Prior to an Economic Treatment of Emissions and Their Uncertainties under the Kyoto Protocol: Scientific Uncertainties that Must be Kept in Mind

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Abstract

In a stepwise fashion we specify the relevant conditions for carrying out temporal signal detection under the Kyoto Protocol and identify a number of scientific uncertainties that economic experts must keep in mind prior to an economic treatment of emissions and their uncertainties under the Protocol. In addition, we answer one of the crucial questions that economic experts will pose: how credible are tradable emission permits? Our exercise is meant to serve as a first basis for economic experts in carrying out useful emission trading assessments and in specifying the validity of their assessments from a physical scientific point of view. Such a basis is missing.

1. Introduction

After several years of scientific work, we still regard full carbon (FCA) or greenhouse gas accounting (FGA), uncertainty and verification in connection with the detection of greenhouse gas net flux changes (also termed GHG signals) as the crucial issues for the functioning of the Kyoto Protocol. However, we observe that they are not concomitantly and rigorously discussed in a holistic context, neither among nor between physical scientists and experts from other disciplines, e.g., economics. Physical scientists do not scrutinize (in the aforementioned holistic context) the basis that has been set by the political negotiators of the Protocol nor do they specify the scientific constraints under which the Protocol will operate. The consequences are manifold. To safeguard their carbon trading assessments from an uncertainty–risk point of view, experts from financial institutions, e.g., will ask questions which physical scientists cannot answer. Economic experts, e.g., carry out assessments that are not integrated in a proper physical scientific framework, i.e., they cannot properly specify the validity of their assessments from a physical scientific point of view. Nor do we assemble crucial knowledge that will prove useful in improving the Protocol prior to and for its follow-up periods.

Here, we make reference to three collaborative IIASA studies [11; 12; 13], which focus on the preparatory detection of uncertain GHG emission signals under the Kyoto Protocol. These studies advance the emission reporting of Annex I countries under the Protocol as they take uncertainty and its consequences into consideration, i.e., (i) the risk of compliance, i.e., that a country's true emissions in the commitment year/period are above its true emission limitation or reduction commitment; and (ii) the detectability of its target. As their approach can be applied to any net emitter, the authors of the studies anticipate that the evaluation of GHG emission signals in terms of risk and detectability might become standard practice and that these two qualifiers will be accounted for in pricing GHG emission permits.

We use these studies as an example to uncover in five steps the crucial physical scientific constraints and choices that are involved in applying signal detection within a FGA–uncertainty–verification framework. That is, the results achieved with the help of signal detection can be properly evaluated against a solid physical scientific background. In so doing, our primary intention is not to undermine the Protocol but to increase the lucidity that we miss in the thinking behind the Kyoto Protocol and the conditions under which it will operate. Moreover, the studies' results are of practical use. They exhibit a straightforward bearing on how carbon permits are evaluated economically. Thus, our second intention is to use these studies in building a sound bridge from the physical sciences to economics, that is, to offer properly specified, physical-scientific uncertainty and risk related information that can be taken over by economic experts and considered by them in their emission trading assessments.

2. Working within a FGA–Uncertainty–Verification Framework

Step 0: Setting the Stage

Where do uncertainties come from? Moss and Schneider [17; see also 5] categorized uncertainties and espoused the use of a straightforward concept within the Intergovernmental Panel on Climate Change (IPCC) to illustrate where scientific uncertainties come from. Their concept reveals the advantage of fundamental structure. It considers four main categories — corresponding to confidence in the theory, the observations, the models and the consensus (understood as soft knowledge) within a field — to which we attach scientific quality labels to indicate whether plausibility, validation or verification (ascending order of strictness) can be achieved (see Fig. 1). These are specified — in line with science theory — according to Merriam-Webster's Collegiate Dictionary [15; 16]:

Plausibility [from *plausibilis* = worthy of applause] → plausible: reasonable; appearing worthy of belief <the argument was both powerful and ~>.

Validation [from *validus* = strong] → valid: well grounded or justifiable: being at once relevant and meaningful <a ~ theory>; logically correct (i.e., having a conclusion correctly derived from premises) <a ~ argument>.

Verification [from *verus* = true] → verify: to establish the truth, accuracy, or reality.[1]

In accordance with these definitions, only observations (measurements) — uncertain per se — can be verified, but none of the other categories. Theories and diagnostic models can only be validated or, alternatively, falsified (which is a controversially discussed issue on its own). Consensus as well as prognostic modeling also give rise to uncertainty. However, these two categories can, at best, only be judged as plausible; they can neither be validated nor verified.

Considering in the context of the Kyoto Protocol that GHG emissions are, in general, not directly measured but only measurement-based, we extend Moss and Schneider's uncertainty category *observations* to also include the (not rigorously specified) category *accounting*. This permits us to also consider statistically surveyed data including (emission) data that are derived with the help of statistically surveyed data (e.g., activity data) in combination with literature-reported data (e.g., emission factors).

Accounting versus diagnostic versus prognostic modeling. Figure 2 shows the difference in terms of uncertainties between accounting versus diagnostic and prognostic modeling. The accounting typically happens with a time step of ≤ 1 yr and may be matched by a model during its diagnostic mode. During its prognostic mode, the model can, at best, only reflect a multi-year period that excludes singular stochastic events (although the model may operate with a time step of ≤ 1 yr). The uncertainty associated with accounting, $U_{Account}$, reflects our real diagnostic capabilities. It is this uncertainty, which underlies our past as well as our current observations and which, under the Kyoto Protocol, we will have to cope with in reality at some time in the future (e.g., commitment year period). This $U_{Account}$ may decrease with increasing knowledge. (For simplification, we let $U_{Account}$ stay constant in absolute terms over time in Figure 2.) By way of contrast, U_{Model}, the uncertainty of the model, always increases due to the model's decreasing prognostic capabilities with time.

Uncertainty concept. Figure 3 presents the uncertainty concept that we apply in order to overcome a mismatch of measured (or measurement-based) mean values including their uncertainties under validation or verification. The concept acknowledges that both available knowledge and lack of knowledge exists when accounting net carbon emissions. Available knowledge can be hard or soft, while lack of knowledge can be interpreted as the difference between an accepted and the (unknown) true value due to unknown biases. Random errors and systematic errors (the latter are also called determinate errors or simply biases, while we prefer quantified systematic error or measured biases) are typically used to evaluate hard as well as soft knowledge in terms of uncertainty. In contrast, lack of knowledge can only be addressed in a way that is necessary but not sufficient. This is done by defining an uncertainty range that encompasses each of the two measured biases plus each of the two standard deviations representing the random errors of the two depicted measurement sets.

Uncertainty classes. The derivation of aggregated uncertainties is typically not unambiguous and even prone to errors. This is why we apply relative uncertainty classes as a common good practice measure. They constitute a robust means to get an effective grip on aggregated uncertainties. In light of the numerous data limitations and inconsistencies that countries face, the reporting of exact relative uncertainties is not justified.

Our work on the Austrian Carbon Database (ACDb) project, which strives for the FCA of Austria, showed that experts, who share the same data sets, typically estimate uncertainty ranges that overlap each other [10]. However, this may not be true any more if the experts use different initial data, process them differently or apply different systems views (e.g., an intra-modular systems view as under partial carbon accounting (PCA) opposed to an inter-modular systems view as under FCA). Our definition of the relative uncertainty classes as specified in Table 1 is arbitrary and attempts to satisfy simple practical considerations as to how many different intervals one wishes to resolve.[2]

Step 1: Bottom-up versus Top-down: Verification of Emissions

The verification of carbon emissions requires — following science-theoretical standards — adopting an approach, which takes an atmospheric view (what matters is what the atmosphere sees) and which is complete (leaving no unverified residues) (see Fig. 4). In the context of the Kyoto Protocol, this leads us to the concept of bottom-up/top-down (consistent or dual-constrained) FCA on the country-scale,[3] that is, the measurement of all fluxes including those into and out of the atmosphere (as observed on earth), but also an atmospheric storage measurement (as observed in the atmosphere), which — to reflect the needs of the Protocol — permits to discriminate a country's *Kyoto biosphere* from its *non-Kyoto biosphere*.[4] This type of FCA would permit verification that is ideal because it would work both ways (bottom-up/top-down). However, it is unattainable as there is no atmospheric measurement available (and will most likely not be available in the immediate future) that can meet this discrimination requirement — not speaking about the measurement's spatial (country-scale) resolution requirements [11: Section 2.2]. As a consequence, PCA or partial greenhouse gas accounting (PGA), respectively, as envisaged under the Kyoto Protocol can not be verified.

Step 2: Bottom-up/Top-down versus Signal Detection: Verification of Emission Changes

Contrary to the verification of <u>emissions</u> (cf. Step 1), the Kyoto Protocol requires that net <u>emission changes</u> (emission signals)[5] of specified GHG sources and sinks, including those of the *Kyoto biosphere* but excluding those of the *non-Kyoto biosphere*, be verified on the spatial scale of countries by the time of commitment, relative to a specified base year. The relevant question is then whether these emission signals outstrip uncertainty and can be "verified" (correctly: detected).

The IPCC (for which the Kyoto Protocol appeals)[6] defines uncertainty with respect to two predefined points in time [18: Section 2.3.7; 19: Chapter 6]. Figure 5 reflects this concept based on two different types of uncertainty, total and trend uncertainty.[7] Notwithstanding, if we ever want to place signal detection meaningfully into a bottom-up-top-down verification context, it is important to realize that it is the total uncertainty in the commitment year/period that matters as long as we are still searching for the accurate mean emission values (see Box 1).[8] Merging bottom-up-top-down verification of emissions and temporal detection of emission signals is the scientific challenge of the day, which can only be addressed if signal detection acknowledges total uncertainty. Trend uncertainty is not favored by researchers in the field of signal detection because it provides only second-order information (related to the difference of a difference); that is, trend uncertainty can be used in investigating how certain or uncertain an emission trend is, but it provides no information whether or not a realized change in net emissions is significant or detectable.

However, as discussed in Step 3, the knowledge of total uncertainty at only two points in time without considering the dynamics of the emission signal might lead to interpretational difficulties as to whether or not the emission signal is detectable (which we will avoid; cf. Step 5).

Step 3: Effectiveness vis-à-vis Compliance: Statistical Significance of an Emission Signal versus its Detectability

Figure 6 illustrates that whether or not an emission signal is statistically significant does not imply its detectability. That is, the IPCC falls short in providing support for the Kyoto Protocol as the problem of detecting emission signals (thus, the issue of the Protocol's effectiveness) still goes unresolved. ([6] argue differently but come to the same conclusion.) We address this problem (following classical approaches) with the help of the Verification Time (VT) concept.[9] This concept makes use of the dynamics of an emission signal and compares it with the uncertainty that underlies the emissions, not the emission signal (see Fig. 7). Only a comparison of this type permits to address signal detection. Considering emissions or emission changes individually within their respective uncertainty bands does not permit doing so.

Step 4: Effectiveness vis-à-vis Credibility: Uncertainty in the Accounting Matters

Uncertainty in the accounting matters, not only scientifically, e.g., when studying the superposition of GHG systems exhibiting different dynamics (see Fig. 8), but also from an economic point of view (see Fig. 9). Figure 8 illustrates the linear and nonlinear behavior of (e.g.) national GHG systems in terms of their VTs, where a national anthropogenic system (simply referred to as fossil fuel or FF system) and a national FF-plus-LUCF system are compared. This comparison shows that the consideration of uncertainty indeed makes a big difference for the detetctability of emission signals and their qualitative interpretation.

The same is true from an economic point of view, e.g., for emission trading. Without uncertainty, sellers of equal amounts of carbon (or their equivalents) cannot be distinguished (Fig. 9a), that is, they cannot be specified in terms of credibility. Figure 9b shows that indeed awkward cases are possible, e.g., when a Party complying with the Kyoto Protocol might perform worse than a Party not complying with the Protocol. (To handle such a case requires the consideration of risk, which we do in Step 5.) This illustration shows that the functioning of an emission market crucially depends on its credibility and, thus, on the reporting of uncertainties.

Step 5: Signal Detection: Different Techniques — Different Findings

The focus in this step is on the preparatory detection of emission signals, which should have been applied prior to/in negotiating the Kyoto Protocol. Our experience so far shows that there is no ideal signal detection technique; each has its pros and cons. We demonstrate this with the help of the Undershooting (Und) concept and the combined Undershooting and Verification Time (Und&VT) concept, which have been described in detail in [11: Sections 3.3, 3.4].

The starting point of both the Und and the Und&VT concepts is that Annex I countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.[10] They also employ the same assumptions, viz.

(1) Uncertainties at t_1 (base year) and t_2 (commitment year/period) are given in the form of intervals, which take into account that a difference might exist between the true but unknown net emissions $\left(x_{t,i}\right)$ and their best estimates $\left(x_i\right)$ (i = 1, 2). These differences are captured with the help of ε_i (i = 1, 2):

$$\left|x_{t,1} - x_1\right| \le \varepsilon_1 \ , \ \left|x_{t,2} - x_2\right| \le \varepsilon_2 \ . \qquad (1), (2)$$

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $\rho = \text{const}$.

The question posed in connection with the Und concept is (see Fig. 10): how much must countries undershoot their Kyoto targets to decrease the risk of compliance (α), i.e., that their true emissions in the commitment year/period do not undershoot (i.e., overshoot) their true emission limitation or reduction commitments? The answer is given by:

$$x_{t,2} \ge \left(1-\delta_{KP}\right) x_{t,1} \quad \text{with risk } \alpha \qquad \Leftrightarrow$$

$$\frac{x_2}{x_1} \le \left(1-\delta_{KP}\right) \frac{1-\left(1-2\alpha\right)\rho}{1+\left(1-2\alpha\right)\rho} \approx 1 - \left\{\delta_{KP} + 2\left(1-2\alpha\right)\left(1-\delta_{KP}\right)\rho\right\}, \qquad (3a,b)$$

where δ_{KP} is the normalized emissions change committed by a country under the Protocol; the undershooting U is specified by

$$U = 2\left(1-\delta_{KP}\right) \frac{\left(1-2\alpha\right)\rho}{1+\left(1-2\alpha\right)\rho} \approx 2\left(1-2\alpha\right)\left(1-\delta_{KP}\right)\rho \ ; \qquad (4a,b)$$

and the country's modified (mod) emission reduction target δ_{mod} is defined by

$$\delta_{mod} = \delta_{KP} + U \ . \qquad (5)$$ [11]

The question posed in connection with the Und&VT concept is similar but additionally considers the detectability of an emission signal (see Fig. 11): how much must countries undershoot their Kyoto-compatible, but <u>detectable</u>, targets to decrease the risk (α) that their true emissions in the commitment year/period do not undershoot (i.e., overshoot) their true emission limitation or reduction commitments? The answer for the case that a country's critical (crit) (detectable) emission reduction target δ_{crit} is greater than its Kyoto reduction target δ_{KP} is given by:

$$x_{t,2} \ge \left(1-\delta_{crit}\right) x_{t,1} \quad \text{with risk } \alpha \qquad \Leftrightarrow$$

$$\frac{x_2}{x_1} \le \left(1-\delta_{crit}\right) \frac{1}{1+\left(1-2\alpha\right)\rho} \approx 1 - \left\{\delta_{KP} + U_{Gap} + \left(1-2\alpha\right)\left(1-\delta_{crit}\right)\rho\right\}, \qquad (6a,b)$$

where δ_{crit}, U and U_{Gap} are specified by

$$\delta_{crit} = \frac{\rho}{1+\rho} \; ; \tag{7}$$

$$U = U_{Gap} + (1-\delta_{crit}) \frac{(1-2\alpha)\rho}{1+(1-2\alpha)\rho} \approx U_{Gap} + (1-2\alpha)(1-\delta_{crit})\rho \; ; \tag{8a,b}$$

and

$$U_{Gap} = \delta_{crit} - \delta_{KP} \; ; \tag{9}$$

while the country's modified emission reduction target δ_{mod} is still given by Equation (5).[12]

Table 2 refers to the Und concept and Table 3 to the Und&VT concept. They list the modified emission reduction targets δ_{mod} for Annex I countries committed to emission reduction, where the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" or "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5. The tables should be read as follows (cf., e.g., Tab. 2): If an Annex I country complies with its emission reduction commitment, that is, $x_2 = (1-\delta_{KP})x_1$, the risk that its true, but unknown, emissions $x_{t,2}$ are actually equal to or greater than its true, but unknown, target $(1-\delta_{KP})x_{t,1}$ is 50%. Undershooting decreases this risk. For instance, a country of group 1 has committed itself to reduce its net emissions by 8%. Reporting with a 7.5% relative uncertainty, the country needs to reduce its emissions from 8% to 20.8% to decrease the risk of compliance from 50% to 0%.

Table 2 shows that the Und concept is difficult to justify politically in the context of the Kyoto Protocol. Under the Protocol, nonuniform emission reduction commitments (see δ_{KP} values in the third column) were determined "off the cuff", meaning that they were derived via horse-trading and not resulting from rigorous scientific considerations. The outcome is discouraging. Varying δ_{KP} while keeping the relative uncertainty ρ and the risk α constant exhibits that Annex I countries complying with a smaller δ_{KP} are better off than countries that must comply with a greater δ_{KP} (see, e.g., δ_{mod} values for ρ = 7.5% and α = 0.3). Such a situation is not in line with the spirit of the Kyoto Protocol.

Table 3, on the other hand, unveils crucial difficulties in connection with the Und&VT concept. This concept requires correcting for non-detectability by introducing an initial or obligatory undershooting (U_{Gap}) so that the countries' emission signals become detectable (i.e., meet the maximal allowable VT) before the countries are permitted to make economic use of their excess emission reductions (see, e.g., the line for $\delta_{KP} = 8\%$: the δ_{mod} value for ρ = 7.5% and α = 0.5 is $\delta_{mod} = \delta_{KP} + U_{Gap} = 13\%$, that is, the initial or obligatory undershooting is $U = U_{Gap} = 13\% - 8\% = 5\%$). It remains to be seen whether this strict interpretation of signal detection will be accepted by Annex I countries as it forces them to strive for detectability, i.e., initial investments before these countries can profit from their economic actions.

However, it must be realized that — although the countries' true net emissions are unknown — the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk or the "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk, respectively, can be grasped and thus be priced. In addition, both the Und concept and the Und&VT concepts show that the countries' committed emission reduction targets — or their Kyoto-compatible but <u>detectable</u> targets, respectively — require considerable undershooting if one wants to keep the risk low ($\alpha \approx 0.1$) that the countries' true emissions in the commitment year/period are above the true equivalents of these targets.

Summary

The lessons that can be drawn from Steps 1 to 5 are:

Step 1: The Kyoto Protocol cannot be verified bottom-up/top-down if the biosphere is split into a *Kyoto biosphere* and a *non-Kyoto biosphere*.

Step 2: The temporal detection of emission changes cannot be placed meaningfully in a bottom-up-top-down verification context if signal detection does not acknowledge total uncertainty.

Step 3: The knowledge of total uncertainty at only two points in time without considering the dynamics of the emission signal permits investigating its statistical significance but not its detectability.

Step 4: Without uncertainty, an effective (credible) emission trading system cannot be established.

Step 5: Signal detection techniques differ; each has its pros and cons. A discussion on which technique to select has not even started. Economists must be aware that the risk of compliance, i.e., that the countries' true emissions in the commitment year/period are above the true equivalents of their committed targets can be grasped (although the countries' true net emissions are unknown) and thus be priced. We believe that not evaluating the countries' emission signals in terms of risk and detectability will miss economic reality.

To recapitulate, we recall that we have 1) step-by-step specified the relevant conditions for carrying out temporal signal detection under the Kyoto Protocol and identified a number of scientific uncertainties that economic experts must keep in mind; and 2) (partially) answered one of the crucial questions that economic experts will pose: how credible are tradable emission permits? Our exercise is meant to serve as a first basis for economic experts in carrying out useful emission trading assessments and in specifying the validity of their assessments from a physical scientific point of view. Such a basis was missing.

References

[1] FCCC (1998). Report of the Conference of the Parties on its Third Session, Held at Kyoto from 1 to 11 December 1997. Addendum. Part Two: Action Taken by the Conference of the Parties at its Third Session. Document FCCC/CP/1997/7/Add.1, UN Framework Convention on Climate Change (FCCC), Bonn, Germany, pp. 60. Available at: http://unfccc.int/resource/docs/cop3/07a01.pdf.

[2] FCCC (2001a). Implementation of the Buenos Aires Plan of Action: Adoption of the Decisions Giving Effect to the Bonn Agreements. Draft Decisions Forwarded for Elaboration, Completion and Adoption. National Systems, Adjustments and Guidelines under Articles 5, 7 and 8 of the Kyoto Protocol. Draft Decision -/CP.7. Guidelines for National Systems under Article 5, Paragraph 1, of the Kyoto Protocol. Document FCCC/CP/2001/L.18. UN Framework Convention on Climate Change (FCCC), Bonn, Germany, pp. 8. Available at: http://unfccc.int/resource/docs/cop7/118.pdf.

[3] FCCC (2001b). Implementation of the Buenos Aires Plan of Action: Adoption of the Decisions Giving Effect to the Bonn Agreements. Draft Decisions Forwarded for Elaboration, Completion and Adoption. National Systems, Adjustments and Guidelines under Articles 5, 7 and 8 of the Kyoto Protocol. Draft Decision -/CP.7. Guidelines for National Systems under Article 5, Paragraph 2, of the Kyoto Protocol. Document FCCC/CP/2001/L.19. UN Framework Convention on Climate Change (FCCC), Bonn, Germany, pp. 5. Available at: http://unfccc.int/resource/docs/cop7/119.pdf.

[4] FCCC (2002). Report of the Conference of the Parties on its Seventh Session, Held at Marrakech from 29 October to 10 November 2001. Addendum. Part Two: Action Taken by the Conference of the Parties. Volume I. Document FCCC/CP/2001/13/Add.1, UN Framework Convention on Climate Change (FCCC), Bonn, Germany, pp. 69. Available at: http://unfccc.int/resource/docs/cop7/13a01.pdf.

[5] Giles, J. (2002). When Doubt is a Sure Thing. *Nature*, **418**, 476–478.

[6] Gupta, J., X. Olsthoorn and E. Rotenberg (2003): The role of sciemtific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention. *Environmental Science & Policy*, **6**, 475–486.

[7] Gusti, M. and W. Jęda (2002). Carbon Management: A New Dimension of Future Carbon Research. Interim Report IR-02-006. International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 100. Available at: http://www.iiasa.ac.at/Publications/Documents/IR-02-006.pdf.

[8] IPCC (1997a,b,c). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 1: Greenhouse Gas Inventory Reporting Instructions; Volume 2: Greenhouse Gas Inventory Workbook; Volume 3: Greenhouse Gas Inventory Reference Manual.* Intergovernmental Panel on Climate Change (IPCC) Working Group I (WG I) Technical Support Unit, IPCC/OECD/IEA, Bracknell, United Kingdom. Available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

[9] Jonas, M., S. Nilsson, M. Obersteiner, M. Gluck and Y. Ermoliev (1999). Verification Times Underlying the Kyoto Protocol: Global Benchmark Calculations. Interim Report IR-99-062. International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 43. Available at: http://www.iiasa.ac.at/Publications/Documents/IR-99-062.pdf.

[10] Jonas, M. and S. Nilsson (2001). The Austrian Carbon Database (ACDb) Study — Overview. Interim Report IR-01-064. International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 131. Available at: http://www.iiasa.ac.at/Research/FOR/acdb.html.

[11] Jonas, M., S. Nilsson, R. Bun *et al.* (2004a). Preparatory Signal Detection for Annex I Countries under the Kyoto Protocol – A Lesson for the Post-Kyoto Policy Process. Interim Report, IR-04-024, International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 91. Available at: http://www.iiasa.ac.at/Publications/Documents/IR-04-024.pdf.

[12] Jonas, M., S. Nilsson, R. Bun *et al.* (2004b). Preparatory Signal Detection for the EU Member States under the EU Burden Sharing – Advanced Monitoring Including Uncertainty (1990–2001). Interim Report, IR-04-029, International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 29. Available at: http://www.iiasa.ac.at/Publications/Documents/IR-04-029.pdf.

[13] Jonas, M., S. Nilsson, R. Bun *et al.* (2004c). Preparatory Signal Detection for the EU Member States under the EU Burden Sharing – Advanced Monitoring Including Uncertainty (1990–2002). Interim Report, IR-04-046, International Institute for Applied Systems Analysis, Laxenburg, Austria. Available at: http://www.iiasa.ac.at/Publications/Documents/IR-04-046.

[14] Jonas, M., S. Nilsson, R. Bun, V. Dachuk, M. Gusti, J. Horabik, W. Jęda and Z. Nahorski (2004d). Preparatory Signal Detection for Annex I Countries under the Kyoto Protocol. In: *COST Action 627: Carbon Storage in European Grasslands.* Joint Meeting of Working Groups 1, 2, 3 and 4, 3–6 June, Abstracts, Ghent, Belgium, 45.

[15] Merriam-Webster (1973). *Webster's New Collegiate Dictionary.* G. & C. Merriam Company, Springfield, MA, USA, pp. 1536.

[16] Merriam-Webster (1997). *Merriam Webster's Collegiate Dictionary.* Merriam-Webster, Incorporated, Springfield, MA, USA, pp. 1559.

[17] Moss, R.H. and S.H. Schneider (2000). Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: R. Pachauri, T. Taniguchi and K. Tanaka (eds.) *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC.* Intergovernmental Panel on Climate Change (IPCC), c/o World Meteorological Organization, Geneva, Switzerland, 33–51. Available at: http://www.ipcc.ch/pub/xcutting.pdf.

[18] Noble, I., M. Apps, R. Houghton, D. Lashof, W. Makundi, D. Murdiyarso, B. Murray, W. Sombroek and R. Valentini (2000). Implications of Different Definitions and Generic Issues. In R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken (eds) *Land Use, Land-Use Change, and Forestry,* Cambridge University Press, Cambridge, United Kingdom, 53–126. Available at: http://www.grida.no/climate/ipcc/land_use/.

[19] Penman, J., D. Kruger, I. Galbally, T. Hiraishi, B. Nyenzi, S. Emmanuel, L. Buendia, R. Hoppaus, T. Martinsen, J. Meijer, K. Miwa, and K. Tanabe (eds.) (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan. Available at: http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

Figures, Boxes and Tables

Box 1: Dual-constrained verification and signal detection. Source: [11: Box 1]; modified.

Table 1: Relative uncertainty classes applied in the Austrian Carbon Database (ACDb) project. Source: [10: Tab. 4].

Table 2: The Und concept (Equation (5) in combination with Equation (4a)) applied to Annex I countries committed to emission reduction ($\delta_{KP} > 0$).[13] The table lists the modified reduction targets δ_{mod} for these countries, where the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5. The maximal allowable VTs (equal to commitment year/period minus base year) are also reported for these countries. Source: [11: Tab. B1]; modified.

Table 3: The Und&VT concept (Equation (5) in combination with Equation (8a)) applied to Annex I countries committed to emission reduction ($\delta_{KP} > 0$).[13] The table lists the modified reduction targets δ_{mod} for these countries, where the "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5 ($\delta_{crit} > \delta_{KP}$).[14] The maximal allowable VTs (equal to commitment year/period minus base year) as well as the critical (detectable) emission reduction targets δ_{crit} are also reported for these countries. Source: [11: Tab. D4]; modified.

Figure 1:

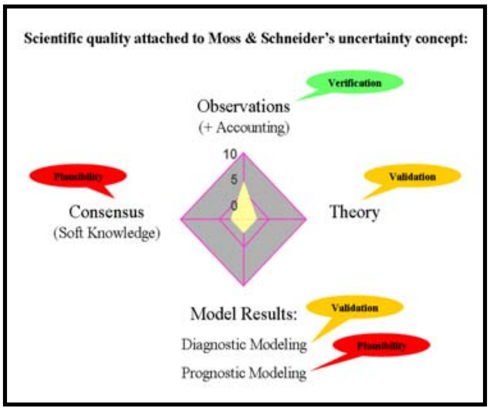


Figure 2:

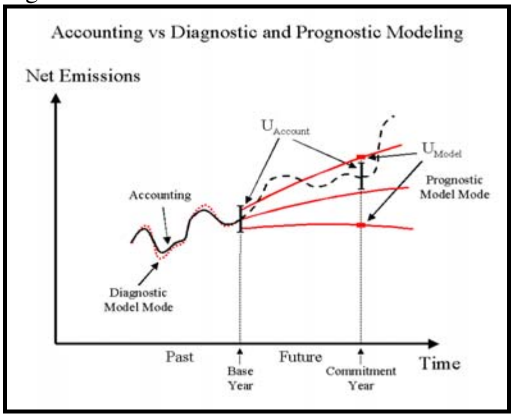


Figure 3:

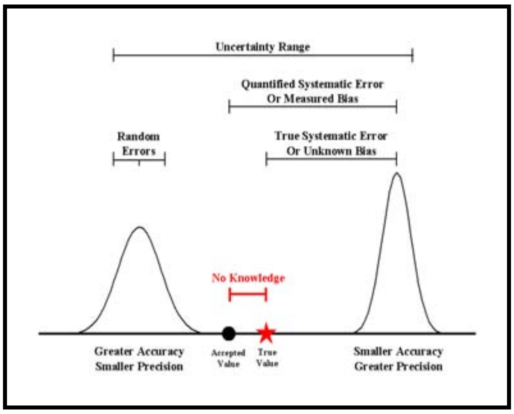


Figure 4:

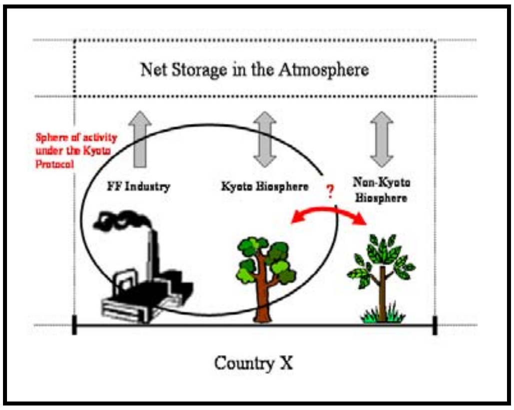


Figure 5:

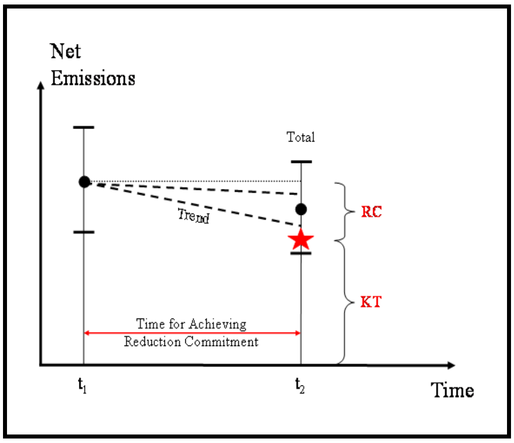


Figure 6:

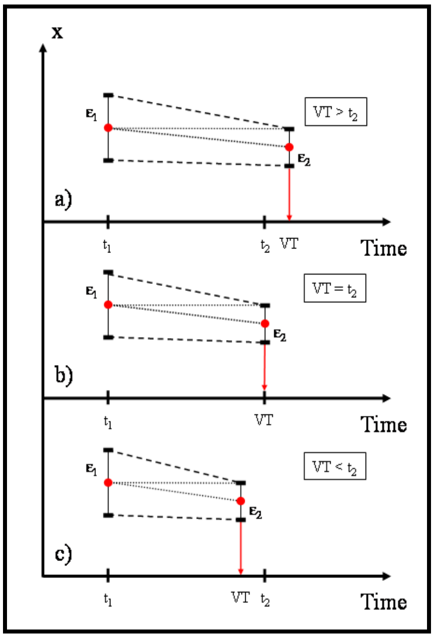


Figure 7:

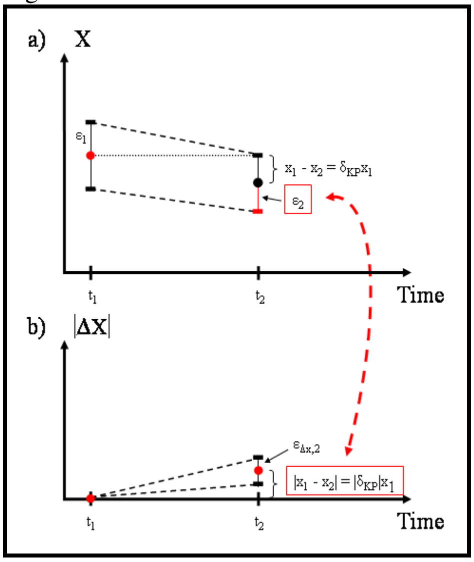


Figure 8:

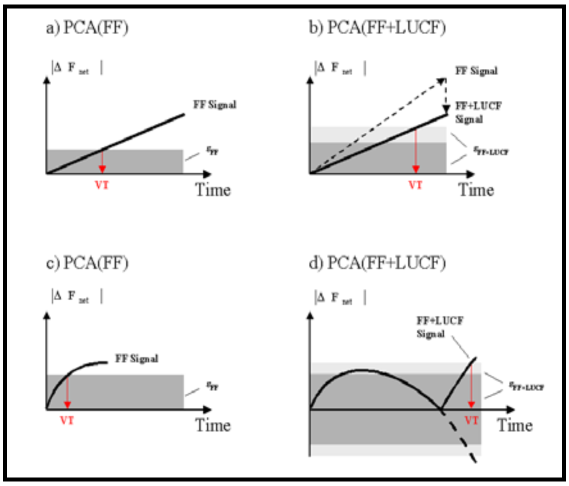


Figure 9:

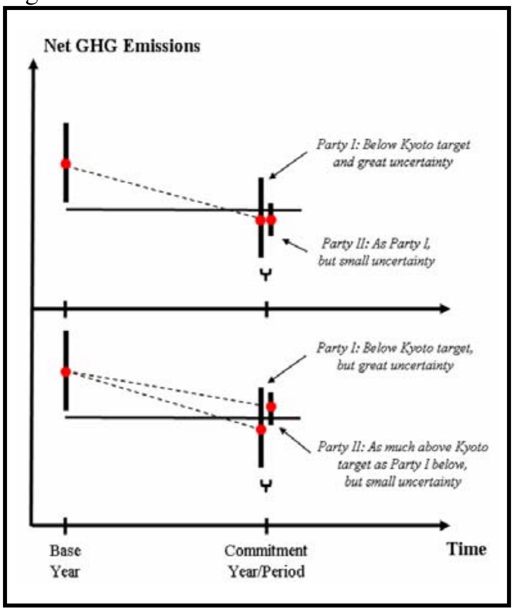


Figure 10:

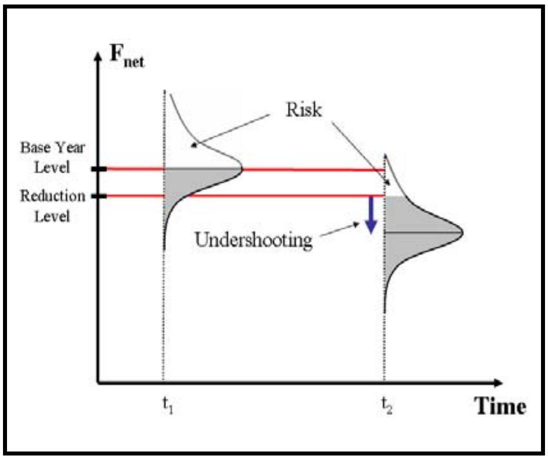
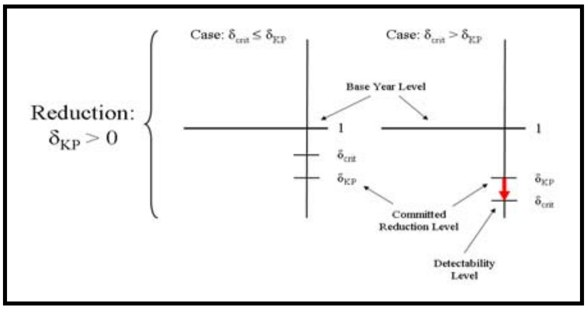
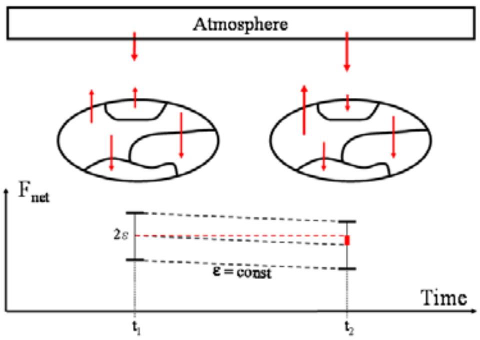


Figure 11:



Box 1:

Dual-Constrained Verification and Signal Detection:



Assume that we were able to repeatedly carry out dual constrained FCA for some terrestrial region at times t_1 and t_2 (appropriately averaged in space and time). Assume further that our bottom-up full carbon account would be higher resolved than our top-down full carbon account. Nevertheless, both the bottom-up and the top-down full carbon account would exhibit "reasonable" agreement, meaning that their mean atmospheric net fluxes would be sufficiently close and could be characterized by a combined uncertainty, which would be "acceptable".
However, although we would work bottom-up/top-down, i.e., apply dual-constrained FCA, we could still encounter potential difficulties, as the graph at the bottom of the figure shows. Here, for example, the change in the net emissions at t_2 disappears within the constant-width uncertainty band. What must be kept in mind is that our bottom-up/top-down FCA technique refers to net atmospheric emissions and their uncertainties, but we need more than this when explicitly considering time and asking when the emission signal is outstripping uncertainty. To handle such situations, we have to additionally utilize signal detection techniques complementing bottom-up/top-down verification.

Table 1:

Class	**Relative Uncertainty [%]**
	0 – 5
2	5 – 10
3	10 – 20
4	20 – 40
5	> 40

Table 2:

Country Group	**Max. Allow. VT** $t_2 - t_1$ **yr**	**KP Commit.** δ_{KP} **%**	**Modified Emission Limitation or Reduction Targets δ_{mod} in % for ρ =** **2.5** **%**	 **7.5** **%**	 **15** **%**	 **30** **%**
			and			
			$\alpha = 0.0$ $\alpha = 0.1$ $\alpha = 0.3$ $\alpha = 0.5$	$\alpha = 0.0$ $\alpha = 0.1$ $\alpha = 0.3$ $\alpha = 0.5$	$\alpha = 0.0$ $\alpha = 0.1$ $\alpha = 0.3$ $\alpha = 0.5$	$\alpha = 0.0$ $\alpha = 0.1$ $\alpha = 0.3$ $\alpha = 0.5$
1a **1b** **1c** **1d**	20 22 21 24	8.0	12.5 11.6 9.8 8.0	20.8 18.4 13.4 8.0	32.0 27.7 **18.4** 8.0	50.5 43.6 27.7 8.0
2	20	7.0	11.5 10.6 8.8 7.0	20.0 17.5 12.4 7.0	31.3 26.9 **17.5** 7.0	49.9 43.0 26.9 7.0
3a **3b** **3c**	20 24 22	6.0	10.6 9.7 7.9 6.0	19.1 16.6 11.5 6.0	30.5 26.1 **16.6** 6.0	49.4 42.4 26.1 6.0
4	20	5.0	9.6 8.7 6.9 5.0	18.3 15.8 10.5 5.0	29.8 25.4 **15.8** 5.0	48.8 41.8 25.4 5.0
---	---	4.0	8.7 7.8 5.9 4.0	17.4 14.9 9.6 4.0	29.0 24.6 **14.9** 4.0	48.3 41.2 24.6 4.0
---	---	3.0	7.7 6.8 4.9 3.0	16.5 14.0 8.7 3.0	28.3 23.8 **14.0** 3.0	47.8 40.5 23.8 3.0
---	---	2.0	6.8 5.8 3.9 2.0	15.7 13.1 7.7 2.0	27.6 23.0 **13.1** 2.0	47.2 39.9 23.0 2.0
---	---	1.0	5.8 4.9 3.0 1.0	14.8 12.2 6.8 1.0	26.8 22.2 **12.2** 1.0	46.7 39.3 22.2 1.0

Table 3:

Country Group	Max. Allow. VT[a)] $t_2 - t_1$ yr	KP Com. δ_{KP} [b)] %	Crit. Targ. δ_{crit} % for ρ = 2.5% 7.5% 15% 30%	Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ = 2.5 % and $a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	7.5 % $a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	15 % $a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	30 % $a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$
1a	20	8.0	2.4	10.2	14.4	24.4	40.8
1b	22		7.0	9.8	13.2	22.4	38.0
1c	21		**13.0**	8.9	10.7	18.0	31.3
1d	24		23.1	8.0	8.0	**13.0**	23.1
2	20	7.0	2.4	9.3	13.5	24.4	40.8
			7.0	8.8	12.3	22.4	38.0
			13.0	7.9	9.7	18.0	31.3
			23.1	7.0	7.0	13.0	23.1
3a	20	6.0	2.4	8.3	13.5	24.4	40.8
3b	24		7.0	7.8	12.2	22.4	38.0
3c	22		13.0	6.9	9.7	18.0	31.3
			23.1	6.0	7.0	13.0	23.1
4	20	5.0	2.4	7.3	13.5	24.4	40.8
			7.0	6.9	12.2	22.4	38.0
			13.0	5.9	9.7	18.0	31.3
			23.1	5.0	7.0	13.0	23.1
---	---	4.0	2.4	6.3	13.5	24.4	40.8
			7.0	5.9	12.2	22.4	38.0
			13.0	5.0	9.7	18.0	31.3
			23.1	4.0	7.0	13.0	23.1
---	---	3.0	2.4	5.4	13.5	24.4	40.8
			7.0	4.9	12.2	22.4	38.0
			13.0	4.0	9.7	18.0	31.3
			23.1	3.0	7.0	13.0	23.1
---	---	2.0	2.4	4.8	13.5	24.4	40.8
			7.0	4.4	12.2	22.4	38.0
			13.0	3.4	9.7	18.0	31.3
			23.1	2.4	7.0	13.0	23.1
---	---	1.0	2.4	4.8	13.5	24.4	40.8
			7.0	4.4	12.2	22.4	38.0
			13.0	3.4	9.7	18.0	31.3
			23.1	2.4	7.0	13.0	23.1

[1] It is noted that in the context of the Kyoto Protocol the term certification is also used, in particular by policy makers. It is specified as [16]:

Certification [from *certus* = certain] → certify: to attest authoritatively; to attest as meeting a standard.

[2] The increasing width of our relative uncertainty classes and our classification of relative uncertainties as unreliable beyond class 3 is in agreement with the IPCC [8a], which advises against the application of the law of uncertainty propagation if the relative uncertainties that are combined under this law are greater than 60% (95% confidence level).

[3] The country scale is the principal reporting unit requested for reporting GHG emissions and removals under the Kyoto Protocol [1].

[4] Articles 3.3 and 3.4 of the Protocol stipulate that human activities related to land-use change and forestry (LUCF) since 1990 can also be used to meet 2008–2012 commitments [1]. The part of the terrestrial biosphere, which is affected by these Kyoto compliant LUCF activities, is hereafter referred to as *Kyoto biosphere* and its complement as *non-Kyoto biosphere*.

[5] In the figures of our paper, we denote net emissions (if not *expressis verbis*) by F and x, and their changes by ΔF and Δx, respectively.

[6] See [1: Article 5; 2: Annex to Draft decision -/CMP.1; 3: Draft decision -/CMP.1; 4: Decision 11/CP.7].

[7] The total (or level) uncertainty reflects our real diagnostic (accounting) capabilities, that is, the uncertainty that underlies our past as well as our current observations (accounts) and that we will have to cope with in reality at some time in the future (e.g., commitment year). The trend uncertainty reflects the uncertainty of the difference in net emissions between two years.

[8] In the commitment year/period t_2 we ask, in accordance with the concept of bottom up–top down verification, for the total uncertainty at that point in time, not whether or not the total uncertainty at t_2 can be decreased, e.g., on the basis of correlative techniques (i.e., our emission and uncertainty knowledge at t_1, the base year).

[9] The term "verification time" was first used by [9] and by other authors since then. Actually, a more correct term is "detection time" as signal detection does not imply verification. However, we continue to use the original term as we do not consider it inappropriate given that signal detection must, in the long-term, go hand-in-hand with bottom up–top down verification.

[10] For data availability reasons and because of the excellent possibility of inter-country comparisons, the Protocol's Annex I countries are used as net emitters. Their emissions/removals due to LUCF are excluded as the reporting of their uncertainties is only soon becoming standard practice.

[11] The Und concept does not consider any correlation between the uncertainty in the base year (ε_1) and the uncertainty in the commitment year/period (ε_2) as it makes use of the triangle inequality, which does not permit doing so.

[12] The Und&VT concept only considers the uncertainty in the commitment year/period (ε_2).

[13] The country groups referred to in Tables 2 and 3 are: **1a:** AT, BE, CH, CZ, DE, DK, EC, EE, ES, FI, FR, GR, IE, IT, LI, LT, LU, LV, MC, NL, PT, SE, SK, UK; **1b:** BG; **1c:** RO; **1d:** SI; **2:** US; **3a:** CA, JP; **3b:** HU; **3c:** PL; **4:** HR. See [11: ISO Country Code] for country abbreviations.

[14] Green-colored fields: $\delta_{crit} \leq \delta_{KP}$. Here, the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk (also termed) α applies.