data uncertainty	Uncertainty introduced into the trend in total national emissions
		Input data	Input data	Input data	Input data							
		Gg CO_2 equivalent	Gg CO_2 equivalent	%	%	%	%	%	%	%	%	%
4 B 1: cattle	CH_4	587	459	10.0	70.0	70.7	0.36	−0.00	0.01	−0.2156	0.0849	0.23
4 B 8: swine	CH_4	448	397	10.0	70.0	70.7	0.31	−0.00	0.01	−0.1215	0.0734	0.14
4 D 1: direct soil emissions	N_2O	1,760	1,518	5.0	150.0	150.1	2.52	−0.01	0.02	−1.1051	0.1404	1.11
4 D 3: indirect emissions	N_2O	1,310	1,086	5.0	150.0	150.1	1.80	−0.01	0.01	−0.9077	0.1005	0.91
6 A: solid waste disposal on land	CH_4	3,377	1,880	12.0	25.0	27.7	0.58	−0.03	0.02	−0.6909	0.4173	0.81
National total		76,439	90,395				3.59					2.55

The emissions of the key source categories cover 96.7% and 96.9% of the total GHG emissions (1990 and 2005, respectively) possible, but in the Austrian inventory, as sources can only be dealt with individually, this would mean adding more than 100 sources.

As error propagation requires the use of normal distributions, the proper implementation of variables characterized by a skewed distribution necessarily requires an arbitrary choice. Especially regarding sources that will eventually contribute significantly to overall uncertainty, this choice can be quite important. Using the range of 0.3 to 3 times the emission factor for N_2O from soils, we chose to apply an uncertainty of 150%.

This appears to be in contrast to guidance provided by IPCC (2000): "If uncertainty is known to be highly asymmetrical, enter the larger percentage difference between the mean and the confidence limit." However, that statement clearly refers to distributions where standard deviations do not exceed 30% of the mean. Although it does not seem useful to represent a given distribution by a normal distribution which, though it follows the guidance, does not represent the occurrence of events of the original distribution (e.g., negative emissions), we also tested the results for an uncertainty of 200% (consistent with the factor 3 increase). In that case, the overall uncertainties would have been 4.51% (level) and 2.85 percentage points (trend) instead of 3.59% and 2.55 percentage points as identified in Table 1.

3.3 Results using the Tier 2 (Monte Carlo) approach

While the iterations representing the Monte Carlo approach are being performed, all randomly selected input data are recorded, as are all the respective results of calculations for a predefined set of output parameters. Here we selected the following outputs (for all three cases: base year 1990, target year 2005, and the difference between them), listed in detail in the background report (Winiwarter 2008):

- Emissions of each of 40 key sources (key gas only);
- Totals of all non-key source emissions (for each of six gases);
- Emission totals (for each of six gases);
- GHG totals as reported to the UNFCCC (different gases added according to their greenhouse warming potential, in CO_2 eq.); and
- National GHG totals, including land use, land use change, and forestry (LULUCF), and international bunker fuels.

As the whole set of data (10,000 individual results) is available for both outputs and inputs, the respective probability distributions can also be derived. Standard deviation, and thus uncertainty (here defined as 2 SD), is just one result of such a probability distribution, and is available for each of the outputs.

We merely display the main results of the Monte Carlo analysis of the Austrian GHG inventory (Table 2). Uncertainty is presented for each gas and for the level of target year 2005 (as a percentage) as well as for the trend (in percentage points relative to the total base year emissions). Detailed results by source category, using the original IPCC version of the table, are available from the background report (Winiwarter 2008).

In addition to overall uncertainties, the Monte Carlo approach also allows contributions to the overall variance of the results to be differentiated, using the correlation of input to output parameters. This result (Fig. 1) denotes the emission factor of soil

Table 2 Key results of the Austrian GHG inventory uncertainty 2005—Monte Carlo approach

Random uncertainty		CO_2	CH_4	N_2O	PFC	HFC	SF_6	Total GHG emissions
1990	Mean value	61.94	9.18	6.26	1.08	0.02	0.50	78.98
	Standard deviation	0.41	0.72	2.64	0.27	0.01	0.04	2.78
	Uncertainty (2 SD) (%)	1.3	15.6	84.3	49.1	49.9	16.6	7.0
2005	Mean value	79.65	7.06	5.24	0.12	0.91	0.29	93.26
	Standard deviation	0.65	0.53	2.26	0.01	0.24	0.03	2.41
	Uncertainty (2 SD) (%)	1.6	14.9	86.4	11.3	53.5	23.9	5.2
Trend	Difference	17.72	−2.12	−1.02	−0.97	0.89	−0.22	14.28
	Uncertainty of trend (percentage points)	2.10	8.00	13.05	49.12	21.20	21.40	2.37

N_2O emissions as clearly the most important factor influencing results, followed by transport activities, and the emission factor for N_2O related to manure handling.

3.3.1 Overall results comparing the two approaches

It is obvious that the level of uncertainty presented for a specific source category would not differ strongly between the error propagation and the Monte Carlo approach, which have basically the same set of assumptions. Moreover, the sectoral combined uncertainties of the underlying template-derived tables (see Winiwarter 2008) agree. The highest contributions to overall uncertainty, both according to the Monte Carlo analysis (Fig. 1) and to the error propagation template (column H in Table 1), are in the agricultural sector (nitrous oxide from soils, direct as well as indirect emissions, covered as one item in the Monte Carlo approach; somewhat smaller are the contributions from cattle emissions). Other sectors that are exposed to high uncertainties with respect to total emissions are transport (specifically transport using diesel fuels) and the waste sector. Other sectors of energy consumption

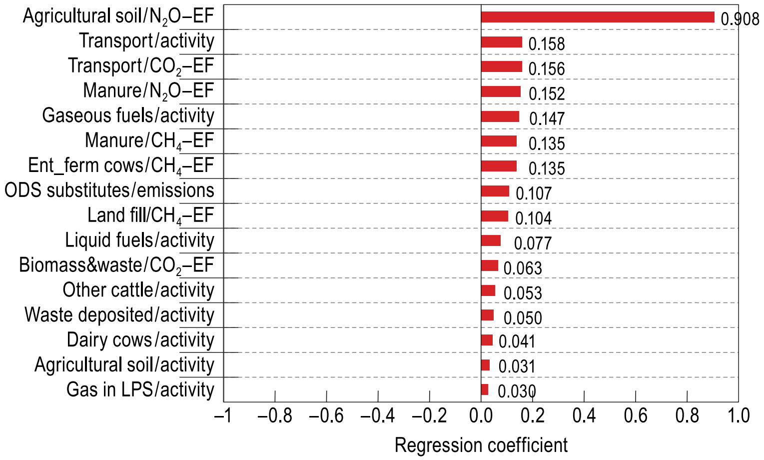

Fig. 1 Contribution of input parameters to the uncertainty of the Austrian 2005 emission levels