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COMPARISON OF PREPARATORY SIGNAL ANALYSIS TECHNIQUES FOR CONSIDERATION IN THE (POST-)KYOTO POLICY PROCESS

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Comparison of Preparatory Signal Analysis Techniques for Consideration in the (Post-) Kyoto Policy Process

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Abstract

Our study is a preparatory exercise. We focus on the analysis of uncertainty in greenhouse gas emission inventories. Inventory uncertainty is monitored, but not regulated, under the Kyoto Protocol. For most countries under the Protocol the agreed emission changes are of the same order of magnitude as the uncertainty that underlies their combined (carbon dioxide—CO_2 equivalent) emissions estimates. We compare six available techniques to analyze the uncertainty in the emission changes that countries agreed to realize by a specified point in time. Any such technique, if implemented, could 'make or break' claims of compliance, especially in cases where countries claim fulfillment of their commitments to reduce or limit emissions. The techniques all perform differently and can thus have a different impact on the design and execution of emission control policies. A thorough comparison of the techniques has not yet been made but is urgently needed to expand the discussion on how to go about dealing with uncertainty under the Kyoto Protocol and its successor.

1. Introduction

The focus of our study is on the analysis of uncertainty in greenhouse gas (GHG) emission inventories. Inventory uncertainty is monitored, but not regulated, under the Kyoto Protocol (KP). The aim of our study is to provide a preparatory guide for dealing with uncertainty in the (post-) Kyoto policy process. We compare available techniques to analyze uncertain emission changes (also called emission signals) that countries agreed to realize by a specified point in time (commitment year/period). A thorough comparison of the techniques has not yet been made available. Even worse: although highly needed, techniques to analyze uncertain emission signals from various points of view, ranging from signal quality (defined adjustments, statistical significance, detectability, etc.) to the way uncertainty is addressed (trend uncertainty or total uncertainty) are not in place. For most Parties to the Protocol (Annex B countries) the agreed emission changes are of the same order of magnitude as the uncertainty that underlies their combined (CO_2-equivalent) emissions estimates (see Table 1). Any such technique, if implemented, could 'make or break' claims of compliance, especially in cases when countries claim fulfillment of their commitments to reduce or limit emissions.

Moreover, as demonstrated by Jonas *et al.* (2004b, c), Bun and Jonas (2006), and Hamal and Jonas (2008a, b), these techniques could also be used to serve monitoring purposes. Emission changes since 1990 (base year of most Annex B countries) that are reported annually can be evaluated in an emissions change-versus-uncertainty context rather than an emissions change-only context. This advanced monitoring service is also not provided under the Protocol.[1]

Jonas *et al.* (2004a) distinguish between preparatory signal analysis, midway signal analysis, and signal analysis in retrospect. Preparatory signal analysis is most advanced. It allows generating useful information beforehand as to how great uncertainties can be depending on the level of confidence of the emission signal, or the signal one wishes to detect, and the risk one is willing to tolerate in not meeting an agreed emission limitation or reduction commitment. We are aware of at least six different preparatory signal analysis techniques, some of which have been presented at the 1st International Workshop on Uncertainty in GHG Inventories (Gillenwater *et al.*, 2007; Jonas and Nilsson, 2007; Nahorski *et al.*, 2007). These techniques need to be scrutinized further, now in a comparative mode, before a discussion on which of them to select can take place. These techniques all agree that uncertainty analysis is a key component of GHG emission analysis. However, they all perform differently and thus can have a different impact on the design and execution of emission control policies. Going through this comparative exercise and making this knowledge available is a legacy of the 1st International Workshop on Uncertainty in GHG Inventories held 2004 in Warsaw, Poland. This exercise is required prior to advancing the discussion on how to go about dealing with uncertainty under the Kyoto Protocol and its successor.

This comparison is technical by nature. We provide necessary definitions and agreements in Section 2 and an overview of the techniques in Section 3. In Section 4 we describe each technique in a standardized fashion. However, mathematical details to and numerical results for all techniques are available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.[2] We summarize our findings in Section 5.

2. Definitions and Agreements

Spatial focus: Annex B countries to the Kyoto Protocol (FCCC, 1998).

Temporal focus: Base year (t_1)—commitment year/period (t_2); we use the year 2010 as commitment year with t_2 referring to the temporal average in net emissions over the commitment period 2008–2012.

Thematic focus: Emissions and/or removals of the six Kyoto GHGs, individually or combined (FCCC, 1998: Annex A).

Grouping of countries: For convenience, the Protocol's Annex B countries are grouped according to their (i) emission limitation or reduction commitments, and (ii) base years (see left side of Table 1).

Table 1

Uncertainty (inventory definition): A general and imprecise term which refers to the lack of certainty (in inventory components) resulting from any causal factor such as unidentified sources and sinks, lack of transparency, etc. (Penman *et al.*, 2000: A3.19).

Total and trend uncertainty: The total (or level) uncertainty reflects our real diagnostic emissions accounting capabilities, that is, the uncertainty that underlies our past (base year) as well as our current accounting and that we will have to cope with in reality at some time in the future (commitment year/period). The trend uncertainty reflects the uncertainty of the difference in net emissions between two years (base year and/or commitment year/period) (Jonas and Nilsson, 2007: Section 4).

Confidence interval: The true value of the quantity for which the interval is to be estimated is a fixed but unknown constant, such as the annual total emissions in a given year for a given country. The confidence interval (CI) is a range that encloses the true value of this unknown fixed quantity with a specified confidence (probability). Typically, a CI of 95% is used in GHG inventories (IPCC, 2006: Section 3.1.3).

Relative uncertainty (of inventory sources and sinks): To make all preparatory signal analysis techniques easily applicable, we build on relevant findings of earlier studies which suggest resolving relative uncertainty of inventory sources and sinks only in terms of intervals or classes and referring to their medians. Our definition of relative uncertainty classes (Class 1: 0–5%; Class 2: 5–10%; Class 3: 10–20%; Class 4: 20–40%; and Class 5: >40%) is arbitrary but appears robust. For further details we refer the reader to Jonas and Nilsson (2007: Section 2.4).

3. Overview of the Techniques and Their Characteristics

Table 2

Table 2 summarizes the major characteristics of the six preparatory signal analysis techniques that we discuss and compare in Section 4. These are (1) the critical relative uncertainty (CRU) concept; (2) the verification time (VT) concept; (3) the undershooting (Und) concept; (4) the undershooting and VT (Und&VT) concepts combined; (5) the adjustment of emissions (Gillenwater, Sussman and Cohen—GSC #1) concept; and (6) the adjustment of emission reductions (Gillenwater, Sussman and Cohen—GSC #2) concept. The techniques' individual characteristics are also explained in Section 4.

4. Preparatory Signal Analysis Techniques

4.1 CRU Concept

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.

Assumptions: (1) The relative uncertainty (ρ) of a country's net emissions (x) shall be symmetrical and not change over time, i.e., $r_1 = r_2 (= r)$.[4]

(2) The absolute change in net emissions shall outstrip absolute uncertainty (ε) at t_2, i.e., $|x_1 - x_2| > e_2$.

Systems View: Intra-systems view suited to support inter-systems (top-down) view: Only our real diagnostic capabilities of grasping emissions at any point in time individually—reflected by absolute uncertainty $\varepsilon(t)$ —are of interest. Correlation of uncertainty over time does not matter.

Question: What are the critical (or maximal) relative uncertainties (CRUs) that can be reported by Annex B countries to ensure favorable detection in the commitment year?

gure 1

Approach: Deterministic (see Figure 1, and Appendix A of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Answer: The answer is given by (see Appendix A of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html)

$$r_{crit} := \frac{|d_{KP}|}{(1 - d_{KP})}, \qquad \text{(A-6)}$$

where ρ_{crit} is the CRU and d_{KP} the normalized emissions change committed under the Kyoto Protocol between t_1 and t_2 ($d_{KP} > 0$: emission reduction; d_{KP} Ł 0: emission limitation).

Result: For the numerical result see Table A-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Table A-1 lists d_{KP} and ρ_{crit} for all Annex B countries under the Kyoto Protocol. A country of group 1, e.g., has committed itself to reduce its net emissions by 8% (2nd column). In the case of compliance and under the condition of constant relative uncertainty, the country's net emissions in the commitment year (t_2) only satisfy this concept favorably if they are reported with a relative uncertainty smaller than 8.7% (3rd column). With reference to the 2005 total uncertainty estimates that are available so far from EU Member States for all Kyoto gases—these countries exhibit relative uncertainties in the range of 5–10% and above rather than below (excluding land use, land-use change, and forestry (LULUCF) and Kyoto mechanisms; see EEA 2007: Table 1.13)—it can be stated that this value appears difficult to achieve for quite a few, especially data poor, Annex B countries.

The CRU concept exhibits a dissimilarity between emission limitation ($d_{KP} < 0$) and reduction ($d_{KP} > 0$). In the case of increasingly stricter Kyoto emission targets, Annex B countries committed to emission limitation must decrease their uncertainties according to this concept; their CRUs decrease (d_{KP} decreases). In contrast, countries committed to emission reduction do not need to do so; their uncertainties can even increase because their CRUs also increase and can be met more easily (d_{KP} increases). The opposite is true in the case of increasingly more lenient Kyoto emission targets. Annex B countries committed to emission reduction must decrease their uncertainties in order to satisfy decreasing CRUs (d_{KP} decreases), while countries committed to emission limitation can even increase their uncertainties because their CRUs also increase and can be met more easily (d_{KP} increases).

According to this concept the stabilized emissions case ($d_{KP} = 0$) should not be allowed—it presupposes zero uncertainty—unless it is ascertained beforehand that relative uncertainties are, or can be expected to be, at least small.

4.2 VT Concept

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.

Assumptions: (1) The relative uncertainty (ρ) of a country's net emissions (x) shall be symmetrical and not change over time, i.e., $r_1 = r_2 (= r)$.

(2) The absolute change in net emissions shall outstrip uncertainty at time t (which can be $\leq$ or $>$ t_2), i.e., $|\Delta x(t)| > \varepsilon(t)$.

Systems View: Intra-systems view suited to support inter-systems (top-down) view: Only our real diagnostic capabilities of grasping emissions at any point in time individually—reflected by absolute uncertainty $\varepsilon(t)$—are of interest. Correlation of uncertainty over time does not matter.

Question: What are the times (also called verification times; VTs) when the countries' emission signals outstrip uncertainty?[6]

Approach: Deterministic (see Figure 2 and Appendix B of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Figure 2

Answer: The answer is given by

$$\frac{\Delta t}{t_2 - t_1} > \frac{r}{|d_{KP}| + d_{KP} r}, \qquad \text{(B-7a)}$$

where Δt is the VT and $t_2 - t_1$ the time between base year and commitment year/period, upon which the VT is normalized.

Result: For the numerical result see Table B-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Table B-1 lists normalized VTs for all Annex B countries under the Kyoto Protocol. The VT concept provides a more detailed detection perspective for negotiators of the Protocol than the CRU concept presented in Section 4.1. It quantifies in detail what the consequences are in the form of normalized VTs if countries report emissions with relative uncertainties that are ≤ or > ρ_{crit}.

Moreover, the VT concept corroborates the dissimilarity between emission limitation and reduction, which has already been found for the CRU concept and which is a direct consequence of not demanding a uniform d_{KP} for all countries under the Protocol. While both the VT concept and the CRU concept favor stricter over more lenient Kyoto emission targets in the case of emission reduction ($d_{KP} > 0$), this is not so in the case of emission limitation ($d_{KP} < 0$): the two concepts favor more lenient over stricter Kyoto emission targets, which is not in line with the spirit of the Kyoto Protocol.

4.3 Und Concept

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.

Assumptions: (1) Uncertainties at t_1 and t_2 are given in the form of intervals, which take into account that a difference (ε) might exist between the true (t) but unknown net emissions (x_t) and their best estimates (x).

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $r_1 = r_2 (= r)$.

Systems View: Intra-systems view: Correlation of uncertainty over time matters.

Question: Taking into account the combined uncertainty at t_2 and considering that the true emissions are not known, how much undershooting (Und) is required to limit the risk α that countries overshoot their true emission limitation or reduction commitments?

Approach: Quasi-statistical, based on interval calculus (see Figure 3 and Appendix C of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Figure 3

Answer: The answer is given by

$x_{t,2} \leq (1 - d_{KP})x_{t,1}$ with risk α ⇔

$$\frac{x_2}{x_1} \leq (1 - d_{KP})\frac{1 - (1 - 2a)(1 - n)r}{1 + (1 - 2a)(1 - n)r} = 1 - d_{mod}, \qquad \text{(C-13a,c)}$$

where v approximates (first-order approach) the net (effective) correlation between ε_1 and ε_2; and d_{mod} is the countries' modified (mod) emission limitation or reduction targets defined via

$$d_{mod} = d_{KP} + U \tag{C-15}$$

and the undershooting U via

$$U = 2(1 - d_{KP})\frac{(1 - 2a)(1 - n)r}{1 + (1 - 2a)(1 - n)r} \ . \tag{C-18}$$

Result: For the numerical result see Table C-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Table C-1 lists d_{mod} values as a result of applying Equation C-15 in combination with Equation C-18. δ_{KP}, ρ and α are treated as parameters, while the correlation v is 0.75 (typical for currently reported uncertainties; see EEA 2007: Table 1.13).[7] The table shows that the Und concept is difficult to justify politically in the context of the Kyoto Protocol. Under the Protocol, nonuniform emission limitation or reduction commitments (see d_{KP} values in the second 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 d_{KP} while keeping the relative uncertainty ρ and the risk α constant exhibits that Annex B countries that must comply with a smaller d_{KP} (they exhibit a small d_{mod}) are better off than countries that must comply with a greater d_{KP} (they exhibit a great d_{mod}). (See, e.g., d_{mod} values for ρ = 7.5% and α = 0.3.) The choice of δ_{KP} dominates Equation C-15, while the influence of δ_{KP} on U (see Equation C-18) is negligible and does not compensate for agreed deviations in the δ_{KP} values. Such a situation is not in line with the spirit of the Kyoto Protocol.

This situation would be different if the nonuniformity of the emission limitation or reduction commitments is the outcome of a rigorously based process resulting in a straightforward rule that applies equally to all countries, as it would be the case, for instance, under the widely discussed contraction and convergence (C&C) approach (e.g., WBGU, 2003: Section 2.3; Pearce, 2003). Under such conditions, it would be the undershooting U that matters, not the modified emission limitation or reduction target d_{mod}.

4.4 Und&VT Concepts Combined

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.

Assumptions: (1) Uncertainties at t_1 and t_2 are given in the form of intervals, which take into account that a difference (ε) might exist between the true (t) but unknown net emissions (x_t) and their best estimates (x).

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $r_1 = r_2 (= r)$.[8]

(3) The absolute change in net emissions shall outstrip uncertainty at time $t \leq t_2$, i.e., the VT shall be equal to, or smaller than, the maximal allowable VT ($\Delta t \leq t_2 - t_1$).

Systems View: Intra-systems view suited to support inter-systems (top-down) view: Only our real diagnostic capabilities of grasping emissions at any point in time individually—reflected by absolute uncertainty $\varepsilon(t)$ —are of interest. Correlation of uncertainty over time does not matter.

Question: Referring to risk as the strength of the Und concept and to time in detecting an emission signal as the strength of the VT concept, can these concepts be combined (Und&VT) to take advantage of the two?

Figure 4

Approach: Quasi-statistical, based on interval calculus (see Figure 4 and Appendix D of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Answer: The answer comprises four cases depending on how δ_{crit}, the critical emission limitation or reduction, and δ_{KP} relate to each other (see Figure 4). δ_{crit} allows distinguishing between detectable and nondetectable emission changes.[9] The complete answer is given by

Case 1: $\delta_{KP} > 0$: $\delta_{crit} \leq \delta_{KP}$:

$x_{t,2} \leq (1- d_{KP})x_{t,1}$ with risk α ⇔

$$\frac{x_2}{x_1} \leq (1- d_{KP})\frac{1}{1+(1- 2a)r} = 1- d_{mod}\,, \qquad \text{(D-3), (C-13c)}$$

where d_{mod} is defined as before (see Equation C-15) and U via

$$U = (1- d_{KP})\frac{(1- 2a)r}{1+(1- 2a)r}\,. \qquad \text{(D-5)}$$

Case 2: $\delta_{KP} > 0$: $\delta_{crit} > \delta_{KP}$:

$x_{t,2} \leq (1- d_{crit})x_{t,1}$ with risk α ⇔

$$\frac{x_2}{x_1}\,\text{Ł}\,\left(1-d_{\text{crit}}\right)\frac{1}{1+\left(1-2a\right)r}=1-d_{\text{mod}}\ , \qquad \text{(D-6), (C-13c)}$$

where d_{mod} is defined as before (see Equation C-15) and U via

$$U=U_{\text{Gap}}+\left(1-d_{\text{crit}}\right)\frac{\left(1-2a\right)r}{1+\left(1-2a\right)r}\ . \qquad \text{(D-8)}$$

$$U_{\text{Gap}}=d_{\text{crit}}-d_{\text{KP}}\ . \qquad \text{(D-9)}$$

Case 3: $\delta_{KP} \leq 0$: $\delta_{crit} < \delta_{KP}$:

$x_{t,2}\ \text{ł}\ \left(1+d_{\text{crit}}\right)x_{t,1}$ with risk α ⇔

$$\frac{x_2}{x_1}\,\text{Ł}\,\left(1+d_{\text{crit}}\right)\frac{1}{1+\left(1-2a\right)r}=1-d_{\text{mod}}\ , \qquad \text{(D-10), (C-13c)}$$

where d_{mod} is defined as before (see Equation C-15) and U via

$$U=U_{\text{Gap}}+\left(1+d_{\text{crit}}\right)\frac{\left(1-2a\right)r}{1+\left(1-2a\right)r} \qquad \text{(D-12)}$$

$$U_{\text{Gap}}=-\left(d_{\text{KP}}+d_{\text{crit}}\right)\ . \qquad \text{(D-13)}$$

Case 4: $\delta_{KP} \leq 0$: $\delta_{crit} \geq \delta_{KP}$:

$x_{t,2}\ \text{ł}\ \left(1+\tilde{d}_{\text{crit}}\right)x_{t,1}$ with risk α ⇔

$$\frac{x_2}{x_1}\,\text{Ł}\,\left(1+\tilde{d}_{\text{crit}}\right)\frac{1}{1+\left(1-2a\right)r}=1-d_{\text{mod}}\ , \qquad \text{(D-14), (C-13c)}$$

where d_{mod} is defined as before (see Equation C-15) and U via

$$U=U_{\text{Gap}}+\left(1+\tilde{d}_{\text{crit}}\right)\frac{\left(1-2a\right)r}{1+\left(1-2a\right)r} \qquad \text{(D-16)}$$

$$U_{\text{Gap}}=-2d_{\text{crit}} \qquad \text{(D-17)}$$

$$-\tilde{d}_{\text{crit}}=d_{\text{KP}}-2d_{\text{crit}}\ . \qquad \text{(D-18)}$$

U_{Gap} in Cases 2–4 is an initial obligatory undershooting, which is introduced to ensure that detectability is given before Annex B countries are permitted to make economic use of potential excess emission reductions.

Result: For the numerical result see Table D-3 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Table D-3 lists d_{mod} values as a result of applying Equation C-15 in combination with: Equation D-5 (Case 1), Equations D-8 to D-9 (Case 2), Equations D-12 to D-13 (Case 3), and Equations D-16 to D-18 (Case 4). δ_{KP}, ρ and α are treated as parameters. By employing a uniform detectability criterion, the Und&VT concept overcomes the dissimilarity of both the VT concept and the CRU concept between countries committed to emission reduction ($d_{KP} > 0$) and emission limitation (d_{KP} Ł 0), which arises if more lenient or stricter Kyoto emission targets are introduced (see Table A-1 and B-1).[10] However, this concept reveals a crucial difficulty from a political perspective. The Und&VT concept requires the Protocol's Kyoto emission targets to be corrected for nondetectability through the introduction of an initial obligatory undershooting (U_{Gap}) so that the countries' emission reductions, not limitations, 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., group 1 countries in Table D-3 ($\delta_{KP} = 8\%$) under Case 2 conditions: the d_{mod} value for $\rho = 15\%$ and $\alpha = 0.5$ is $d_{mod} = d_{KP} + U_{Gap} = 13\%$ ($U = U_{Gap}$); that is, the initial obligatory undershooting is $U_{Gap} = 13\% - 8\% = 5\%$.) It remains to be seen whether this strict interpretation of signal detection will be accepted by Annex B countries as it forces them to strive for detectability (i.e., to make initial investments before they can profit from their economic actions). Notwithstanding, opponents to this concept must realize that the countries' detectability, i.e.: the '$x_{t,2}$-greater-than-$(1 - d_{KP})x_{t,1}$' risk (Case 1), the '$x_{t,2}$-greater-than-$(1 - d_{crit})x_{t,1}$' risk (Case 2), the '$x_{t,2}$-greater-than-$(1 + d_{crit})x_{t,1}$' risk (Case 3), and the '$x_{t,2}$-greater-than-$(1 - (d_{KP} - 2d_{crit}))x_{t,1}$' risk (Case 4) of their emission signals can be grasped—and thus priced—although the countries' true net emissions at t_1 and t_2 are unknown!

4.5 GSC #1 Concept

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.[11]

Assumptions:

(1) It is accepted *a priori* that the true, but unknown, net emissions at t_2 ($x_{t,2}$) can exceed (overshoot) the target emissions commitment (x_2) by some fractional or percentage amount (p or p%, respectively).

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $r_1 = r_2 (= r)$.[12]

(3) The probability distributions for estimated emissions are normal and the shape of the emissions probability distribution for each country does not change significantly as emissions change.

Systems View: Intra-systems view suited to support inter-systems (top-down) view: Only our real diagnostic capabilities of grasping emissions at any point in time individually—reflected by absolute uncertainty $\varepsilon(t)$ —are of interest. Correlation of uncertainty over time does not matter.

Question: Can we attain a reasonable level of confidence that countries will have actually achieved the target emissions levels stated in their commitments under the Kyoto Protocol and are in compliance? That is: 1) Would we consider it acceptable if true emissions will exceed (overshoot) the target emissions commitment by some fractional or percentage amount? 2) How much is that amount? 3) How confident do we want to be in our result?

Figure 5

Approach: Statistical (see Figure 5 and Appendix E of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Answer: Depending on whether or not excess emissions are accepted and favorable compliance conditions exist *a priori*, the modified GSC #1 concept of Gillenwater *et al.* comprises three cases (see Figure 5). The complete answer is given by

Cases 1 and 2: $\delta_{KP} > 0$: $p = \delta_{crit}$:

$$\mathrm{Adj} = \begin{cases} 1 & \text{for} \quad 1 + z_{u,2}(F_N)\dfrac{\rho}{1.96} \le 1 + \rho_{crit} \\ & \quad\quad (\text{excess emissions accepted}) \\ \dfrac{1 + z_{u,2}(F_N)\dfrac{\rho}{1.96}}{1 + \rho_{crit}} & \quad\quad 1 + z_{u,2}(F_N)\dfrac{\rho}{1.96} > 1 + \rho_{crit} \\ & \quad\quad (\text{excess emissions accepted}) \end{cases} \qquad \text{(E-7,8)}$$

Case 3: $\delta_{KP} \le 0$: $p = 0$:

$$\mathrm{Adj} = 1 + z_{u,2}(F_N)\frac{\rho}{1.96} \qquad (\text{excess emissions not accepted}), \qquad \text{(E-9)}$$

where $\rho/1.96$ is the standard deviation, F_N the standardized cumulative normal distribution, $z_{u,2}$ the standardized accepted upper (u) emissions limit at t_2, and ρ_{crit} the CRU introduced in Appendix A of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Result: For the numerical result see Table E-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Table E-1 lists adjustment (Adj) values as a result of applying Equation E-7 (Case 1), Equation E-8 (Case 2) and Equation E-9 (Case 3). ρ is treated as parameter as well as the confidence F_N or $(1-\alpha)$ that true emissions do not exceed (overshoot) target emissions by more than $p=\delta_{crit}$ (Cases 1 and 2) and $p=0$ (Case 3); $(1-\alpha)$ is specified to be 0.9, 0.7 and 0.5. The table shows that the GSC #1 concept is not easy to handle politically in the context of the Kyoto Protocol. Emission reduction $(\delta_{KP}>0)$ under the GSC #1 concept behaves mirror-inverted to the Und concept as a consequence of nonuniform emission reduction commitments: Varying d_{KP} while keeping the relative uncertainty ρ and the confidence $(1-\alpha)$ constant exhibits that Annex B countries that must comply with a great d_{KP} (they exhibit a small Adj) are better off than countries that must comply with a small d_{KP} (they exhibit a great Adj). (See, e.g., Adj values for $\rho=15\%$ and $1-\alpha=0.9$.) However, this is only true if adjustments must be compensated for by additional emission reductions (undershooting mode) and are not misused by policy and decision-makers to only establish a country comparison in terms of confidence (confidence mode). Then countries that must comply with a small d_{KP} (they exhibit a great Adj) are better off than countries that must comply with a great d_{KP} (they exhibit a small Adj). This situation would not be in line with the spirit of the Kyoto Protocol.

4.6 GSC #2 Concept

Starting Point: Annex B countries comply with their emission limitation or reduction commitments under the Kyoto Protocol.[11]

Assumptions: (1) It is accepted *a priori* that true emission reductions (increases) fall below (above) the committed level of reductions (increases) by some fractional or percentage amount (p or p%, respectively).

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $r_1 = r_2 (= r)$.

(3) The probability distributions for estimated emissions and emission changes are normal and the shape of the emissions and emissions change probability distributions for each country do not change significantly as emissions change.

Systems View: Intra-systems view: Correlation of uncertainty over time matters.

Question: Can we attain a reasonable level of confidence that countries will have actually achieved the emission changes, measured relative to base-year emissions, stated in their commitments under the Kyoto Protocol and are in compliance? That is: 1) Would we consider it acceptable if true emission reductions (increases) will fall below (above) the committed level of reductions (increases) by some fractional or percentage amount?

2) How much is that amount? 3) How confident do we want to be in our result?

Approach: Statistical (see Figure 6 and Appendix F of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html).

Figure 6

Answer: Depending on whether or not diminished reductions (additional increases) are accepted and favorable compliance conditions exist *a priori*, the modified GSC #2 concept of Gillenwater *et al.* comprises four cases (see Figure 5). The complete answer is given by

Cases 1 and 2: $\delta_{KP} > 0$: $p = 0.1$:

$$\mathrm{Adj} = \begin{cases} 1 & \text{for } 2(1-\nu)\dfrac{z_{u,2}(F_N)\rho}{1.96\rho_{crit}} \le 0.1 \text{ diminished reduction accepted} \\[2ex] \dfrac{1-\left(1-2(1-\nu)\dfrac{z_{u,2}(F_N)\rho}{1.96\rho_{crit}}\right)\delta_{KP}}{1-0.9\delta_{KP}} & \text{for } 2(1-\nu)\dfrac{z_{u,2}(F_N)\rho}{1.96\rho_{crit}} > 0.1 \text{ diminished reduction accepted} \end{cases} \qquad \text{(F-7,8)}$$

Case 3: $\delta_{KP} = 0$: $p = 0$:

$$\mathrm{Adj} = 1 \qquad \begin{pmatrix}\text{additional increase} \\ \text{not accepted}\end{pmatrix} \qquad \text{(F-9)}$$

Case 4: $\delta_{KP} < 0$: $p = 0$:

$$\mathrm{Adj} = \frac{1-\left(1+2(1-\nu)\dfrac{z_{u,2}(F_N)\rho}{1.96\rho_{crit}}\right)\delta_{KP}}{1-\delta_{KP}} \qquad \begin{pmatrix}\text{additional increase} \\ \text{not accepted}\end{pmatrix}, \qquad \text{(F-10)}$$

where $\rho/1.96$ is the standard deviation, ν approximates (first-order approach) the net (effective) correlation between the absolute uncertainties ε_1 and ε_2, F_N is the standardized cumulative normal distribution, $z_{u,2}$ the standardized accepted smaller (upper) limit of reduction (increase) at t_2, and ρ_{crit} the CRU introduced in Appendix A of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Result: For the numerical result see Table F-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html.

Table F-1 lists Adj values as a result of applying Equation F-7 (Case 1), Equation F-8 (Case 2), and Equations F-9 and F-10 (Cases 3 and 4). δ_{KP}, ρ and ρ_{crit} are treated as parameters, as well as the confidence F_N or $(1-\alpha)$ that true emission reductions (increases) will not fall below (above) the committed level of reductions (increases) by more than $p = 0.1$ (Cases 1 and 2) and $p = 0$ (Cases 3 and 4); $(1-\alpha)$ is specified to be 0.9, 0.7 and 0.5. The correlation v is 0.75 (as in Appendix C of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html). The table shows that the GSC #2 concept is also not easy to handle politically in the context of the Kyoto Protocol. Emission reduction $(\delta_{KP} > 0)$ under the GSC #2 concept behaves, like under the GSC #1 concept, mirror-inverted to the Und concept as a consequence of nonuniform emission reduction commitments. That is, the GSC #2 concept would not run counter to the spirit of the Kyoto Protocol if applied in the undershooting mode (adjustments must be compensated for by additional emission reductions). But it must be mentioned that, for the given set of parameters (notably, $p = 0.1$ and $v = 0.75$), the span between smallest and greatest Adj values is negligible.

5. Conclusions

We have scrutinized six preparatory signal analysis techniques in a comparative mode. The purpose of this exercise is to provide a basis for discussing on how to go about dealing with uncertainty under the Kyoto Protocol and its successor, and which of the technique(s) to eventually select. The authors of these techniques all agree that uncertainty analysis is a key component of GHG emissions analysis although their perceptions range from using an investigation-focused approach to uncertainty analysis to only improve inventory quality to actually apply a technique, or a combination of techniques, to check compliance. As shown, all techniques perform differently (see Table 3) and can thus have a different impact on the design and execution of emissions control policies. However, what is more important is to realize that a single best technique cannot yet be identified (and will, most likely, not exist); the main reason for this being that the techniques suffer from shortfalls that are not scientific but are related to the way the Kyoto Protocol has been designed and implemented politically. As the two most important shortfalls on the side of policy-making can be identified (1) the overall neglect of uncertainty confronting experts with the situation that for most Annex B 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. The techniques manifest these shortfalls differently:

able 3

CRU and VT. These two concepts exhibit a dissimilarity between countries committed to emission reduction (stricter over more lenient Kyoto emission targets are favored) and emission limitation (more lenient over stricter Kyoto emission targets are favored).

Und and GSC #2. Varying d_{KP}, the normalized emissions change committed under the Kyoto Protocol, while keeping the relative uncertainty ρ and the risk α constant exhibits that under the Und concept countries that must comply with a small d_{KP} (they exhibit a small d_{mod}) are better off than countries that must comply with a great d_{KP} (they exhibit a great d_{mod}). Such a situation is not in line with the spirit of the Kyoto Protocol. Emission reduction under the GSC #2 concept avoids this situation if applied in the undershooting mode. Countries that must comply with a great d_{KP} (they exhibit a small Adj) are better off than countries that must comply with a small d_{KP} (they exhibit a g Adj). But it must be mentioned that, for the given set of parameters (notably, $\rho = 0.1$ and $v = 0.75$), the span between smallest and greatest Adj values is negligible. So far, emission reduction and emission limitation under the GSC #2 are not treated uniformly. The GSC #2 concept still lacks clear guidelines as to whether or not, and to what extent diminishments in, emission reductions shall be accepted under these two regimes.

Und&VT and GSC #1. The Und&VT overcomes situations that run (Und concept) or can run counter to the spirit of the Kyoto Protocol (GSC #1 and GSC #2 concepts if applied in the confidence mode). However, by requiring *a priori* detectable emission reductions, not limitations, the Und&VT concept corrects the Protocol's emission limitation or reduction targets for nondetectability through the introduction of an initial or obligatory undershooting so that the countries' emission signals become detectable before the countries are permitted to make economic use of their excess emission reductions. This, *de facto*, nullifies the politically agreed targets under the Kyoto Protocol! We do not consider this a realistic scenario. By way of contrast, the GSC #1 concept builds on the notion of confidence, not detectability. If applied in the undershooting mode it would not run counter to the spirit of the Kyoto Protocol. Nonetheless, it would enforce additional emission reductions, which would be smaller than those under the Und&VT concept but still be considerable and thus also difficult to sell politically. So far, emission reduction and emission limitation under the GSC #1 are not treated uniformly. The GSC #1 concept still lacks clear guidelines as to whether or not, and how many, excess emissions shall be accepted under these two regimes.

It appears very probable that the first shortfall (emission changes and uncertainty are of the same order of magnitude) will vanish soon as mankind is getting increasingly under pressure to adopt a longer-lasting perspective and to realize greater emission reductions in the mid to long-term. However, we suggest that policy-makers revisit the second shortfall. If nonuniform, country-specific emission reduction commitments are favored, then these must be decided on the basis of a straightforward rule that applies equally and rigorously to all countries and should not be determined 'off the cuff'. Only then can scientists finalize their discussion and give meaningful feedback on which technique(s) to select for the preparatory analysis of uncertainty in the countries' emission changes—and which numerical advantages and disadvantages between countries we then have to accept and tolerate.

[1] For an overview of IIASA's emissions change-versus-uncertainty monitoring (reports and countries) see http://www.iiasa.ac.at/Research/FOR/unc_overview.html.

[2] Click on *mathematical background* or *numerical results* to *Jonas et al. (2007)* under *Overview over six preparatory emissions change analysis techniques.*

[3] ISO country code: AT Austria; AU Australia; BE Belgium; BG Bulgaria; BY Belarus; CA Canada; CH Switzerland; CY Cyprus; CZ Czech Republic; DE Germany; DK Denmark; EC European Community; EE Estonia; ES Spain; FI Finland; FR France; GR Greece; HR Croatia; HU Hungary; IE Ireland; IS Iceland; IT Italy; JP Japan; LI Liechtenstein; LT Lithuania; LU Luxembourg; LV Latvia; MA Malta; MC Monaco; NL Netherlands; NO Norway; NZ New Zealand; PL Poland; PT Portugal; RO Romania; RU Russian Federation; SE Sweden; SI Slovenia; SK Slovak Republic; TR Turkey; UA Ukraine; UK United Kingdom; US United States.

[4] The CRU concept only considers uncertainty in the commitment year/period, not in the base year (i.e., formally $\varepsilon_1 = 0$). However, for reasons of comparability, we continue to abide by the condition of constant relative uncertainty.

[5] The absolute change in emissions is given according to Equation A-2 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html by $|x_1 - x_2| = |d_{KP}| x_1$.

[6] The term 'verification time' was first used by Jonas *et al.* (1999) and by other authors since then. 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 of emissions (see Jonas and Nilsson, 2007: Section 4).

[7] Applying Equation C-7b of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html with $\varepsilon_{12} \approx 0.03$ (typically reported), $\delta_{KP} = 0.08$ (valid for many Annex B countries) and $\varepsilon_1 = \varepsilon_2 \approx 0.075$ (see right side of Table 1) results in $\nu \approx 0.79$.

[8] The Und&VT concept only considers uncertainty in the commitment year/period, not in the base year (i.e., formally $x_{1,t} = x_1$ and $\nu = 0$). However, for reasons of comparability, we continue to abide by the condition of constant relative uncertainty.

[9] Recalling Equation D-1 of the supporting mathematical details available at: http://www.iiasa.ac.at/Research/FOR/unc_prep.html, δ_{crit} is given by $\rho/(1+\rho)$ in the case $\delta_{KP} > 0$ (emission reduction) and $-\rho/(1-\rho)$ in the case $\delta_{KP} \le 0$ (emission limitation).

[10] Moreover, by employing a uniform detectability criterion the Und&VT concept partially rectifies (see Cases 2 and 3, the cases of nondetectability before correction) the politically unfavourable situation under the Und concept, under which countries

complying with a small δ_{KP} exhibit a small δ_{mod} while countries complying with a great δ_{KP} exhibit a great δ_{mod} (cf. Table C-1)

[11] The two emissions adjustment methods presented by Gillenwater, Sussman and Cohen (GSC #1 and GSC #2) were meant to be applied in retrospect (Gillenwater *et al.*, 2007: Section 2.1). However, their methods can also be used to generate information that one would like to discuss beforehand; that is, they can also be perceived as preparatory signal analysis techniques and thus be compared with the other techniques discussed so far.

[12] The GSC #1 concept only considers uncertainty in the commitment year/period, not in the base year. However, for reasons of comparability, we continue to abide by the condition of constant relative uncertainty.

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Figure 1: Illustration of the critical relative uncertainty concept ($\rho_1 = \rho_2$): The absolute change in emissions ($|x_1 - x_2| = |d_{KP}| x_1$) outstrips uncertainty at t_2.[5] Kyoto (emissions) target (KT). Source: Jonas *et al.* (2004a: Figure 8).

Figure 2: Illustration of the verification time concept ($\rho_1 = \rho_2$): The absolute change in emissions ($|Dx(t)|$) outstrips uncertainty at **a)** $VT > t_2$, **b)** $VT = t_2$ and **c)** $VT < t_2$.[5] Source: Jonas *et al.* (2007: Figure 7), modified.

Figure 3: Illustration of the undershooting concept ($\rho_1 = \rho_2$) with the help of normal probability density functions: Undershooting helps to limit the risk α that countries overshoot their true emission limitation or reduction commitments. Source: Jonas *et al.* (2007: Figure 11); modified.

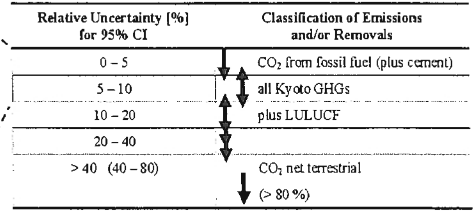
Figure 4: Illustration of the undershooting and verification time concept ($\rho_1 = \rho_2$): It preserves risk as the strength of the undershooting concept and detectability as the strength of the verification time concept. Depending on how δ_{crit} and δ_{KP} relate to each other, four cases can be distinguished (see text). These differ in terms of detectability (Cases 1 and 4) versus nondetectability (Cases 2 and 3) and an initial obligatory undershooting U_{Op} that is introduced (Cases 2–4) to ensure that detectability of emission reductions, not increases, is given before Annex B countries are permitted to make economic use of potential excess emission reductions. Emission reduction: $\delta_{KP} > 0$; emission limitation: $\delta_{KP} \leq 0$. Source: Hamal and Jonas (2008b: Figure 4).

Figure 5: Illustration of the Gillenwater, Sussman and Cohen #1 concept ($\rho_1 = \rho_2$) with the help of the standard normal probability density function: It allows specifying the confidence $(1-\alpha)$ via F_N that a country's true, but unknown, emissions comply with its Kyoto emissions target. Depending on whether or not excess emissions are accepted and favorable compliance conditions exist *a priori*, three cases are distinguished. Here, Case 2 is shown: Given an uncertainty of ρ%, this case requires adjusting a country's emissions estimate at t_2 upward if we want to be $(1-\alpha)$% confident that its true emissions do not exceed its Kyoto emissions target (here referred to as 1) by more than ρ_{crit}%. Emission reduction: $\delta_{KP} > 0$; emission limitation: $\delta_{KP} \leq 0$.

Figure 6: Illustration of the Gillenwater, Sussman and Cohen #2 concept ($\rho_1 = \rho_2$) with the help of the standard normal probability density function: It allows specifying the confidence $(1-\alpha)$ via F_N that a country's true, but unknown, emissions change complies with its committed change. Depending on whether or not diminished reductions (additional increases) are accepted and favorable compliance conditions exist *a priori*, four cases are distinguished. Here, Case 2 is shown: Given an uncertainty of ρ%, this case requires adjusting a country's emissions estimate at t_2 upward if we want to be $(1-\alpha)$% confident its true emission reduction equals at least (100 – ρ)% of the committed reduction (here referred to as 1). Emission reduction: $\delta_{KP} > 0$; emission limitation: $\delta_{KP} \leq 0$.

Table 1: **Left:** Countries included in Annex B to the Kyoto Protocol (KP) and their emission limitation and reduction commitments.[3] Sources: FCCC (1996: Decision 9/CP.2; 1998: Article 3.8, Annex B; 1999: Decision 11/CP.4; 2008: National Inventory Submissions); COM (2006: Section 2.b). **Right:** Emissions and/or removals of greenhouse gases (GHGs), or combinations of GHGs, classified according to their relative uncertainty ranges. The bars of the arrows indicate the dominant uncertainty range for these emissions and removals, while the tops of the arrows point at the neighboring uncertainty ranges, which cannot be excluded but appear less frequently. LULUCF stands for the direct human-induced land use, land-use change, and forestry activities stipulated by Articles 3.3 and 3.4 under the Kyoto Protocol (FCCC, 1998). The arrows are based on the total uncertainties that are reported for the Member States of the EU-25 (EEA, 2007) and the expertise available at IIASA's Forestry Program (cf. http://www.iiasa.ac.at/Research/FOR/unc_bottomup.html) and elsewhere (e.g., Watson *et al.*, 2000: Sections 2.3.7, 2.4.1; Penman *et al.*, 2003: Section 5.2). Source: Jonas and Nilsson (2007: Table 1), modified.

Country Group	**Annex B Country**	**Base Year(s) for CO_2, CH_4, N_2O (for HFCs, PFCs, SF_6)**	**Commitment Period**	**KP Commitment %**
1a	see below[1)] see below[2)]	1990 (1995) 1990 (1990)	2008–12	92
1b	RO	1989 (1989)	2008–12	
1c	BG	1988 (1995)	2008–12	
1d	SI	1986 (1995)	2008–12	
2	US[3)]	1990 (1990)	2008–12	93
3a	JP CA	1990 (1995) 1990 (1990)	2008–12	94
3b	PL	1988 (1995)	2008–12	
3c	HU	1985–87 (1995)	2008–12	
4	HR	1990 (1995)	2008–12	95
5a	RU	1990 (1995)	2008–12	100
5b	NZ, UA	1990 (1990)	2008–12	
6	NO	1990 (1990)	2008–12	101
7	AU	1990 (1990)	2008–12	108
8	IS	1990 (1990)	2008–12	110



Relative Uncertainty [%] for 95% CI	**Classification of Emissions and/or Removals**
0 – 5	CO_2 from fossil fuel (plus cement)
5 – 10	all Kyoto GHGs
10 – 20	plus LULUCF
20 – 40	
> 40 (40 – 80)	CO_2 net terrestrial
	(> 80 %)

1) Country Group 1a: BE, CZ, DE, DK, EC (= EU-15; the EU-27 does not have a common Kyoto target), EE, ES, FI, GR, IE, LT, LU, LV, MC, NL, PT, SE, UK. Member States of the EU-27 but without individual Kyoto targets: CY, ML. Listed in the Convention's Annex I but not included in the Protocol's Annex B: BY and TR (BY and TR were not Parties to the Convention when the Protocol was adopted). BY requested becoming an Annex B country by amendment to the Kyoto Protocol at CMP 2 in 2006. BY's base years and KP commitment are 1990 (1995) and 92%, respectively.

2) Country Group 1a: AT, CH, FR, IT, LI, SK.

3) Country Group 2: The US has indicated its intention not to ratify the Kyoto Protocol.

The US reports all its emissions with reference to 1990. However, information on 1990 in its national inventory submissions does not reflect or prejudge any decision that may be taken in relation to the use of 1995 as base year for hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) in accordance with Article 3.8 of the Kyoto Protocol.

Table 2: Major characteristics of the six preparatory signal analysis (SA) techniques compared in this study. 1: critical relative uncertainty concept (Gusti and Jęda, 2006); 2: verification time concept (Jonas *et al.*, 1999); 3: undershooting concept (Nahorski *et al.*, 2003); 4: undershooting and verification time concepts combined (Jonas *et al.*, 2004a); 5: Gillenwater, Sussman and Cohen #1 concept (Gillenwater *et al.*, 2007: Section 2.1); 6: Gillenwater, Sussman and Cohen #2 concept (Gillenwater *et al.*, 2007: Section 2.1). Sources: Jonas *et al.* (2004a: Table 3), Bun (2008: Table 2); modified.

Taken into account by the technique	**Preparatory SA Technique**					
	1	**2**	**3**	**4**	**5**	**6**
Trend uncertainty			√			√
Total uncertainty	√	√		√	√	
Intra-systems view			√			√
Intra-systems view but suited to support inter-systems (top-down) view	√	√		√	√	
Emissions gradient between t_1 and t_2		√		√		
Detectability of when an emission signal outstrips total uncertainty	√	√				
Undershooting			√	√		
Upward adjustment of reported emissions					√	√
Risk with reference to the concept of significance			√		√	√
Risk with reference to the concept of detectability				√		

Table 3: Summary: The six signal analysis techniques and the characteristics of their numerical responses. To facilitate easy comparison, the techniques are grouped in pairs of two. Kyoto (emissions) target (KT).

Technique	Given	Characteristics of Numerical Response
CRU, VT	d_{KP}	The two concepts exhibit a dissimilarity between countries committed to emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \leq 0$) depending on whether more lenient or stricter KTs are introduced
Und, GSC #2	d_{KP}	risk $\alpha \downarrow$ $\Rightarrow$ undershooting Und $\uparrow$ confidence $(1-\alpha) \uparrow$ $\Rightarrow$ adjustment Adj $\uparrow$ for any uncertainty ρ
	d_{KP}	uncertainty $\rho \uparrow$ $\Rightarrow$ undershooting Und $\uparrow$ uncertainty $\rho \uparrow$ $\Rightarrow$ adjustment Adj $\uparrow$ for any risk α or confidence $(1-\alpha)$
	ρ and α (or $1-\alpha$)	$d_{KP} \downarrow$ $\Rightarrow$ undershooting Und $\uparrow$ but modified KT $d_{mod} \downarrow$ $d_{KP} \downarrow$ $\Rightarrow$ adjustment Adj $\uparrow$[a]
Und&VT, GSC #1	d_{KP}	as under Und and GSC #2
	d_{KP}	as under Und and GSC #2
	ρ and α (or $1-\alpha$)	$d_{KP} \downarrow$ $\Rightarrow$ undershooting Und $\uparrow$ resulting in modified KT $d_{mod} = \text{const}$[b] $d_{KP} \downarrow$ $\Rightarrow$ adjustment Adj $\uparrow$[a]

[a] Statement refers to emission reduction ($d_{KP} > 0$: Cases 1 and 2).

[b] Statement refers to nondetectability under emission reduction ($d_{crit} > d_{KP} > 0$: Case 2) and emission limitation ($d_{crit} < d_{KP}$ Ł 0: Case 3).