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Preparatory Signal Detection for Annex I Countries under the Kyoto Protocol — A Lesson for the Post-Kyoto Policy Process

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Contents

Abstract

In our study we address the detection of uncertain GHG emission changes (also termed emission signals) under the Kyoto Protocol. The question to be probed is *how well do we need to know net emissions if we want to detect a specified emission signal after a given time?* No restrictions exist as to what concerns the net emitter. However, 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. Another restriction concerns the exclusion of emissions/removals due to land-use change and forestry (LUCF) as the reporting of their uncertainties is only soon becoming standard practice.

Our study centers on the preparatory detection of emission signals, which should have been applied prior to/in negotiating the Kyoto Protocol. Rigorous preparatory signal detection has not yet been carried out, neither prior to the negotiations of the Kyoto Protocol nor afterwards. The starting point for preparatory signal detection is that the Annex I countries under the Kyoto Protocol comply with their emission limitation or reduction commitments.

Uncertainties are already monitored. However, monitored emissions and uncertainties are still dealt with in isolation. A connection between emission and uncertainty estimates for the purpose of an advanced country evaluation has not yet been established.

We apply four preparatory signal detection techniques. These are the Critical Relative Uncertainty (CRU) concept, the Verification Time (VT) concept, the Undershooting (Und) concept, and the Undershooting and Verification Time (Und&VT) concepts combined. All of the techniques identify an emission signal and consider the total uncertainty that underlies the countries' emissions, either in the commitment year/period or in both the base year and the commitment year/period. The techniques follow a hierarchical order in terms of complexity permitting to explore their robustness. The most complex technique, the Und&VT concept, considers in addition to uncertainty (1) the dynamics of the signal itself permitting to ask for the verification time, the time when the signal is outstripping total uncertainty; (2) the risk (probability) that the countries' true emissions in the commitment year/period are above (below) their true emission limitation or reduction commitments; (3) the undershooting that is needed to reduce this risk to a prescribed level; and (4) a corrected undershooting/risk that accounts for detectability, i.e., that fulfills a given commitment period or, equivalently, its maximal allowable verification time.

Our preparatory signal detection exercise exemplifies that the negotiations for the Kyoto Protocol were imprudent because they did not consider the consequences of uncertainty, i.e., (1) the risk that the countries' true emissions in the commitment year/period are above their true emission limitation or reduction commitments; and (2) detectable targets.

Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, both the CRU concept and VT concept show that it is virtually impossible for most of the Annex I countries to meet the condition that their overall relative uncertainties are smaller than their CRUs or, equivalently, that their VTs are smaller than their maximal allowable verification times.

Moreover, the Und and the Und&VT concepts show that the countries' committed emission limitation or reduction targets — or their Kyoto-compatible but detectable targets, respectively — require considerable undershooting if one wants to keep the risk low that the countries' true emissions in the commitment year/period are above the true equivalents of these targets.

The amount by which a country undershoots its Kyoto target or its Kyoto-compatible but detectable target can be traded. Towards installing a successful trading regime, countries may want to also price the risk associated with this amount. We anticipate that the evaluation of the countries' emission signals in terms of risk and detectability will become reality.

The Intergovernmental Panel on Climate Change (IPCC) also suggests assessing total uncertainties. However, a connection between monitored emission and uncertainty estimates for the purpose of an advanced country evaluation, which considers the aforementioned risk as well as detectable targets, has not yet been established. The IPCC has to take up this challenge.

Acknowledgments

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1 Introduction

1.1 Scope of the Study

The focus of this study is on the preparatory detection of uncertain net greenhouse gas (GHG) emission changes (also termed emission signals) under the Kyoto Protocol. The crucial question to be addressed is:

> *How well do we need to know net emissions if we want to detect a specified emission signal after a given time?*

No restrictions exist as to what concerns the net emitter, which may be any GHG source or sink, e.g., a fossil-fuel powered plant, a terrestrial biospheric system or any part of it, or a combination of anthropogenic and terrestrial biospheric systems as envisaged under the Kyoto Protocol.

Annex I countries are chosen as net emitters, simply for reasons of data availability and because of the excellent possibility of comparing net emitters (inter-country comparison). The countries' emissions — in an increasing number of cases even their uncertainties — are available permitting the application of preparatory signal detection techniques, which are suited to address the aforementioned question.

We currently discuss four hierarchically-ordered detection concepts to assess emission signals in a preparatory manner, that is, at two predefined points in time, t_1 in the past/present (typically the base year) when emissions are known, and t_2 in the future (typically the commitment year/period) when emissions are supposed to meet an agreed-upon target. These concepts allow to generate useful information beforehand as to how great uncertainties can be depending on the emission signal one wishes to detect and whether or not one tolerates risk. It is this knowledge on the required quality of reporting vis-à-vis uncertainty that one wishes to have at hand before negotiating international environmental treaties such as the Kyoto Protocol. The concepts can be considered standard as well as novel.

In contrast, signal detection in retrospect ($t = t_2$) and midway signal detection ($t_1 < t < t_2$) work differently and require a greater effort.[1] Signal detection in retrospect is carried out at t_2 and considers how an emission signal has evolved in reality between t_1 and t_2, taking its dynamics into account; while midway signal detection is carried out at some point in time between t_1 and t_2 and considers a signal's path realized so far vis-à-vis a possible path towards the agreed-upon emission target at t_2.

To facilitate structured acquaintance with the signal-uncertainty issue, we confine our study to preparatory signal detection. We discuss midway signal detection and signal detection in retrospect in follow-up studies. Another restriction concerns the exclusion of emissions/removals due to land-use change and forestry (LUCF) as the reporting of their uncertainties is only soon becoming standard practice. Therefore, we narrow the focus of our study to the countries' anthropogenic GHG emissions (i.e., excluding CO_2 emissions/removals due to LUCF), when we refer to the detection of their emission signals. Nevertheless, we discuss extending preparatory signal detection upon carbon stocks.

1.2 Signal Detection Under the Kyoto Protocol — Current Status

Rigorous preparatory signal detection has not yet been carried out, neither prior to the negotiations of the Kyoto Protocol nor afterwards. The same is true for midway signal detection.

Nevertheless, monitoring of GHG emissions takes place. The secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) coordinates the development of guidelines for reporting GHG emissions and removals and for the technical review of emission inventories, while organizing these reviews and archiving inventory data (FCCC, 2004).[2]

In addition to reporting annually on GHG inventories within the area covered by its Member States, the European Community, as a Party to the UNFCCC, also monitors all anthropogenic GHG emissions not controlled by the Montreal Protocol in the Member States and evaluates progress towards meeting GHG reduction commitments under the UNFCCC and the Kyoto Protocol. (Gugele *et al.*, 2003:6). This monitoring process is illustrated in Figures 1 and 2 as well as Table 1. They give details, for each Member State and the European Union (EU) as a whole, of trends in emissions of the GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF6) up to 2001.[3] Figure 1 follows the total emissions of the EU over time since 1990, while the distance-to-target indicator (DTI) introduced in

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[1] For instance, Article 3.2 of the Kyoto Protocol requires midway signal detection by 2005 when Annex I countries must have made demonstrable progress in achieving their commitments (FCCC, 1998).

[2] In accordance with Articles 4 and 12 of the Framework Convention on Climate Change (FCCC, 1992), and the relevant decisions of the Conference of the Parties (COP), Parties to the Convention submit to the secretariat national GHG inventories of anthropogenic emissions by sources and removals by sinks of GHGs not controlled by the Montreal Protocol. For Annex I countries, two sequential processes have been established: the annual reporting of national GHG inventories, and the annual review of the inventories (FCCC, 2004).

[3] Emissions from international aviation and shipping, and emissions/removals due to LUCF, are not covered (EEA, 2003).

Figure 2, based on the country data listed in Table 1, is a measure of the derivation of actual GHG emissions in 2001 from the linear target path between 1990 and the Kyoto Protocol target for 2008–2012, assuming that only domestic measures will be used.[4]

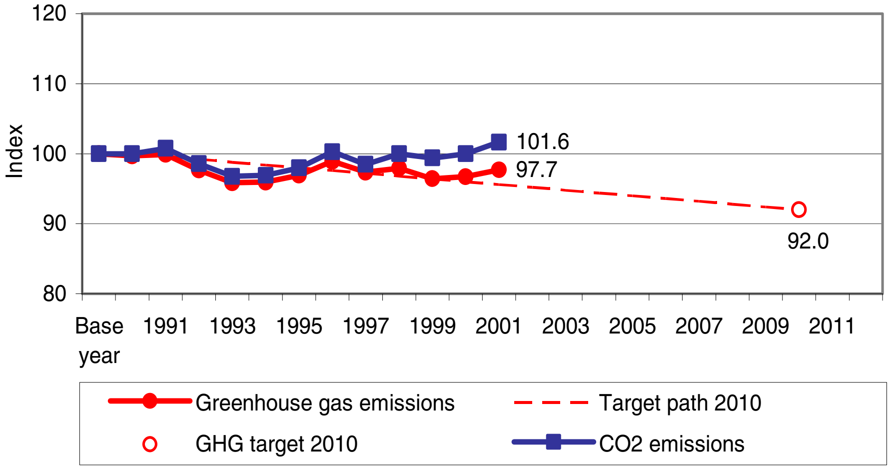
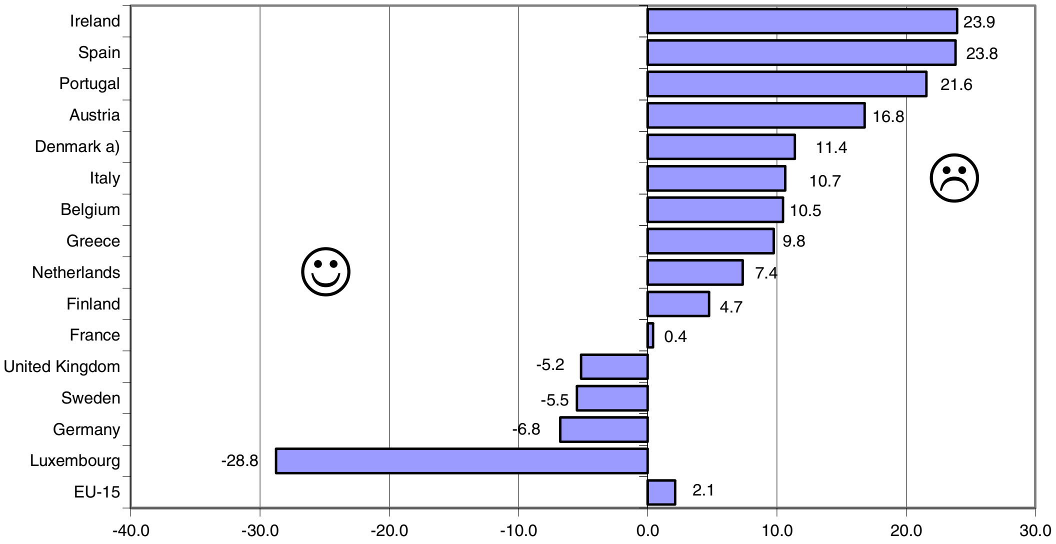


Figure 1: Total EU GHG emissions for 1990–2001 in relation to the Kyoto target. Source: EEA (2003).



[a] The Danish DTI is + 0.9 if Danish GHG emissions in the base year are adjusted for electricity trade (import and export) and for temperature variations.

Figure 2: Distance-to-target indicator (DTI) for EU Member States in 2001 (Kyoto Protocol and EU burden sharing targets). Source: EEA (2003).

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[4] For example, Ireland is allowed a 13% increase from 1990 levels by 2008–2012, so its theoretical “linear target” for 2001 is a rise of no more than 7.2%. Its actual emissions in 2001 show an increase of 31.1% since 1990; hence, its “distance-to-target” is 31.1 − 7.2, or 23.9 index points. Germany’s Kyoto target is a 21% reduction, so its theoretical “linear target” for 2001 is a decrease of 11.5%. Actual emissions in 2001 were 18.3% lower than in 1990; hence, its “distance-to-target” is (–18.3) – (–11.5), or –6.8 index points (EEA, 2003).

Table 1: 2008–2012 targets for EU Member States under the Kyoto Protocol and EU burden sharing. Source: EEA (2003).

Member State	Base Year[a] (million tonnes)	2001 (million tonnes)	Change 2000–2001 (%)	Change Base Year–2001 (%)	Targets 2008–12 under Kyoto Protocol and "EU burden sharing" (%)
Austria	78.3	85.9	4.8	9.6	-13.0
Belgium	141.2	150.2	0.2	6.3	-7.5
Denmark[b]	69.5	69.4	1.8	-0.2 (-10.7)	-21.0
Finland	77.2	80.9	7.3	4.7	0.0
France	558.4	560.8	0.5	0.4	0.0
Germany	1216.2	993.5	1.2	-18.3	-21.0
Greece	107.0	132.2	1.9	23.5	25.0
Ireland	53.4	70.0	2.7	31.1	13.0
Italy	509.3	545.4	0.3	7.1	-6.5
Luxembourg	10.9	6.1	1.3	-44.2	-28.0
Netherlands	211.1	219.7	1.3	4.1	-6.0
Portugal	61.4	83.8	1.9	36.4	27.0
Spain	289.9	382.8	-1.1	32.1	15.0
Sweden	72.9	70.5	2.2	-3.3	4.0
United Kingdom	747.2	657.2	1.3	-12.0	-12.5
EU-15	4204.0	4108.3	1.0	-2.3	-8.0

[a] Base year for CO_2, CH_4 and N_2O is 1990; 1995 is used as the base year for fluorinated gases, as allowed for under the Kyoto Protocol. This reflects the preference of most Member States.

[b] For Denmark, data that reflect adjustments in 1990 for electricity trade (import and export) and for temperature variations are given in brackets. This methodology is used by Denmark to monitor progress towards its national target under the EU "burden sharing" agreement. For the EU emissions total non-adjusted Danish data have been used.

Uncertainties are extracted from the national inventory reports of the Member States and are monitored separately. However, a connection between emission and uncertainty estimates for the purpose of an advanced country evaluation has not yet been established. A recent compilation of uncertainties has been presented by Gugele *et al.* (2003:Table 6) (see Table 2). This compilation makes available quantified uncertainty estimates from Austria, Finland, Netherlands and United Kingdom (total emissions and individual GHGs) and from Ireland (total emissions only). The uncertainties refer to a 95% confidence interval[5] and neglect, with the exception of the United Kingdom, emissions/removals due to LUCF.[6]

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[5] The IPCC Good Practice Guidelines suggest the use of a 95% confidence interval, which is the interval that has a 95% probability of containing the unknown true emission value in the absence of biases (and that is equal to approximately two standard deviations if the emission values are normally distributed) (Penman *et al.*, 2000: p. 6.6).

[6] In the case of Ireland, the CO_2 emissions arising from the liming of agricultural lands are not included under *Agriculture*, category 4 of the Revised 1996 IPCC Guidelines for National GHG Inventories (hereafter IPCC Guidelines; IPCC, 1997a,b,c), but they are accounted for under *Land Use Change and Forestry: CO_2 Emissions and Removals from Soil*, LUCF category 5D of the IPCC Guidelines. The IPCC Guidelines make allowance for the alternative source allocation in the case of this activity (McGettigan and Duffy, 2003:Sections 1.5 and 1.8).

Table 2: Overview of uncertainty estimates available from Member States (MS) excluding LUCF (with the exception of the United Kingdom). Source: Modified from Gugele *et al.* (2003:Table 6).

MS	**Uncertainty estimates extracted from MS national inventory reports**	**Source**
Austria[a]	Uncertainty analysis including systematic and random uncertainty was carried out for CO_2, CH_4 and N_2O for 1990 and 1997. The results of the calculations are as follows: Total uncertainty CO_2 CH_4 N_2O Total GHG emissions (excl. fluorinated gases) 1990 2.3% 48.3% 89.6% 9.8% 1997 2.1% 47.4% 85.9% 8.9%	Federal Environment Agency, Austria (2001)
Denmark	The national inventory report refers to Denmark's second national communication where the uncertainty of NMVOC, CH_4 and N_2O is assumed to be the highest (perhaps with an uncertainty factor 2). The uncertainty of CO and NO_x inventories is assumed to be less than 30–40% and the uncertainty of CO_2 may be as low as 1–2%. Applying the methodology mentioned in Annex 1 of the reporting instructions of the *Revised 1996 IPCC Guidelines for national GHG inventories* these estimates lead to an overall uncertainty of the GHG emissions in CO_2 equivalents of +/-23%. This estimate does not take into account the 35% uncertainty of the GWP-factors. Sensitivity analysis shows that it is the huge uncertainty of N_2O emissions from agricultural soils, which are the key factor for overall uncertainty of the Danish GHG inventory. Work is underway to implement uncertainty according to GPG. The results of this work are expected to be included in the Danish NIR 2004.	National Environmental Research Institute (2002)
Finland	In 2001 inventory, the uncertainty assessment was performed for the first time using the Monte Carlo simulation (Tier 2 method). The uncertainties in the input parameters were estimated using the IPCC default uncertainties, expert elicitation, domestic and international literature and available measurement data. A separate report on the uncertainty estimates (Monni and Syri 2003) will be published in 2003. According to the calculations, the uncertainty estimates for 2001 were as follows: Total GHGs CO_2 CH_4 N_2O Fluorinated gases -5/+6% -4/+6% -19/+20% -33/+40% -53/+32% The share of CO_2 emissions from fuel combustion, which has low uncertainties, is large in Finland, thus resulting in a rather low total inventory uncertainty, though some input parameters in other emission categories have very large uncertainties.	Ministry of the Environment (2003a)
France	Work is underway for estimating uncertainties of GHG emissions according to the *Good practice guidance* (IPCC, 2000). The uncertainties of CO_2 and SO_2 from energy use are assumed to be less than 5%.	CITEPA (2001)
Germany	The report states that partly emission uncertainties are considerable. This is due to uncertainties of activity data and emission factors and — to a much lesser extent — to a lack of information on emission-causing activities. In general, the uncertainty of combustion-related emissions is considerably lower than uncertainty of non-combustion-related emissions. The uncertainties are estimated to be higher for emissions after 1999 because they have to be considered as preliminary estimates. For qualitative estimates of emission uncertainties the report refers to the relevant CRF tables.	Bericht 2002 der Bundesrepublik Deutschland (2002)
Ireland	The Tier 1 method provided by IPCC (2000) has been used to make an uncertainty estimate of the Irish inventory time series for the years 1990–2000. This analysis results in an overall uncertainty of approximately 11% in the 2000 inventory of GHGs and a trend uncertainty of 5% for the period 1990 to 2000. This outcome is determined largely by the uncertainty in the estimate of N_2O emissions from agricultural soils, where an emission factor uncertainty of 100% is assumed in order to complete the analysis. This highlights the need for more reliable data on this particular emission source in Ireland. Two-thirds of total Irish emissions, i.e., the proportion contributed by CO_2, are estimated to have an uncertainty of less than 2%. When CH_4 is included, bringing the proportion up to 85%, the total uncertainty remains less than 4%, even though there are large uncertainties assigned to the CH_4 emission factors in most source categories. However, it is the influence of N_2O that leads to a substantial uncertainty in total emissions. This influence is not as large in the case of the trend, due to the modest change in emissions of N_2O from 1990 to 2000 and the relatively small share of this gas in total emissions. The impact of HFC, PFC and SF_6 on inventory uncertainty in the year 2000 is negligible because these gases account for less than 1% of total emissions.	Environmental Protection Agency (2002)
Netherlands	The Netherlands estimated uncertainty in annual emissions and in emission trends by applying the IPCC Tier 1 uncertainty approach at the level of the IPCC list of possible key sources. The results of the uncertainty estimates for 2000 CO_2 equivalent emissions is as follows: Total GHGs CO_2 CH_4 N_2O HFCs PFCs SF_6 ±4% ±3% ±25% ±50% ±50% ±50% ±50% The results of the uncertainty estimates for the trend 1990–2000 CO_2 equivalent emissions is as follows: Total GHGs CO_2 CH_4 N_2O Fluorinated gases ±3% ±3% ±7% ±12% ±11%	Olivier, J.G.J, Brandes, L.J., Peters, J.A.H.W. and Coenen, P.W.H.G. (2002)

Table 2: continued

<table>
<tr><td>Spain</td><td>The Spanish report mentions that the assessment of uncertainty (estimation of emission quality) is shown in Table 7 of the CRF using the quality codes H (high), M (medium), and L (low). This ordinal classification of quality is only a first stage in the analysis of the uncertainty associated with the inventory estimations. Work is now in progress for the implementation of a quantitative estimation of uncertainty in accordance with the approach recommended in IPCC (2000).</td><td>Ministry of the Environment (2003b)</td></tr>
<tr><td>Sweden</td><td>The uncertainty in reported emissions arises from the uncertainty in the activity data, uncertainty in emission factors and uncertainty arising from whether all (major) sources of emissions are included in the inventory. For most sectors Swedish official statistics are used as activity data, except for industrial processes, emissions from F-gases and for solvent use where information comes from the industries annual environmental reports. Used emission factors originate either from measurements from existing Swedish plants or from comparable European installations, where IPCC default emission factors are not used. In 2003 validation of uncertainties for the emission estimates will be started. It is assumed that the uncertainty is largest for the inventories of CH_4 and N_2O, perhaps with an uncertainty factor of 2, for NMVOC, which have been recalculated possibly in the order of 50%, while the uncertainty on the CO, SO_2 and NO_x inventories is assumed to be less than 30–40% and the uncertainty with the CO_2 may be as low as 1–2%.</td><td>Swedish Environmental Protection Agency (2003)</td></tr>
<tr><td>United Kingdom</td><td>Quantitative estimates of the uncertainties in the emissions were calculated by using Monte Carlo simulation. This corresponds to the IPCC Tier 2 approach discussed in the *Good practice guidance* (IPCC, 2000). The results for the United Kingdom are as follows (calculated as 2s/E where s is the standard deviation and E is the mean, calculated in the simulation):
<table>
<tr><th></th><th>Total GHGs</th><th>CO_2</th><th>CH_4</th><th>N_2O</th><th>HFCs</th><th>PFCs</th><th>SF_6</th></tr>
<tr><td>Emissions 2001 (%)</td><td>13</td><td>2.2</td><td>14</td><td>204</td><td>25</td><td>19</td><td>13</td></tr>
<tr><td>Range of likely percentage change (2001 and 1990)</td><td>-15/-10</td><td>-6.9/-4.2</td><td>-49/-31</td><td>-73/-17</td><td>-47/9</td><td>-76/-59</td><td>103/192</td></tr>
</table>
The Tier 1 approach based on the error propagation equations suggests an uncertainty of 17% in the combined GWP total emissions in 2001. The analysis also estimates an uncertainty of 2% in the trend between 1990 and 2000.</td><td>National Environmental Technology Centre (2003)</td></tr>
</table>

[a] Austria has, as the only Member State of the EU, carried out full carbon accounting (FCA) for 1990. Jonas and Nilsson (2001:Table 14) constructed a full carbon account, which serves as a basis for extracting a partial carbon account that is extended by CH_4 and N_2O and that is in line with the IPCC Guidelines (IPCC, 1997a,b,c). The respective relative uncertainties (more exactly: the median values of the respective relative uncertainty classes) are 2.5% for CO_2; 30% for CH_4; >40% for N_2O; and 7.5% for $CO_2 + CH_4 + N_2O$.

1.3 Guide Through the Study

The main focus of our study is on the preparatory detection of uncertain GHG emission signals. In Section 3, we present four hierarchically-ordered concepts and discuss their application in the context of Annex I country commitments. As mentioned before, such an assessment has not yet been carried out, neither prior to the negotiations of the Kyoto Protocol nor afterwards. However, signal detection of GHG emission signals without discussing its underlying theoretical basis may run the risk of falling short. Therefore, we present in Section 2 our uncertainty and verification framework, within which we see the detection of emission signals under the Kyoto Protocol embedded. An overview and the conclusions of our findings are presented in Section 4.

2 Uncertainty and Verification Framework

Section 2 puts the issues uncertainty, verification and signal detection into context. In Section 2.1, we discuss the question of where scientific uncertainties come from and scientific quality in terms of plausibility, validation and verification. In Section 2.2, we address the question of whether the Kyoto Protocol is verifiable and describe in Section 2.3 our understanding of signal detection in the presence of verification. In Section 2.4, we return to the issue of uncertainty and present a generally applicable uncertainty concept.

2.1 Where Do Uncertainties Come From?

We refer to Moss and Schneider (2000; see also Giles, 2002), who categorize uncertainties and espouse 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 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 Figure 3). Here, we make use of Merriam-Webster's Collegiate Dictionary (Merriam-Webster, 1973; 1997), which specifies plausibility, validation and verification — in line with science theory — as follows:

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.[7]

In accordance with these definitions, only observations (measurements) — uncertain per se — can be verified within Moss and Schneider's four-axis uncertainty concept, but none of the other categories.

To justify theory as a self-standing uncertainty category, reference can be made, e.g., to the famous Michelson-Morley experiment performed by Albert Michelson (1852–1931) and Edward Morley (1838–1923) in 1887. It was motivated by the search for an absolute reference frame, within which absolute motion can be measured. This experiment can serve as a classical and illustrative example that theory and observation, although individually "solid", did not match simply because the current physical understanding at that time was insufficient. However, theories, like diagnostic models, are our reflection of reality and can never be considered complete; final truth cannot be achieved. Therefore, theories and diagnostic models can only be validated or, alternatively, falsified (which is a controversially discussed issue on its own).

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[7] 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 (Merriam-Webster, 1997):

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

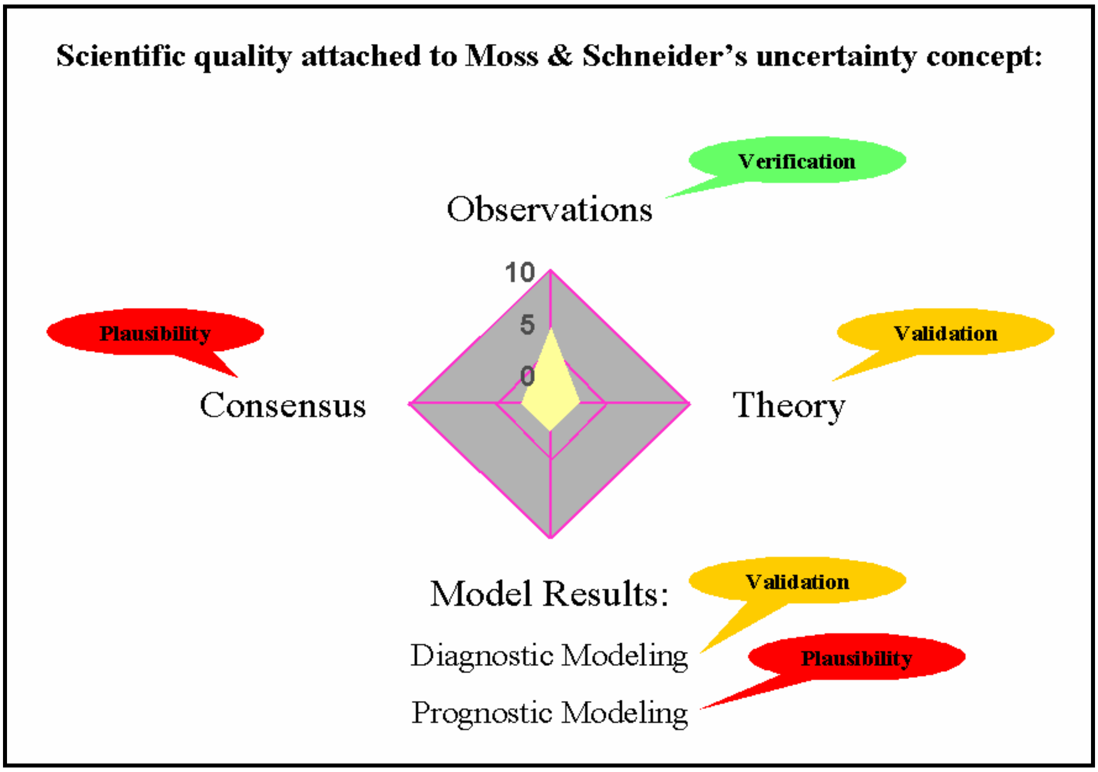

Figure 3: The four-axis concept of Moss and Schneider (2000; see also Giles, 2002) to trace where uncertainty comes from, modified to show which scientific quality in terms of plausibility, validation and verification can be achieved.

Consensus (soft knowledge) as well as prognostic modeling also gives 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).

Admittedly, the understanding of verification varies widely. For instance, the IPCC Good Practice Guidelines define verification with the view on GHG emission inventories (Penman *et al.*, 2000:Annex 3):

> *"Inventory definition: Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory. Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases."*

However, this definition requires discussion as it is not sufficiently rigorously in line with science theory[8] and/or the intended purpose of the Kyoto Protocol, which may be colloquially expressed as: *What matters is what the atmosphere sees!*

According to this definition, verification is a scientific process that aims at establishing the reliability of a measurement (here: inventory). However, similar to *validity*, a system-internal quality criterion, *reliability* is a measurement-reflexive quality criterion that should not be misunderstood with *verification*. Verification is more as it goes beyond validation or reliability. Moreover, towards checking the truth of an inventory, this definition allows putting "comparisons with [bottom-up emission] estimates made by other bodies"[9] on the same level with "emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases", which is unacceptable from a science-theoretical point of view.

It is instructive to examine the difference in terms of uncertainties between the two categories *observations* (including accounting) and *modeling* (see Figure 3) in more detail. Figure 4 presents a simplified illustration featuring accounting versus diagnostic and prognostic modeling. The accounting typically happens with a time step of ≤1 year (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 4) By way of contrast, U_{Model}, the uncertainty of the model, always increases due to the model's decreasing prognostic capabilities with time.[10]

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[8] See, e.g., Lauth and Sareiter (2002).

[9] In this context, the terms *third-party verification* or *independent verification* are also used.

[10] The interrelation between U_{Model} and $U_{Account}$ during the model's diagnostic mode can be made clear with the help of the notion of an *ideal* model. An ideal model perfectly reflects reality during the model's diagnostic mode, that is, $U_{Account}$ is identical with U_{Model}. However, in practice, models are generally not able to reproduce $U_{Account}$ for a number of reasons. An important reason is that, traditionally, model builders focused mainly on grasping mean values. In order to reflect more a complex reality, they resolved more detailed mean values. However, the consideration of uncertainties requires the opposite, that is, to simplify models, ideally to a level, which permits treating uncertainties as statistically independent (or as statistically independent as possible). In general, it may be noted that the choice of a (sufficiently) ideal model is a task in itself.

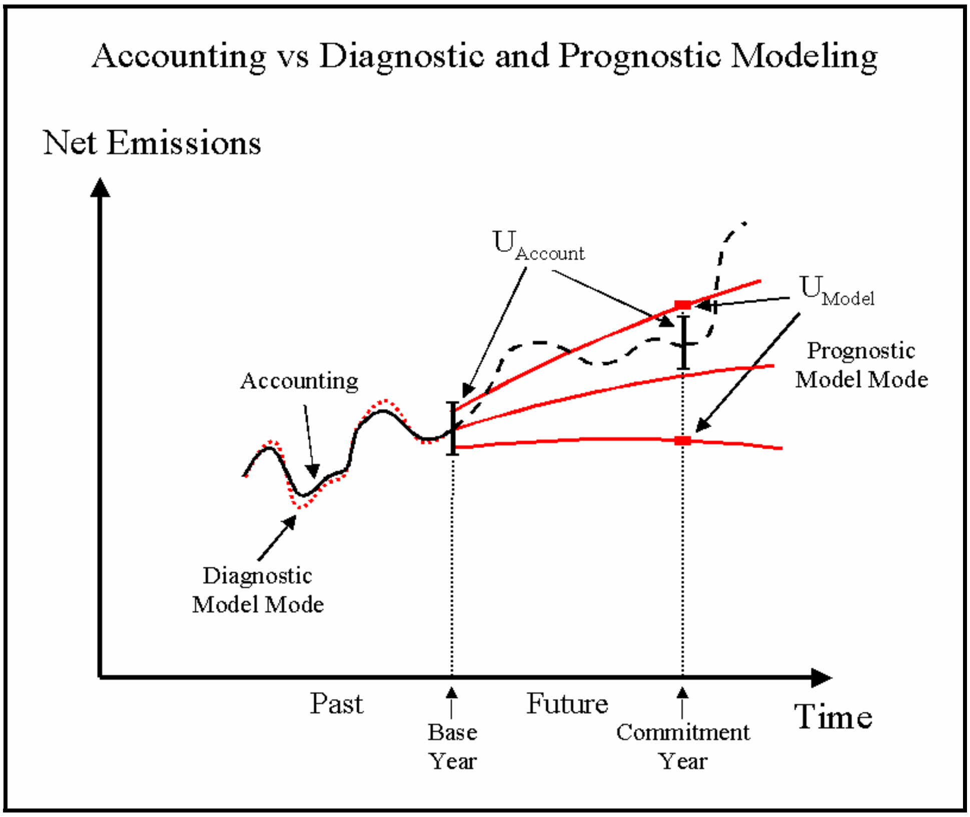

Figure 4: Simplified illustration featuring accounting versus diagnostic and prognostic modeling. U: uncertainty. Source: Modified from Jonas and Nilsson (2001:Section 2.2.2).

2.2 Is the Kyoto Protocol Verifiable?

Today's global carbon research priorities focus primarily on the global and sub-global (regional) quantification of carbon sources and sinks and their combination in a closed budget, as well as understanding how the budget changes over time as a function of natural and anthropogenic perturbations. A number of measurements, including those of carbon isotopes and atmospheric oxygen as well as eddy covariance measurements, are combined to identify the different fluxes that result from the use of fossil fuels or are exchanged between land or ocean and the atmosphere (Heimann, 1996; Heimann *et al.*, 1999; Battle *et al.,* 2000; Bousquet *et al.*, 2000; Falkowski *et al.*, 2000; Canadell and Noble, 2001; Prentice *et al.*, 2001; House *et al.,* 2003). In brief, this community follows in the footsteps of bottom-up/top-down verification on global and sub-global scales.

However, the Kyoto Protocol requires that net emission changes (emission signals) of specified GHG sources and sinks, including those of the *Kyoto biosphere* but excluding those of the *non-Kyoto biosphere*,[11] be verified on the spatial scale of countries[12] by the

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[11] Articles 3.3 and 3.4 of the Protocol stipulate that human activities related to LUCF since 1990 can also be used to meet 2008–2012 commitments (FCCC, 1998). 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*.

time of commitment, relative to a specified base year. The relevant question is then whether these emission signals outstrip uncertainty and can be verified. Living up to the intended purpose of the Kyoto Protocol and following science-theoretical standards require that these changes be verified by adopting an approach that takes an atmospheric view (what matters is what the atmosphere sees) and that is complete (leaving no unverified residues) (see Figure 5).

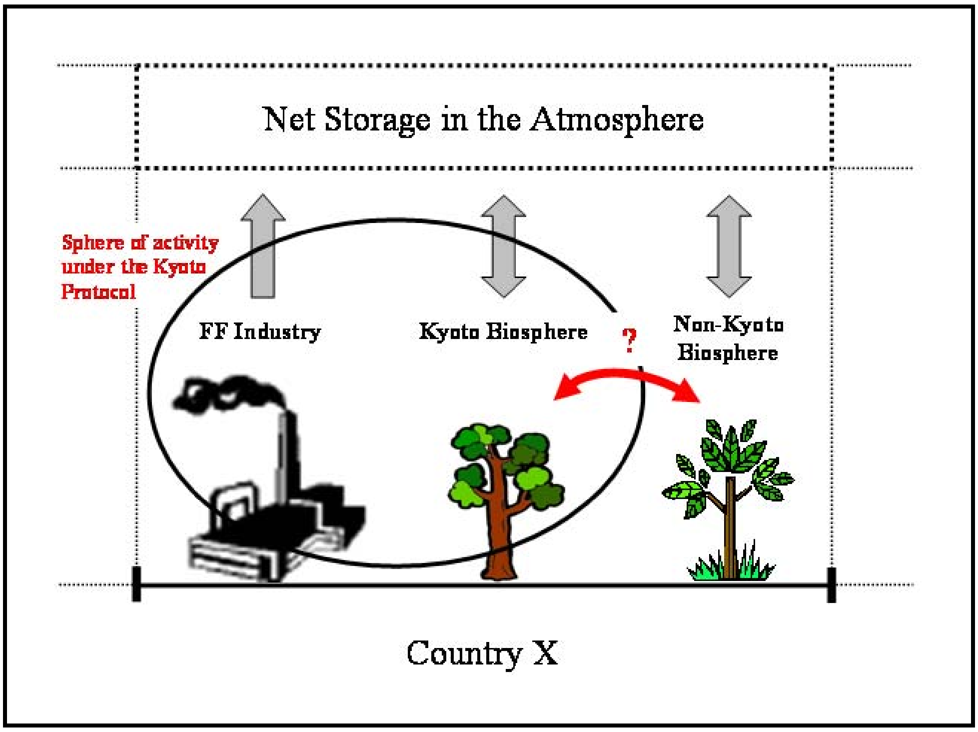

Figure 5: Partial carbon accounting (PCA), as envisaged under the Kyoto Protocol (KP), is understood as a logical subset of consistent FCA. Consistent FCA on the spatial scales of countries requires the measurement of all fluxes, including those into and out of the atmosphere, and an atmospheric storage measurement, which — to reflect the needs of the Kyoto Protocol — permits to discriminate a country's *Kyoto biosphere* from its *non-Kyoto biosphere*. The *anthropogenic* sector (simply referred to as fossil fuel of FF industry) also includes ground-based fluxes between countries (e.g., trade) and carbon stocks other than biospheric stocks. Source: Modified from Jonas and Nilsson (2001:Figure 14).

Hence, verification under the Kyoto Protocol would require applying the concept of bottom-up/top-down (consistent or dual-constrained) full carbon accounting (FCA) on the country-scale, 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*. This type of

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

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 (WBGU, 1998; Jonas *et al.*, 2000; 2004a,b; Jonas and Nilsson, 2001:Sections 3.1.2 and 3.1.5).[13] As a consequence, partial carbon accounting (PCA) as envisaged under the Kyoto Protocol can not be verified.

2.3 Verification and Signal Detection

To account for changes in anthropogenic CO_2-equivalent emissions (simply referred to as fossil fuel or FF emissions) over time, the Kyoto Protocol stipulates that mean values are to be compared on the basis of percentages (of both the base year and the commitment period) (FCCC, 1998:Annex B). Subtracting mean values (referring either to the beginning and end of the commitment period or to the base year and commitment period) is proposed for LUCF activities. Changes in net LUCF emissions are added to the countries' change in FF emissions (FCCC, 1998:Articles 3.3, 3.4; 1999:Decision 9/CP.4; 2002:Annex to Draft decision -/CMP.1).

The IPCC (to which the Kyoto Protocol refers)[14] defines uncertainty with respect to two predefined points in time (Noble *et al.*, 2000:Section 2.3.7; Penman *et al.*, 2000:Chapter 6). Figure 6 reflects this concept, based on two different types of uncertainty, total and trend uncertainty.[15] As we will see in the course of the study, the knowledge of total uncertainty at only two points in time may lead to interpretational difficulties as to what the emission signal is in consideration of its underlying 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 detectable.

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[13] In this context, it is useful to bear the following two remarks in mind:

(i) It is almost impossible to trace emissions back to individual sources/sinks or source/sink categories (here: *Kyoto* and *non-Kyoto* LUCF sources/sinks) if their emissions/removals do not contain some sort of (e.g., CO_2 or CH_4) fingerprint that characterizes them (Penman *et al.*, 2000:Annex 2, p.8; Jonas *et al.*, 2000; Jonas and Nilsson, 2001:Sections 3.1.2; 3.1.5).

(ii) The measurement of changes in a biospheric stock represents — from a verification point of view — a not necessarily consistent bottom-up measurement of the terrestrial biospheric net flux.

[14] See FCCC (1998:Article 5; 2001a:Annex to Draft decision -/CMP.1; 2001b:Draft decision -/CMP.1; 2002:Decision 11/CP.7).

[15] 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.

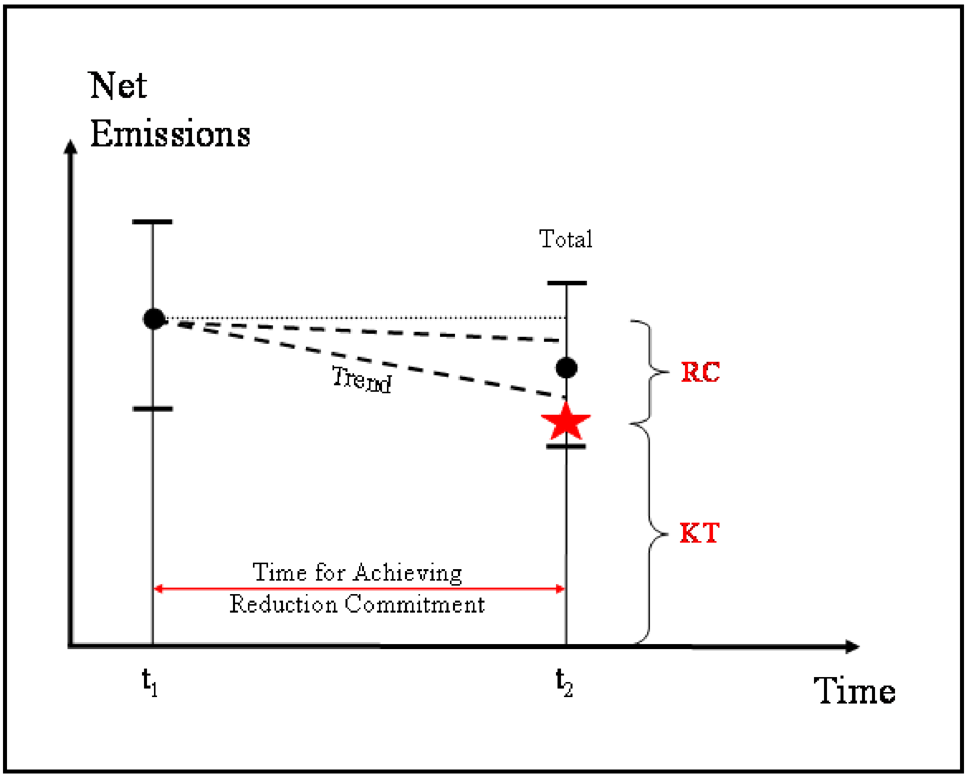

Figure 6: IPCC's definition of uncertainty with respect to two predefined points in time based on two different types of uncertainty, total and trend uncertainty (see text for references). KT: Kyoto emission target; RC: emission reduction commitment.

Looking ahead, we consider the merging of bottom up–top down (dual constrained) verification, as pursued by the global carbon research community, with temporal "verification" (better: signal detection), as demanded by the Kyoto Protocol, as a major research challenge. Box 1 visualizes this challenge graphically.[16]

2.4 Uncertainty Concept

An important question that remains to be answered is how to go about a mismatch of measured (or measurement-based) mean values including their uncertainties under validation or verification? Below, we propose an uncertainty concept that has already been put into practice under FCA to address the issue of consistency, as required for any system, or set of systems, under consistent FCA. The concept is presented graphically in Figure 7 (and discussed in more detail in Nilsson *et al.*, 2000:Section 2.5; Jonas and Nilsson, 2001:Section 2.2.2).

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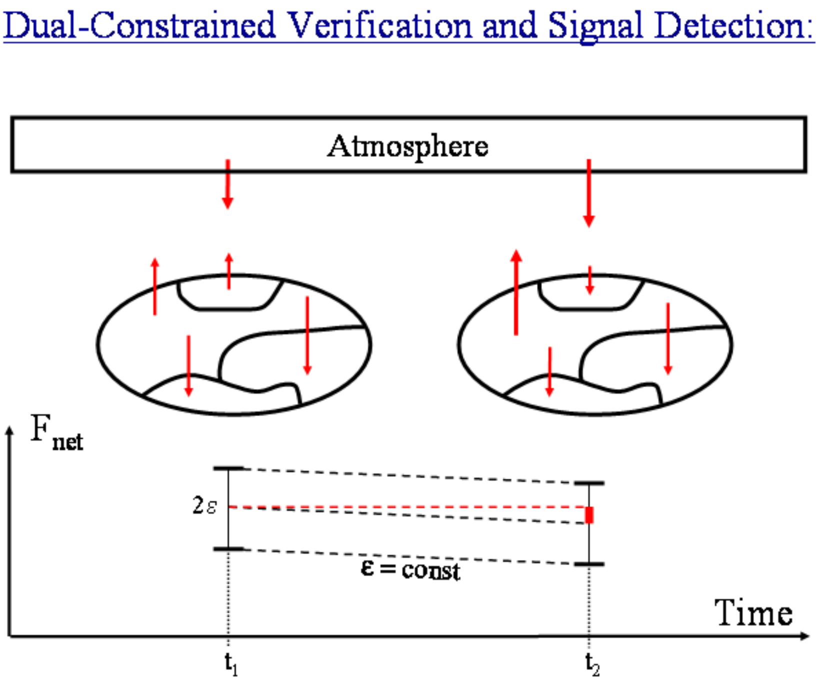
[16] In Box 1 as well as in the remainder of the study, we use ε to symbolize total uncertainty. We prefer ε over σ, which is commonly used, to indicate that our understanding of uncertainty may go beyond the classical statistical understanding of uncertainty (see also Section 2.4).

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 to achieve robust and sound verification.

The uncertainty 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. (The term *value* may be understood, e.g., as the net atmospheric carbon emissions of a country. Only a measurement device, located in the atmosphere, which would measure the country’s net carbon flux into the atmosphere, would permit cross-checking the ground-based experts’ estimate and thus the elimination of 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, as shown in the figure, 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.

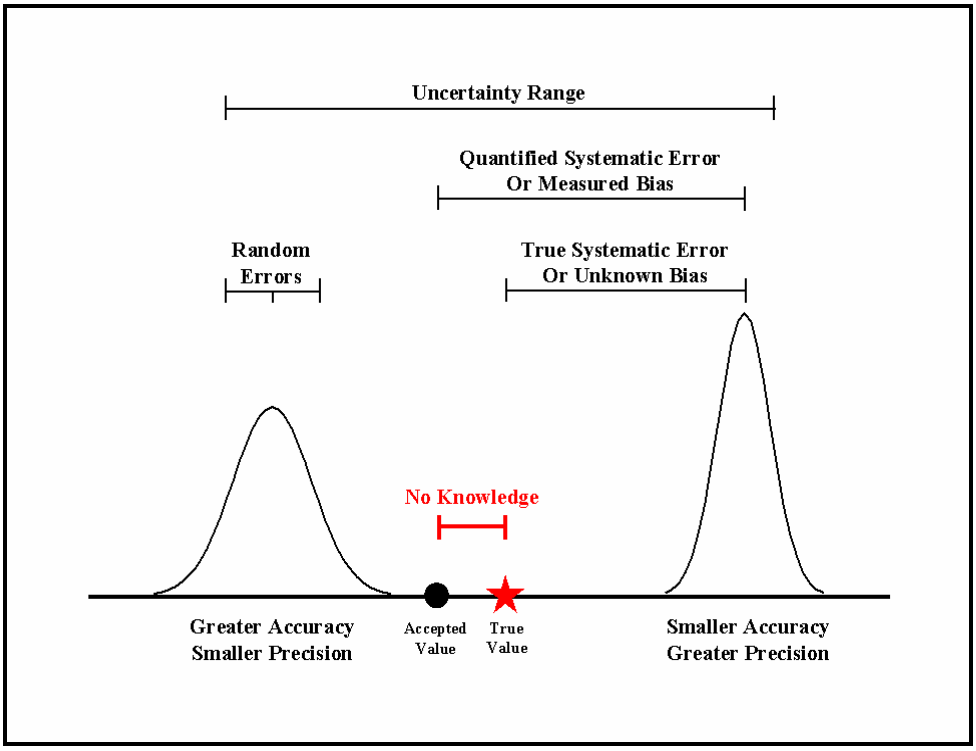


Figure 7: The uncertainty concept applied under FCA to address the issue of consistency. The hypothetical starting point is an uncertainty range for two sets of measurements of the same phenomenon. Here, the uncertainty range encompasses each of the two measured biases plus each of the two standard deviations representing the random errors of the underlying measurement sets. Sources: Nilsson *et al.* (2000:Section 2.5), Jonas and Nilsson (2001:Section 2.2.2).

In IIASA's FCA studies with a focus on Russia and Austria, the term *uncertainty* was used exclusively in accordance with the International Organization for Standardization (ISO, 1995) (see also Taylor and Kuyatt, 1994; NIST, 2001). For instance, the Austrian study only deals (with a few exceptions) with measured or measurement-based data, which are available either from one-sided statistics (a complementary data set does not exist) or from two-sided statistics (a complementary data set exists). Thus, the term *uncertainty* stands for random error or (0.5 * uncertainty range). Soft knowledge is generally not dealt with (thus, measured biases are not considered).

3 Preparatory Signal Detection

In this section we present four hierarchically-ordered detection concepts to assess emission signals in a preparatory manner, that is, at two predefined points in time, t_1 in the past/present (typically the base year) when emissions are known, and t_2 in the future (typically the commitment year/period) when emissions are supposed to meet an agreed-upon target. These concepts allow to generate useful information beforehand as to how great uncertainties can be depending on the emission signal one wishes to detect and whether or not one tolerates risk. It is this knowledge on the required quality of reporting vis-à-vis uncertainty that one wishes to have at hand before negotiating international environmental treaties such as the Kyoto Protocol.

In contrast to signal detection in retrospect ($t = t_2$) and midway signal detection ($t_1 < t < t_2$), preparatory signal detection is straightforward and requires the least effort. The four preparatory concepts presented in Sections 3.1–3.4 are the critical relative uncertainty (CRU) concept, the verification time (VT) concept, the undershooting (Und) concept, and the undershooting and verification time (Und&VT) concepts combined. They can be considered standard as well as novel. Their main features are summarized in Table 3.

Table 3: The four preparatory signal detection concepts presented in Sections 3.1–3.4. Common to all of them is that the emission signal is investigated with reference to only two pre-defined points in time (t_1 and t_2).

Taken into Account by the Technique	Preparatory Signal Detection Technique			
	Section 3.1 CRU	**Section 3.2 VT**	**Section 3.3 Und**	**Section 3.4 Und&VT**
Uncertainty	✓	✓	✓	✓
Emission gradient between t_1 and t_2		✓		✓
Undershooting			✓	✓
Risk of not meeting committed target			✓	✓
Corrected undershooting/risk				✓
Relevant background documents	Jonas and Nilsson (2001:Section 3.1.3); Gusti and Jęda (2002:Section 3.2)	Jonas *et al.* (1999, 2004a,b); Jonas and Nilsson (2001:Section 3.1.2)	Nahorski *et al.* (2003)	

The following three arrangements facilitate easy notation throughout Sections 3.1–3.4:

(1) Annex I countries are classified according to their emission limitation or reduction commitments (as a percentage of base year or period) under the Kyoto Protocol. Thus, they can be grouped into eight classes (see Table 4).

(2) As already indicated in Section 2.3, different combinations of time points are referred to in the context of the Kyoto Protocol to account for GHG emissions and

removals by sink and source categories on the level of countries. Without restricting generality, we continue to use t_1 and t_2. They may refer to any two points on the time scale $T_0 = 1990$, …, $T_{15} = 2005$, …, $T_{18} = 2008$, …, $T_{20} = 2010$, …, $T_{22} = 2012$.[17]

(3) The Protocol assigns different base years/periods to CO_2, CH_4 and N_2O on the one hand and to the fluorinated gases on the other hand (see Table 4). However, as the Annex I countries' emissions of CO_2, CH_4 and N_2O by far exceed those of the fluorinated gases (HCFs, PCFs, SF_6) (see the GHG Inventory Database of the UNFCCC: http://ghg.unfccc.int/), we can use the "CO_2-CH_4-N_2O system of gases" as a reference in connection with temporal considerations, e.g., when we specify the time between a country's base year/period and its commitment year/period.

Table 4: Emission limitation and reduction commitments of Annex I countries under the Kyoto Protocol (KP). See ISO Country Code for country abbreviations. Sources: FCCC (1996:Annex B, Decision 9/CP.2); (1998:Article 3.8); (1999:Decision 11/CP.4).

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

Note: 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.

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[17] In Section 3, the year 2010 is used as commitment year if t_2 refers to the temporal average in net emissions over the commitment period 2008–2012.

3.1 Critical Relative Uncertainty Concept

Starting Point:	Annex I 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 is symmetrical and does not change over time, i.e., $\rho(t_1) = \rho(t_2)$. (2) The absolute change in net emissions outstrips uncertainty at t_2; i.e., the risk (probability) at t_2 is zero (one) that a country's net emissions are above (below) its base year emission levels in the case of a committed emission reduction (limitation).
Key Question:	What are the critical (or maximal) relative uncertainties that can be reported by Annex I countries so as to ensure favorable detection in the commitment year?

With x_i denoting the net emissions (best estimate) and ε_i their absolute uncertainty at t_i (i = 1, 2), we can write for the relative uncertainty:

$$\rho = \frac{\varepsilon_1}{x_1} = \frac{\varepsilon_2}{x_2} = \text{const} \qquad (1a,b,c)$$

and for the ratio of emissions:

$$1 - \delta = \frac{x_2}{x_1} \qquad (2)$$

with $\delta := \delta_{KP}$, where δ_{KP} is the normalized emissions change committed under the Kyoto Protocol (KP) between t_1 and t_2 ($\delta_{KP} > 0$: emission reduction; $\delta_{KP} \le 0$: emission limitation). Requiring that the absolute change in emissions outstrips uncertainty,

$$|x_1 - x_2| > \varepsilon_2 \qquad (3)$$

(see Figure 8 and also Appendix A), and making use of equations (1) and (2), we find:

$$|x_1 - (1-\delta_{KP})x_1| > (1-\delta_{KP})\varepsilon_1 \qquad (4)$$

or

$$\frac{|\delta_{KP}|}{(1-\delta_{KP})} > \rho \ , \qquad (5)$$

where

$$\rho_{crit} := \frac{|\delta_{KP}|}{(1-\delta_{KP})} \qquad (6)$$

is called the CRU (Gusti and Jęda, 2002:Section 3.2).

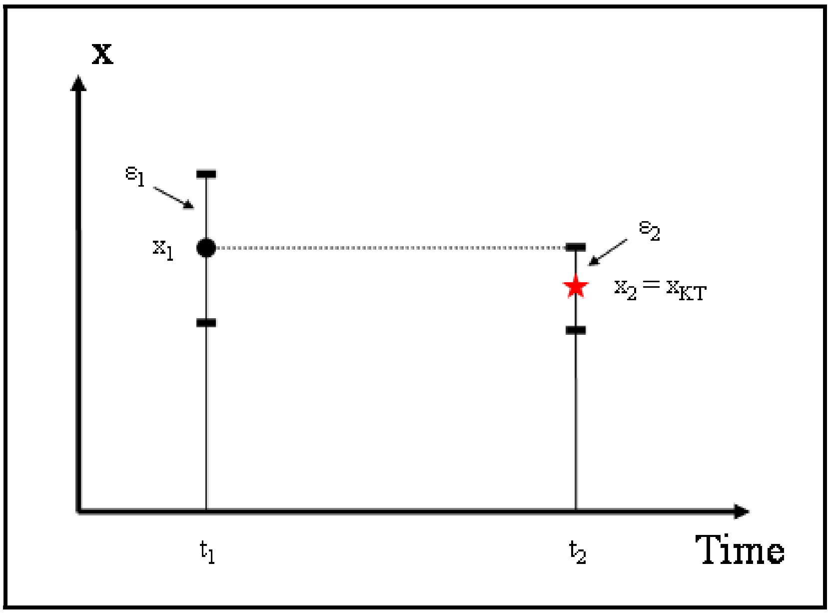

Figure 8: Illustration of the CRU concept $\left(\rho_1 = \rho_2\right)$: The absolute change in emissions, $\left|x_1 - x_2\right| = \left|\delta_{KP}\right| x_1$, outstrips uncertainty at t_2. KT: Kyoto target.

Figure 9 displays equation (6) graphically, along with the positions that groups of Annex I countries hold (see also Table 5). For instance, a country of group 1 has committed itself to reduce its net emissions by 8% ($(1-\delta_{KP})$-axis). In the case of perfect compliance and under the condition of constant relative uncertainty, the country's net emissions in the commitment year (t_2) can only be detected favorably according to this concept if they are reported with a relative uncertainty that is smaller than 8.7% (ρ_{crit} axis). With reference to the uncertainty estimates available from EU Member States, it appears that this value is difficult to achieve even for data rich and reliable countries like, for instance, Austria and Great Britain (see Table 2).[18]

Note that a major dissimilarity exists between emission limitation ($\delta_{KP} \leq 0$) and reduction ($\delta_{KP} > 0$). In the case of undershooting (increase in δ), Annex I countries committed to emission limitation must decrease their uncertainties in order to stay verifiable; their CRUs decrease. In contrast, countries committed to emission reduction do not need to do so; their uncertainties can even increase because their CRUs increase and can be more easily met. The opposite is true in the case of overshooting (decrease in δ). Now, Annex I countries committed to emission reduction must decrease their uncertainties in order to stay detectable, while countries committed to emission limitation can even increase their uncertainties because their CRUs increase and can be more easily met. As also illustrated by Figure 9, the stabilized emissions case ($\delta_{KP} = 0$)

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[18] Finland's and Netherlands' overall uncertainty estimates for CO_2, CH_4 and N_2O are smaller than Austria's and Great Britain's (see Table 2), mainly because of their smaller uncertainty estimates for CH_4 (in comparison to Austria's) and N_2O (in comparison to Austria's and Great Britain's). Our experience indicates that Finland's and Netherlands' uncertainty estimates for CH_4 and N_2O are possibly too over-optimistic.

requires relative uncertainties that are at least “small”. It becomes immediately obvious that this dissimilarity between emission limitation and reduction, which we will also encounter in the following section, will have far-reaching consequences, e.g., as to how emissions are rated economically. This dissimilarity is a direct consequence of not demanding δ_{KP} that is uniform for all countries under the Kyoto Protocol.

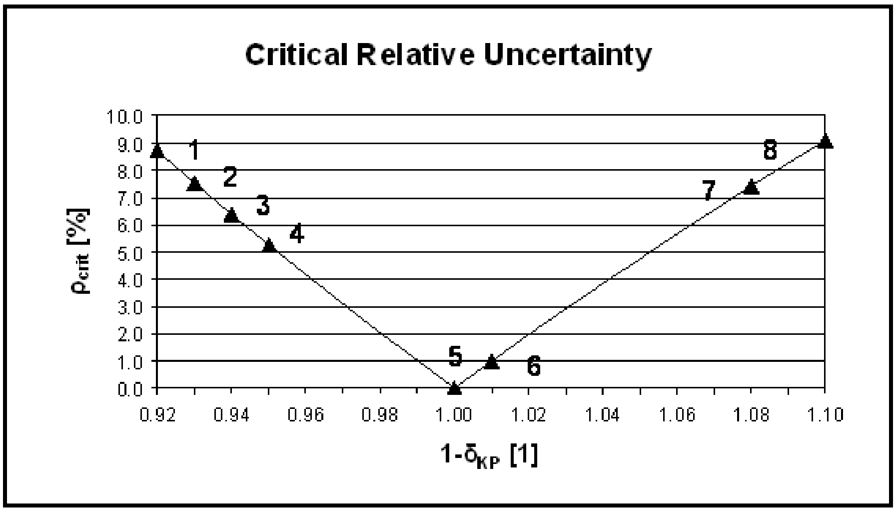

Figure 9: Critical relative uncertainty for Annex I countries according to equation (6). See Table 5 for country grouping.

3.2 Verification Time Concept

Starting Point: Annex I 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 is symmetrical and does not change over time, i.e., $\rho(t_1) = \rho(t_2)$.

(2) The absolute change in net emissions outstrips uncertainty at times $\leq$ or $>$ t_2; i.e., the risk (probability) at these times is zero (one) that a country’s net emissions are above (below) its base year emission levels in the case of a committed emission reduction (limitation).

Key Question: What are the times (also called verification times) until the countries’ emission signals outstrip uncertainty?

Table 5: The CRU concept (equation (6)) applied to Annex I countries. In the last column, we assess the hypothetical situation that the CRU concept had been applied prior to/in negotiating the Kyoto Protocol. Note the over-/undershooting dissimilarity between countries committed to emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \leq 0$).

Country Group	Base Year(s) for CO_2, CH_4, N_2O	Commitment Period	KP Commitment δ_{KP}[a] %	CRU ρ_{crit} %	If the CRU Concept had been applied
1a	1990	2008–12	8.0	8.7	(a) Compliance with the target: It must be expected that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/ removals due to LUCF. Thus, it is virtually impossible for most of the countries in groups 1–4 to meet the condition that their overall relative uncertainties are smaller than their CRUs ($\rho < \rho_{crit}$).
1b	1988	2008–12			
1c	1989	2008–12			
1d	1986	2008–12			
2	1990	2008–12	7.0	7.5	
3a	1990	2008–12	6.0	6.4	
3b	1985–87	2008–12			
3c	1988	2008–12			
4	1990	2008–12	5.0	5.3	(b) Overshooting the target: To unambiguously attest a decrease in emissions, Annex I countries would have to fulfill even smaller CRUs as given in the column to the left.
--	--	--	4.0	4.2	
--	--	--	3.0	3.1	
--	--	--	2.0	2.0	
--	--	--	1.0	1.0	(c) Undershooting the target: CRUs increase and could be met more easily.
5	1990	2008–12	0.0	0.0	(a) Compliance with the target: Same conclusion for countries in groups 5–8 as for countries committed to emission reduction (see (a) above).
6	1990	2008–12	-1.0	1.0	
--	--	--	-2.0	2.0	
--	--	--	-3.0	2.9	(b) Overshooting the target: CRUs increase and could be met more easily.
--	--	--	-4.0	3.8	
--	--	--	-5.0	4.8	(c) Undershooting the target: To unambiguously attest a decrease in emissions, Annex I countries would have to fulfill even smaller CRUs (as given in the column to the left).
--	--	--	-6.0	5.7	
--	--	--	-7.0	6.5	
7	1990	2008–12	-8.0	7.4	
--	--	--	-9.0	8.3	
8	1990	2008–12	-10.0	9.1	

[a] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ — emission reduction; $\delta_{KP} \leq 0$ — emission limitation.

To analyze the impact of uncertainty on the detectability of emission signals exhibiting different dynamics, we make use of the VT concept,[19] which requires that the absolute change in net emissions (absolute emission signal) at time t_2, $\left|\Delta x(t_2)\right|$, is greater than the total uncertainty in the net emissions at time t_2, $\varepsilon(t_2)$ (Jonas *et al.*, 1999; Jonas and Nilsson, 2001:Section 3.1.2; see Figure 10 and also Appendix A). Mathematically, this condition is expressed as

$$\left|\Delta x(t_2)\right| > \varepsilon(t_2) \; . \tag{7}$$

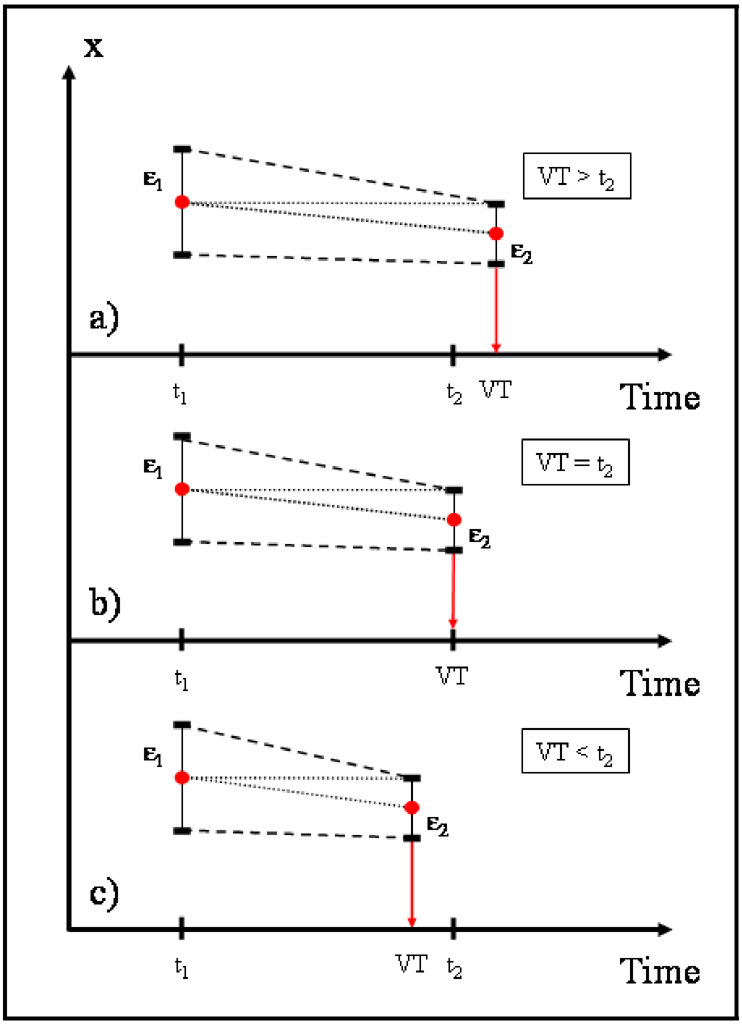

Figure 10: Illustration of the VT concept $(\rho_1 = \rho_2)$: The absolute change in emissions, $\left|x_1 - x_2\right| = \left|\delta_{KP}\right| x_1$, outstrips uncertainty at a) $VT > t_2$, b) $VT = t_2$ and c) $VT < t_2$.

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[19] The term "Verification Time" was first used by Jonas *et al.* (1999) 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 in this study 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.

Making use of linear approximations — in line with preparatory signal detection — we can specify $\left|\Delta x\left(t_2\right)\right|$ and write for $\varepsilon\left(t_2\right)$:

$$\left|\frac{dx}{dt}\right|_{t_1} \Delta t > \varepsilon\left(t_1\right) + \left(\frac{d\varepsilon}{dt}\right)_{t_1} \Delta t \ . \tag{8}$$

Rearranging inequality (8), we can solve for the VT, the minimal time Δt required for the emission signal to outstrip its underlying uncertainty:

$$\Delta t > \frac{\varepsilon\left(t_1\right)}{\left|\frac{dx}{dt}\right|_{t_1} - \left(\frac{d\varepsilon}{dt}\right)_{t_1}} \ , \tag{9}$$

where:

$$\left|\frac{dx}{dt}\right|_{t_1} > \left(\frac{d\varepsilon}{dt}\right)_{t_1} \ . \tag{10}$$

With the help of δ_{KP}, the committed normalized change in emissions between t_1 and t_2 (see Section 3.1), we can write for two terms in the denominator on the right side of inequality (9):

$$\left|\frac{dx}{dt}\right|_{t_1} = \frac{\left|\delta_{KP}\right|}{t_2 - t_1} x\left(t_1\right) \tag{11}$$

$$\left(\frac{d\varepsilon}{dt}\right)_{t_1} = -\frac{\delta_{KP}}{t_2 - t_1} \varepsilon\left(t_1\right) \ . \tag{12}$$

Thus, inequality (9) reads:

$$\Delta t > \frac{\varepsilon\left(t_1\right)}{\left|\delta_{KP}\right| x\left(t_1\right) + \delta_{KP} \varepsilon\left(t_1\right)} \left(t_2 - t_1\right) \ ; \tag{13}$$

or, if the VT is normalized and expressed with the help of the relative uncertainty ρ:

$$\frac{\Delta t}{t_2 - t_1} > \frac{\rho}{\left|\delta_{KP}\right| + \delta_{KP} \rho} = \frac{\rho}{\left|\delta_{KP}\right| \left\{1 + \mathrm{sgn}\left(\delta_{KP}\right) \rho\right\}} \ . \tag{14a,b}$$

The right side of inequality (14) becomes 1 for $\rho = \rho_{crit}$, the CRU (see equation (6)). Table 6 lists with the help of inequality (14a) the normalized VTs for all Annex 1 countries under the Kyoto Protocol. The VT concept provides a more generalized detection perspective for negotiators of the Protocol than the CRU concept presented in Section 3.1 because it quantifies in more detail what the consequences are in the form of normalized VTs if countries report emissions with relative uncertainties that are ≤ or > ρ_{crit}.

Table 6: The VT concept (inequality (14a)) applied to Annex I countries. In the table, the countries' maximal allowable VTs ($t_2 - t_1$) are reported instead of their base years and commitment periods (see second and third columns in Table 5). The table should be read as follows: The maximal allowable VT for an Annex 1 country is given for $\rho = \rho_{\text{crit}}$. For instance, for a country of group 1a the maximal allowable VT is 20 years or 1, if normalized. Normalized VTs equal to or smaller than 1 (see green fields for emission reduction and orange fields for emission limitation) are compatible with the Kyoto Protocol, i.e., countries report with $\rho \leq \rho_{\text{crit}}$; normalized VTs greater than 1 (see red fields) are not, i.e., countries report with $\rho > \rho_{\text{crit}}$. In the last column, we assess the hypothetical situation that the VT concept had been applied prior to/in negotiating the Kyoto Protocol. Note the over/undershooting dissimilarity between countries committed to emission reduction ($\delta_{\text{KP}} > 0$) and emission limitation ($\delta_{\text{KP}} \leq 0$).

Country Group	Max. Allow. VT[a] t_2 - t_1	KP Commit. δ_{KP}[b]	CRU ρ_{crit}	Normalized VTs if Countries report with ρ =				If the VT Concept had been applied
	yr	%	%	2.5%	7.5%	15%	30%	
1a	20	8.0	8.7	0.3	0.9	1.6	2.9	(a) Compliance with the target: It must be expected that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/ removals due to LUCF. Thus, it is virtually impossible for most of the countries in groups 1–4 to meet the condition ρ < ρ_{crit} or, equivalently, achieve normalized VTs ≤ 1. (b) Overshooting the target: To unambiguously attest a decrease in emissions, Annex I countries would have to fulfill even smaller CRUs as given in the column to the left or, equivalently, find it even more difficult complying with normalized VTs ≤ 1. (c) Undershooting the target: CRUs increase and could be met more easily or, equivalently, compliance with VTs ≤ 1 becomes less difficult.
1b	22							
1c	21							
1d	24							
2	20	7.0	7.5	0.3	< 1.0	1.9	3.3	
3a	20	6.0	6.4	0.4	1.2	2.2	3.8	
3b	24							
3c	22							
4	20	5.0	5.3	0.5	1.4	2.6	4.6	
--	--	4.0	4.2	0.6	1.7	3.3	5.8	
--	--	3.0	3.1	0.8	2.3	4.3	7.7	
--	--	2.0	2.0	1.2	3.5	6.5	11.5	
--	--	1.0	1.0	2.4	7.0	13.0	23.1	
5	20	0.0	0.0	infinite				(a) Compliance with the target: Same conclusion for countries in groups 5–8 as for countries committed to emission reduction (see (a) above). (b) Overshooting the target: CRUs increase and could be met more easily or, equivalently, compliance with VTs ≤ 1 becomes less difficult. (c) Undershooting the target: To unambiguously attest a decrease in emissions, Annex I countries would have to fulfill even smaller CRUs as given in the column to the left or, equivalently, find it even more difficult complying with normalized VTs ≤ 1.
6	20	-1.0	1.0	2.6	8.1	17.6	42.9	
--	--	-2.0	2.0	1.3	4.1	8.8	21.4	
--	--	-3.0	2.9	0.9	2.7	5.9	14.3	
--	--	-4.0	3.8	0.6	2.0	4.4	10.7	
--	--	-5.0	4.8	0.5	1.6	3.5	8.6	
--	--	-6.0	5.7	0.4	1.4	2.9	7.1	
--	--	-7.0	6.5	0.4	1.2	2.5	6.1	
7	20	-8.0	7.4	0.3	> 1.0	2.2	5.4	
--	--	-9.0	8.3	0.3	0.9	2.0	4.8	
8	20	-10.0	9.1	0.3	0.8	1.8	4.3	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{\text{KP}} > 0$ – emission reduction; $\delta_{\text{KP}} \leq 0$ – emission limitation.

In short, the VT concept corroborates what has already been indicated by the CRU concept and which is a direct consequence of not demanding δ_{KP} that is uniform for all countries under the Protocol. For countries committed to an emission limitation ($\delta_{KP} \leq 0$), both the VT and the CRU concepts favor increasing over decreasing emissions, which is not in line with the spirit of the Kyoto Protocol.

The VT concept has also been expressed on a probabilistic basis (Hudz, 2002; Hudz *et al.*, 2002). However, before applying this approach in a preparatory signal detection context, we considered it more important to further deal with the over/undershooting dissimilarity of the VT concept between countries committed to emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \leq 0$) (see Section 3.4).

3.3 Undershooting Concept

Starting Point: Annex I 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 might exist between the true but unknown net emissions and their best estimates.

(2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $\rho(t_1) = \rho(t_2)$.

Key Question: Taking into account the combined uncertainty at t_2 and considering that the true emissions are not known, how much undershooting is required to decrease the risk that countries do not undershoot (i.e., overshoot) their true emission limitation or reduction commitments?

To capture any potential difference at t_i between the true (t) but unknown net emissions $x_{t,i}$ and their best estimate x_i, we introduce ε_i (i = 1, 2):

$$\left|x_{t,1} - x_1\right| \leq \varepsilon_1 \ , \ \left|x_{t,2} - x_2\right| \leq \varepsilon_2 \ . \tag{15), (16}$$

Applying the triangle inequality to the differences at t_2 between target and actual emissions with respect to both the true emissions and their best estimates, we find:

$$\left|\underbrace{\left\{(1-\delta_{KP})x_1 - x_2\right\}}_{\substack{\text{Best estimates:}\\ \text{Target — Actual}}} - \underbrace{\left\{(1-\delta_{KP})x_{t,1} - x_{t,2}\right\}}_{\substack{\text{True emissions:}\\ \text{Target — Actual}}}\right|$$

$$= \left|-(1-\delta_{KP})(x_{t,1} - x_1) + (x_{t,2} - x_2)\right| \tag{17a,b}$$

$$\leq (1-\delta_{KP})\left|x_{t,1} - x_1\right| + \left|x_{t,2} - x_2\right| = (1-\delta_{KP})\varepsilon_1 + \varepsilon_2 \ . \tag{17c}$$

Let

$$\varepsilon_{12} := \left(1-\delta_{\mathrm{KP}}\right)\varepsilon_1 + \varepsilon_2 \tag{18}$$

denote the combined uncertainty at t_2.[20] Thus:

$$\left\{\left(1-\delta_{\mathrm{KP}}\right)x_1 - x_2\right\} - \left\{\left(1-\delta_{\mathrm{KP}}\right)x_{t,1} - x_{t,2}\right\} \in \left[-\varepsilon_{12}, \varepsilon_{12}\right] \tag{19}$$

or

$$x_{t,2} - \left(1-\delta_{\mathrm{KP}}\right)x_{t,1} \in \left[\mathrm{Dx} - \varepsilon_{12}, \mathrm{Dx} + \varepsilon_{12}\right] \ , \tag{20}$$

where:

$$\mathrm{Dx} := x_2 - \left(1-\delta_{\mathrm{KP}}\right)x_1 \ .^{21} \tag{21}$$

We now introduce α to capture the risk that $x_{t,2}$ is equal to or greater than $\left(1-\delta\right)x_{t,1}$ with the help of:

$$\mathrm{Dx} + \varepsilon_{12} \le 2\alpha\varepsilon_{12} \ , \tag{22}$$

where $0 \le \alpha \le 0.5$ (see Figure 11). The risk $\alpha = 0.5$ corresponds to the situation $\mathrm{Dx} = 0 \Leftrightarrow x_2 = \left(1-\delta_{\mathrm{KP}}\right)x_1$, when we can judge with equal confidence that $x_{t,2}$ is ≤ or $\ge \left(1-\delta_{\mathrm{KP}}\right)x_{t,1}$. With Dx decreasing ($\mathrm{Dx} < 0$), the risk α also decreases that $x_{t,2} \ge \left(1-\delta_{\mathrm{KP}}\right)x_{t,1}$.

Rewriting inequality (22), we find:

$$\frac{x_2}{x_1} \le \left(1-\delta_{\mathrm{KP}}\right) - \left(1-2\alpha\right)\frac{\varepsilon_{12}}{x_1} = 1 - \left\{\delta_{\mathrm{KP}} + \left(1-2\alpha\right)\frac{\varepsilon_{12}}{x_1}\right\} \ . \tag{23a,b}$$

---

[20] Equation (18) does not consider any correlation between ε_1 and ε_2 as the triangle inequality does not permit doing so. As a consequence, ε_{12} is greater than ε_1 as well as ε_2 (for the range of δ_{KP} values considered under the Kyoto Protocol).

[21] With the help of the inequalities (15) and (16) in the form of

$$x_{t,1} \in \left[x_1 - \varepsilon_1, x_1 + \varepsilon_1\right] \ , \ x_{t,2} \in \left[x_2 - \varepsilon_2, x_2 + \varepsilon_2\right] \ , \tag{15a), (16a}$$

inequality (20) can also be derived if interval calculus is applied to the difference $x_{t,2} - \left(1-\delta_{\mathrm{KP}}\right)x_{t,1}$ at t_2 (Nahorski *et al.*, 2003):

$$x_{t,2} - \left(1-\delta_{\mathrm{KP}}\right)x_{t,1} \in \left[x_2 - \varepsilon_2, x_2 + \varepsilon_2\right] - \left(1-\delta_{\mathrm{KP}}\right)\left[x_1 - \varepsilon_1, x_1 + \varepsilon_1\right] \tag{20a}$$

$$= \left[x_2, x_2\right] + \left[-\varepsilon_2, \varepsilon_2\right] - \left(1-\delta_{\mathrm{KP}}\right)\left[x_1, x_1\right] + \left[-\left(1-\delta_{\mathrm{KP}}\right)\varepsilon_1, \left(1-\delta_{\mathrm{KP}}\right)\varepsilon_1\right] \tag{20b}$$

$$= \left[x_2 - \left(1-\delta_{\mathrm{KP}}\right)x_1, x_2 - \left(1-\delta_{\mathrm{KP}}\right)x_1\right] + \left[-\left(1-\delta_{\mathrm{KP}}\right)\varepsilon_1 - \varepsilon_2, \left(1-\delta_{\mathrm{KP}}\right)\varepsilon_1 + \varepsilon_2\right] \tag{20c}$$

$$= \left[\mathrm{Dx} - \varepsilon_{12}, \mathrm{Dx} + \varepsilon_{12}\right] \ . \tag{20}$$

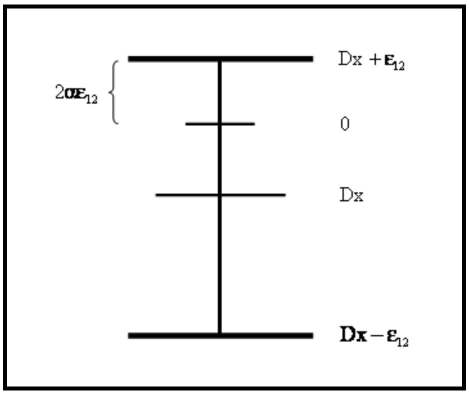

Figure 11: Illustration of the risk α ($0 \leq \alpha \leq 0.5$) to capture the situation $x_{t,2} \geq (1-\delta_{KP})x_{t,1}$. Source: Modified from Nahorski *et al.* (2003).

Using equations (1a,b) in combination with equation (18), $\frac{\varepsilon_{12}}{x_1}$ can be expressed as:

$$\frac{\varepsilon_{12}}{x_1} = (1-\delta_{KP})\rho + \frac{x_2}{x_1}\rho \tag{24}$$

and inserted into equation (23a):

$$\frac{x_2}{x_1} \leq (1-\delta_{KP}) - (1-2\alpha)\left\{(1-\delta_{KP})\rho + \frac{x_2}{x_1}\rho\right\} \ . \tag{25}$$

After rearrangement:

$$\frac{x_2}{x_1} \leq (1-\delta_{KP})\frac{1-(1-2\alpha)\rho}{1+(1-2\alpha)\rho} = (1-\delta_{KP})\frac{\{1-(1-2\alpha)\rho\}^2}{1-(1-2\alpha)^2\rho^2} \ . \tag{26a,b}$$

For the ranges of α and ρ values, which are of interest and which we consider in Table 7, we can approximate inequality (26b) by

$$\approx (1-\delta_{KP})\{1-2(1-2\alpha)\rho\} \tag{26c}$$

$$= 1-\delta_{KP} - 2(1-2\alpha)(1-\delta_{KP})\rho = 1-\{\delta_{KP} + 2(1-2\alpha)(1-\delta_{KP})\rho\} \ . \tag{26d,e}$$

The last term on the right of inequality (26d),

$$U := 2(1-2\alpha)(1-\delta_{KP})\rho \ , \tag{27}$$

allows calculating the amount of undershooting, which is required for decreasing the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk that one is willing to tolerate vis-à-vis the combined uncertainty ε_{12} (Nahorski *et al.*, 2003). Table 7 lists with the help of the second term on the right of inequality (26e),

$$\delta_{\text{mod}} := \delta_{\text{KP}} + \text{U} = \delta_{\text{KP}} + 2(1-2\alpha)(1-\delta_{\text{KP}})\rho \ ,^{22} \tag{28a,b}$$

modified (mod) emission limitation or reduction targets for all Annex I countries, where the "$\text{x}_{t,2}$-greater-than-$(1-\delta_{\text{KP}})\text{x}_{t,1}$" risk is specified to be 0, 0.1, 0.3 and 0.5. For comparison, Table B1 in Appendix B does the same but makes use of inequality (26a).

Table 7 (see last column) 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 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 $\rho = 7.5\%$ and $\alpha = 0.3$). Such a situation is not in line with the spirit of the Kyoto Protocol.

However, the situation is 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 currently discussed contraction and convergence (C&C) approach (e.g., WBGU, 2003; Pearce, 2003). Under such conditions, it is the undershooting U that matters, not the modified emission limitation or reduction target $\delta_{\text{mod}} = \delta_{\text{KP}} + \text{U}$. Table 8 shows the undershooting U that is contained in the modified emission limitation and reduction targets δ_{mod} listed in Table 7. For comparison, Table B2 in Appendix B shows the undershooting U that is contained in the accurate modified emission limitation and reduction targets δ_{mod} listed in Table B1.

However, here we proceed on the assumption that the emission limitation or reduction commitments δ_{KP} under the Kyoto Protocol were arbitrarily set.

Appendix C generalizes the Und concept stochastically.

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[22] Equations (27) and (28b) can also be derived if equation (24) is approximated by

$$\frac{\varepsilon_{12}}{\text{x}_1} \le 2(1-\delta_{\text{KP}})\rho \ , \tag{24b}$$

and can, as a consequence, be formulated more correctly:

$$\text{U} \le 2(1-2\alpha)(1-\delta_{\text{KP}})\rho \tag{27a}$$

$$\delta_{\text{mod}} \le \delta_{\text{KP}} + 2(1-2\alpha)(1-\delta_{\text{KP}})\rho \ . \tag{28c}$$

Table 7: The Und concept (equation (28b)) applied to Annex I countries. The table lists modified emission limitation or reduction targets δ_{mod} for all Annex I 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 table should be read as follows: If an Annex I country complies with its emission limitation or 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 by 21.8% to decrease the risk from 50% to 0%. In the last column, we assess the hypothetical situation that the Und concept had been applied prior to/in negotiating the Kyoto Protocol. Note the politically unfavorable situation, which arises when δ_{KP} varies while ρ and α are kept constant. In the table, the countries' maximal allowable VTs as well as their CRUs are also reported (see Tables 5 and 6).

Country Group	**Max. Allow. VT**[a] **t_2 - t_1** **yr**	**KP Commit. δ_{KP}**[b] **%**	**CRU ρ_{crit}** **%**	**Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ =** **2.5%** **and** α = 0.0 α = 0.1 α = 0.3 α = 0.5	**7.5%** α = 0.0 α = 0.1 α = 0.3 α = 0.5	**15%** α = 0.0 α = 0.1 α = 0.3 α = 0.5	**30%** α = 0.0 α = 0.1 α = 0.3 α = 0.5	**If the Und Concept had been applied**
1a **1b** **1c** **1d**	20 22 21 24	8.0	8.7	12.6 11.7 9.8 8.0	21.8 19.0 13.5 8.0	35.6 30.1 19.0 8.0	63.2 52.2 30.1 8.0	(a) For given δ_{KP} and α: The greater the ρ, the greater the modified emission reduction target δ_{mod} is that keeps the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk α at a constant level (see, e.g., country group 1: third line: δ_{mod} values for α = 0.3). (b) For given ρ and α: The smaller the δ_{KP}, the smaller the modified emission reduction target δ_{mod} is that keeps the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk α at a constant level (see, e.g., δ_{mod} values for ρ = 7.5% and α = 0.3). As a consequence, countries complying with a smaller δ_{KP} (they exhibit a small δ_{mod}) are better off than countries that must comply with a greater δ_{KP} (they exhibit a great δ_{mod}).
2	20	7.0	7.5	11.7 10.7 8.9 7.0	21.0 18.2 12.6 7.0	34.9 29.3 18.2 7.0	62.8 51.6 29.3 7.0	
3a **3b** **3c**	20 24 22	6.0	6.4	10.7 9.8 7.9 6.0	20.1 17.3 11.6 6.0	34.2 28.6 17.3 6.0	62.4 51.1 28.6 6.0	
4	20	5.0	5.3	9.8 8.8 6.9 5.0	19.3 16.4 10.7 5.0	33.5 27.8 16.4 5.0	62.0 50.6 27.8 5.0	
--	--	4.0	4.2	8.8 7.8 5.9 4.0	18.4 15.5 9.8 4.0	32.8 27.0 15.5 4.0	61.6 50.1 27.0 4.0	
--	--	3.0	3.1	7.9 6.9 4.9 3.0	17.6 14.6 8.8 3.0	32.1 26.3 14.6 3.0	61.2 49.6 26.3 3.0	
--	-	2.0	2.0	6.9 5.9 4.0 2.0	16.7 13.8 7.9 2.0	31.4 25.5 13.8 2.0	60.8 49.0 25.5 2.0	
--	--	1.0	1.0	6.0 5.0 3.0 1.0	15.9 12.9 6.9 1.0	30.7 24.8 12.9 1.0	60.4 48.5 24.8 1.0	

Table 7: continued.

5	20	0.0	0.0	5.0	15.0	30.0	60.0	(a) For given δ_{KP} and α: Same conclusion for country groups 5–8 as for countries committed to emission reduction (see (a) above).
				4.0	12.0	24.0	48.0	
				2.0	**6.0**	**12.0**	**24.0**	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	4.1	14.2	29.3	59.6	(b) For given ρ and α: Same conclusion for country groups 5–8 as for countries committed to emission reduction (see (b) above).
				3.0	11.1	23.2	47.5	
				1.0	**5.1**	11.1	23.2	
				-1.0	-1.0	-1.0	-1.0	
--	--	-2.0	2.0	3.1	13.3	28.6	59.2	
				2.1	10.2	22.5	47.0	
				0.0	**4.1**	10.2	22.5	
				-2.0	-2.0	-2.0	-2.0	
--	--	-3.0	2.9	2.2	12.5	27.9	58.8	
				1.1	9.4	21.7	46.4	
				- 0.9	**3.2**	9.4	21.7	
				-3.0	-3.0	-3.0	-3.0	
--	--	-4.0	3.8	1.2	11.6	27.2	58.4	
				0.2	8.5	21.0	45.9	
				-1.9	**2.2**	8.5	21.0	
				-4.0	-4.0	-4.0	-4.0	
--	--	-5.0	4.8	0.3	10.8	26.5	58.0	
				-0.8	7.6	20.2	45.4	
				-2.9	**1.3**	7.6	20.2	
				-5.0	-5.0	-5.0	-5.0	
--	--	-6.0	5.7	-0.7	9.9	25.8	57.6	
				-1.8	6.7	19.4	44.9	
				-3.9	**0.4**	6.7	19.4	
				-6.0	-6.0	-6.0	-6.0	
--	--	-7.0	6.5	-1.7	9.1	25.1	57.2	
				-2.7	5.8	18.7	44.4	
				-4.9	**-0.6**	5.8	18.7	
				-7.0	-7.0	-7.0	-7.0	
7	20	-8.0	7.4	-2.6	8.2	24.4	56.8	
				-3.7	5.0	17.9	43.8	
				-5.8	**-1.5**	5.0	17.9	
				-8.0	-8.0	-8.0	-8.0	
--	--	-9.0	8.3	-3.6	7.4	23.7	56.4	
				-4.6	4.1	17.2	43.3	
				-6.8	**-2.5**	4.1	17.2	
				-9.0	-9.0	-9.0	-9.0	
8	20	-10.0	9.1	-4.5	6.5	23.0	56.0	
				-5.6	3.2	16.4	42.8	
				-7.8	**-3.4**	3.2	16.4	
				-10.0	-10.0	-10.0	-10.0	

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[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Table 8: The Und concept (equation (27)) applied to Annex I countries. The table lists the undershooting U contained in the modified emission limitation and reduction targets δ_{mod} listed in Table 7, 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. For further explanations confer to the caption of Table 7.

Country Group	Max. Allow. VT[a] $t_2 - t_1$ yr	KP Commit. δ_{KP}[b] %	CRU ρ_{crit} %	Undershooting U in % for ρ = 2.5%	7.5%	15%	30%	If the Und Concept had been applied
				and α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	
1a **1b** **1c** **1d**	20 22 21 24	8.0	8.7	4.6 3.7 1.8 0.0	13.8 11.0 5.5 0.0	27.6 22.1 11.0 0.0	55.2 44.2 22.1 0.0	The undershooting U is not commented because of its secondary importance in this context (see text).
2	20	7.0	7.5	4.7 3.7 1.9 0.0	14.0 11.2 5.6 0.0	27.9 22.3 11.2 0.0	55.8 44.6 22.3 0.0	
3a **3b** **3c**	20 24 22	6.0	6.4	4.7 3.8 1.9 0.0	14.1 11.3 5.6 0.0	28.2 22.6 11.3 0.0	56.4 45.1 22.6 0.0	
4	20	5.0	5.3	4.8 3.8 1.9 0.0	14.3 11.4 5.7 0.0	28.5 22.8 11.4 0.0	57.0 45.6 22.8 0.0	
--	--	4.0	4.2	4.8 3.8 1.9 0.0	14.4 11.5 5.8 0.0	28.8 23.0 11.5 0.0	57.6 46.1 23.0 0.0	
--	--	3.0	3.1	4.9 3.9 1.9 0.0	14.6 11.6 5.8 0.0	29.1 23.3 11.6 0.0	58.2 46.6 23.3 0.0	
--	--	2.0	2.0	4.9 3.9 2.0 0.0	14.7 11.8 5.9 0.0	29.4 23.5 11.8 0.0	58.8 47.0 23.5 0.0	
--	--	1.0	1.0	5.0 4.0 2.0 0.0	14.9 11.9 5.9 0.0	29.7 23.8 11.9 0.0	59.4 47.5 23.8 0.0	

Table 8: continued.

5	20	0.0	0.0	5.0	15.0	30.0	60.0	The undershooting U is not commented because of its secondary importance in this context (see text).
				4.0	12.0	24.0	48.0	
				2.0	6.0	12.0	24.0	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	5.1	15.2	30.3	60.6	
				4.0	12.1	24.2	48.5	
				2.0	6.1	12.1	24.2	
				0.0	0.0	0.0	0.0	
--	--	-2.0	2.0	5.1	15.3	30.6	61.2	
				4.1	12.2	24.5	49.0	
				2.0	6.1	12.2	24.5	
				0.0	0.0	0.0	0.0	
--	--	-3.0	2.9	5.2	15.5	30.9	61.8	
				4.1	12.4	24.7	49.4	
				2.1	6.2	12.4	24.7	
				0.0	0.0	0.0	0.0	
--	--	-4.0	3.8	5.2	15.6	31.2	62.4	
				4.2	12.5	25.0	49.9	
				2.1	6.2	12.5	25.0	
				0.0	0.0	0.0	0.0	
--	--	-5.0	4.8	5.3	15.8	31.5	63.0	
				4.2	12.6	25.2	50.4	
				2.1	6.3	12.6	25.2	
				0.0	0.0	0.0	0.0	
--	--	-6.0	5.7	5.3	15.9	31.8	63.6	
				4.2	12.7	25.4	50.9	
				2.1	6.4	12.7	25.4	
				0.0	0.0	0.0	0.0	
--	--	-7.0	6.5	5.3	16.1	32.1	64.2	
				4.3	12.8	25.7	51.4	
				2.1	6.4	12.8	25.7	
				0.0	0.0	0.0	0.0	
7	20	-8.0	7.4	5.4	16.2	32.4	64.8	
				4.3	13.0	25.9	51.8	
				2.2	6.5	13.0	25.9	
				0.0	0.0	0.0	0.0	
--	--	-9.0	8.3	5.4	16.4	32.7	65.4	
				4.4	13.1	26.2	52.3	
				2.2	6.5	13.1	26.2	
				0.0	0.0	0.0	0.0	
8	20	-10.0	9.1	5.5	16.5	33.0	66.0	
				4.4	13.2	26.4	52.8	
				2.2	6.6	13.2	26.4	
				0.0	0.0	0.0	0.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 7).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

3.4 Undershooting and Verification Time Concepts Combined

Starting Point:	Annex I 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 might exist between the true but unknown net emissions and their best estimates. (2) The relative uncertainty (ρ) of a country's net emissions is symmetrical and does not change over time, i.e., $\rho(t_1) = \rho(t_2)$.
Key Question:	Can the Und and VT concepts be combined, in accordance with the concept of bottom up–top down verification, so as to take advantage of both the Und and the VT concepts?

Here, we refer to the introduction of risk as the strength of the Und concept and to the explicit consideration of time in detecting an emission signal as the strength of the VT concept. To be in accordance with the concept of bottom up–top down verification, we continue to compare the emission signal with the uncertainty that underlies the emissions, not the emission signal. This comparison builds upon total uncertainty, which is treated as statistically independent (see Appendix A for details).

We proceed in three steps. In step 1 we consider our standard, which is given by the maximal allowable VT. In step 2 we focus on emission reduction ($\delta_{KP} > 0$). We introduce an initial or obligatory undershooting, where necessary, 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. In step 3 we focus on emission limitation ($\delta_{KP} \leq 0$). We continue making use of the initial or obligatory undershooting unconditionally for all countries, before detectable reductions that countries might have already realized are considered.

Step 1: Maximal Allowable VT

Consider the case of (arbitrarily, but) linearly decreasing or increasing emissions. For decreasing emissions, the maximal allowable VT, $t_2 - t_1$, is given for

$$x_2 = x_1 - \varepsilon_2 , \tag{29a}$$

i.e., the maximal allowable VT applies when the upper (upp) border of the uncertainty band, $x_{upp}(t) = -\frac{\varepsilon_1}{t_2 - t_1} t + x_1 + \frac{\varepsilon_1 t_2}{t_2 - t_1}$, intersects the horizontal line $x = x_1$ at t_2. Similarly, for increasing emissions:

$$x_2 = x_1 + \varepsilon_2 \ . \tag{29b}$$

The maximal allowable VT applies when the lower (low) border of the uncertainty band, $x_{low}(t) = \frac{\varepsilon_1}{t_2 - t_1} t + x_1 - \frac{\varepsilon_1 t_2}{t_2 - t_1}$, intersects the horizontal line $x = x_1$ at t_2. We can summarize equations (29a) and (29b) similar to equation (2):

$$\frac{x_2}{x_1} = 1 - \delta_{crit} \ , \tag{30}$$

where

$$\delta_{crit} = \begin{cases} \frac{\varepsilon_2}{x_1} & x_2 < x_1 \ \left(\delta_{KP} > 0\right) \\ & \text{for} \\ -\frac{\varepsilon_2}{x_1} & x_2 \geq x_1 \ \left(\delta_{KP} \leq 0\right) \end{cases} \tag{31a,b}$$

denotes the critical (crit) emission limitation or reduction target that matches an arbitrary ρ. (Note that we proceeded the other way around in Section 3.1, where we determined ρ_{crit} for a given δ_{KP}.) To arrive at a more advantageous equation for determining δ_{crit}, we make use of $\frac{\varepsilon_2}{x_1} = \rho \frac{x_2}{x_1}$ and equation (30) in combination with equation (31):

$$\delta_{crit} = \begin{cases} \frac{\rho}{1+\rho} & x_2 < x_1 \ \left(\delta_{KP} > 0\right) \\ & \text{for} \\ -\frac{\rho}{1-\rho} & x_2 \geq x_1 \ \left(\delta_{KP} \leq 0\right) \end{cases} \ . \tag{32a,b}$$

Referring to the VT concept (confer equation (9) of Section 3.2),

$$\Delta t > \frac{\varepsilon(t_1)}{\left|\frac{dx}{dt}\right|_{t_1} - \left(\frac{d\varepsilon}{dt}\right)_{t_1}} \ , \tag{9}$$

where $\varepsilon(t_1) = \varepsilon_1$,

$$\left|\frac{dx}{dt}\right|_{t_1} = \frac{|\delta_{crit}| x_1}{t_2 - t_1} = \frac{\varepsilon_2}{t_2 - t_1} \tag{33a,b}$$

(after inserting equations (30) and (31)), and

$$\left(\frac{d\varepsilon}{dt}\right)_{t_1} = \frac{\varepsilon_2 - \varepsilon_1}{t_2 - t_1} \ , \tag{34}$$

we find $\Delta t > t_2 - t_1$, with $t_2 - t_1$ being the maximal allowable VT.

To proceed, we distinguish between emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \leq 0$).

Step 2: Initial or Obligatory Undershooting for $\delta_{KP} > 0$

To begin, let us assume that Annex I countries comply with their emission reduction commitments under the Kyoto Protocol. Nevertheless, the uncertainties that the countries report might or might not be in accordance with δ_{KP}, depending on whether δ_{crit} given by equation (32a) is $\leq \delta_{KP}$ (Case 1) or $> \delta_{KP}$ (Case 2); and, as a consequence, entail detectability or non-detectability. In the case of detectability, the VT is $\leq t_2 - t_1$, the maximal allowable VT; while in the case of non-detectability, the VT is $> t_2 - t_1$ (see also Table 6). Case 2 requires correcting for non-detectability. The idea is to introduce 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. To adjust the Und concept to the conditions agreed upon above, we modify equation (18) of Section 3.3 by limiting ε_{12} by ε_2 (to be in accordance with the concept of bottom up–top down verification)[23] and write equation (22) of Section 3.3 in the form:

$$Dx + \varepsilon_2 \leq 2\alpha\varepsilon_2 \ . \tag{35}$$

Inserting

$$Dx := x_2 - (1-\delta)x_1 \tag{36}$$

(equation (21) generalized with respect to δ) for Dx in equation (35) and considering equality leads to

$$x_2 - x_1 = -\delta x_1 - (1-2\alpha)\varepsilon_2 \tag{37}$$

or

$$|x_2 - x_1| = \delta x_1 + (1-2\alpha)\varepsilon_2 \ . \tag{38}$$

Making use of equation (38), i.e.,

$$\left|\frac{dx}{dt}\right|_{t_1} = \frac{\delta x_1 + (1-2\alpha)\varepsilon_2}{t_2 - t_1} \ , \tag{39}$$

in the VT concept instead of equation (33) leads to

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[23] Here, ε_{12} is actually reduced as it does not consider any correlation between ε_1 and ε_2 (see footnote 20).

$$\frac{\Delta t}{t_2 - t_1} > \frac{\varepsilon_1}{\delta x_1 + (1-2\alpha)\varepsilon_2 - (\varepsilon_2 - \varepsilon_1)} = \frac{\rho}{\delta + \rho - 2\alpha \frac{\varepsilon_2}{x_1}} \ . \tag{40a,b}$$

We write δ as the sum of δ_{KP} and U_{Gap} and investigate inequality (40b) with respect to our standard, the maximal allowable VT, i.e.:

$$\frac{\rho}{(\delta_{KP} + U_{Gap}) + \rho - 2\alpha \frac{\varepsilon_2}{x_1}} = 1 \ . \tag{41}$$

Specifying $\alpha = 0.5$, we find by making use of equation (31a):

$$U_{Gap} = \frac{\varepsilon_2}{x_1} - \delta_{KP} = \delta_{crit} - \delta_{KP} \ . \tag{42a,b}$$

Equation (42b) is used to determine the initial or obligatory undershooting U_{Gap}, which is introduced so that the countries' emission signals become detectable.

As a consequence of introducing U_{Gap}, the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk (α) changes. To grasp the changed, i.e., "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk (α_v) (where "v" refers to "verifiable"), we start from a given undershooting with reference to δ_{KP}, expressed by an inequality similar to inequality (26), namely[24]

$$\frac{x_2}{x_1} \le (1-\delta_{KP}) \frac{1}{1+(1-2\alpha)\rho} = (1-\delta_{KP}) \frac{1-(1-2\alpha)\rho}{1-(1-2\alpha)^2 \rho^2} \tag{43a,b}$$

$$\approx 1 - \left\{ \delta_{KP} + (1-2\alpha)(1-\delta_{KP})\rho \right\} \ , \tag{43c}$$

where

$$\delta_{mod} = \delta_{KP} + U \ \text{and} \ U = (1-2\alpha)(1-\delta_{KP})\rho \ ; \tag{28a), (44}$$

and express it correspondingly but with reference to δ_{crit}:

$$\frac{x_2}{x_1} \le (1-\delta_{crit}) \frac{1}{1+(1-2\alpha_v)\rho} = (1-\delta_{crit}) \frac{1-(1-2\alpha_v)\rho}{1-(1-2\alpha_v)^2 \rho^2} \tag{45a,b}$$

$$\approx 1 - \left\{ \delta_{crit} + (1-2\alpha_v)(1-\delta_{crit})\rho \right\} = 1 - \left\{ \delta_{KP} + U_{Gap} + (1-2\alpha_v)(1-\delta_{crit})\rho \right\} \tag{45c,d}$$

where

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[24] As a consequence of limiting ε_{12} by ε_2 in equation (24), inequality (26) — which makes use of equation (24) — has to be re-derived, resulting in inequality (43).

$$\delta_{\text{mod}} = \delta_{\text{KP}} + \text{U}_{\text{v}} \text{ and } \text{U}_{\text{v}} = \text{U}_{\text{Gap}} + (1 - 2\alpha_{\text{v}})(1 - \delta_{\text{crit}})\rho \ . \qquad (46), (47)$$

Continuing with the approximations and comparing inequalities (43c) and (45c), we thus find

$$\delta_{\text{mod}} = \delta_{\text{crit}} + (1 - 2\alpha_{\text{v}})(1 - \delta_{\text{crit}})\rho \qquad (48)$$

or

$$\alpha_{\text{v}} = \frac{1}{2}\left\{1 - \frac{\delta_{\text{mod}} - \delta_{\text{crit}}}{(1 - \delta_{\text{crit}})\rho}\right\} , \qquad (49)$$

respectively. Equation (49) is used to determine the changed risk α_{v} for a given modified emission reduction target δ_{mod}, where δ_{mod} is given by equation (28a) in combination with equation (44) and δ_{crit} by equation (32a). Tables 9 and 10 reflect the Und part of the Und&VT concept. They list, similar to Tables 7 and 8, modified emission reduction targets δ_{mod} (equation (28a) in combination with equation (44)) and the undershooting U contained in δ_{mod} (equation (44)) for Annex I countries, where the risk α is specified to be 0, 0.1, 0.3 and 0.5. The validity range of α_{v} vis-à-vis α is specified in Table 11. This table serves as a guide for Table 12, where α_{v} values are calculated.

Table 12 (see last column) shows that α_{v} is greater than α. This is a consequence of the corrective increase of δ_{KP} to δ_{crit} (where necessary). Part of the undershooting is used for this correction, with the result that the remainder of the undershooting — now referring to $\delta_{\text{crit}} > \delta_{\text{KP}}$ — exhibits a greater risk α_{v}.

Tables 13 and 14 reflect the straightforward application of the Und&VT concept, i.e., they make the step from "δ_{mod} given $\rightarrow$ α_{v} to be calculated" to "α_{v} given $\rightarrow$ δ_{mod} to be calculated", where δ_{crit} is now the new reference relevant for undershooting. The two tables list the modified emission reduction targets δ_{mod} (equation (46) in combination with equation (47)) and the undershooting U_{v} contained in δ_{mod} (equation (47)) for Annex I countries, where the "$\text{x}_{\text{t,2}}$-greater-than-$(1 - \delta_{\text{crit}})\text{x}_{\text{t,1}}$" risk α_{v} is specified to be 0, 0.1, 0.3 and 0.5.

Table 9: The Und part of the Und&VT concept (equation (28a) in combination with equation (44)) applied to Annex I countries committed to emission reduction ($\delta_{\mathrm{KP}} > 0$). The table lists modified emission reduction targets δ_{mod} for all Annex I countries, where the "$x_{t,2}$-greater-than-$\left(1-\delta_{\mathrm{KP}}\right)x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5. For further explanations confer to the caption of Table 7.

Country Group	Max. Allow. VT[a] t_2 - t_1 yr	KP Commit. δ_{KP} %	CRU ρ_{crit} %	Modified Emission Reduction Target δ_{mod} in % for ρ = 2.5%	7.5%	15%	30%	If the Und Concept had been applied
				and α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	
1a **1b** **1c** **1d**	20 22 21 24	8.0	8.7	10.3 9.8 8.9 8.0	14.9 13.5 10.8 8.0	21.8 19.0 13.5 8.0	35.6 30.1 19.0 8.0	See Und concept (Table 7).
2	20	7.0	7.5	9.3 8.9 7.9 7.0	14.0 12.6 9.8 7.0	21.0 18.2 12.6 7.0	34.9 29.3 18.2 7.0	
3a **3b** **3c**	20 24 22	6.0	6.4	8.4 7.9 6.9 6.0	13.1 11.6 8.8 6.0	20.1 17.3 11.6 6.0	34.2 28.6 17.3 6.0	
4	20	5.0	5.3	7.4 6.9 6.0 5.0	12.1 10.7 7.9 5.0	19.3 16.4 10.7 5.0	33.5 27.8 16.4 5.0	
--	--	4.0	4.2	6.4 5.9 5.0 4.0	11.2 9.8 6.9 4.0	18.4 15.5 9.8 4.0	32.8 27.0 15.5 4.0	
--	---	3.0	3.1	5.4 4.9 4.0 3.0	10.3 8.8 5.9 3.0	17.6 14.6 8.8 3.0	32.1 26.3 14.6 3.0	
--	--	2.0	2.0	4.5 4.0 3.0 2.0	9.4 7.9 4.9 2.0	16.7 13.8 7.9 2.0	31.4 25.5 13.8 2.0	
--	--	1.0	1.0	3.5 3.0 2.0 1.0	8.4 6.9 4.0 1.0	15.9 12.9 6.9 1.0	30.7 24.8 12.9 1.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 10: The Und part of the Und&VT concept (equation (44)) applied to Annex I countries committed to emission reduction ($\delta_{KP} > 0$). The table lists the undershooting U contained in the modified emission reduction targets δ_{mod} listed in Table 9, 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. For further explanations confer header to Table 8.

Country Group	**Max. Allow. VT**[a] **t_2 - t_1 yr**	**KP Commit. δ_{KP} %**	**CRU ρ_{crit} %**	**Undershooting U in % for ρ =**				**If the Und Concept had been applied**
				2.5% and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**7.5%** and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**15%** and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**30%** and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
1a **1b** **1c** **1d**	20 22 21 24	8.0	8.7	2.3 1.8 0.9 0.0	6.9 5.5 2.8 0.0	13.8 11.0 5.5 0.0	27.6 22.1 11.0 0.0	See Und concept (Table 8).
2	20	7.0	7.5	2.3 1.9 0.9 0.0	7.0 5.6 2.8 0.0	14.0 11.2 5.6 0.0	27.9 22.3 11.2 0.0	
3a **3b** **3c**	20 24 22	6.0	6.4	2.4 1.9 0.9 0.0	7.1 5.6 2.8 0.0	14.1 11.3 5.6 0.0	28.2 22.6 11.3 0.0	
4	20	5.0	5.3	2.4 1.9 1.0 0.0	7.1 5.7 2.9 0.0	14.3 11.4 5.7 0.0	28.5 22.8 11.4 0.0	
--	--	4.0	4.2	2.4 1.9 1.0 0.0	7.2 5.8 2.9 0.0	14.4 11.5 5.8 0.0	28.8 23.0 11.5 0.0	
--	--	3.0	3.1	2.4 1.9 1.0 0.0	7.3 5.8 2.9 0.0	14.6 11.6 5.8 0.0	29.1 23.3 11.6 0.0	
--	--	2.0	2.0	2.5 2.0 1.0 0.0	7.4 5.9 2.9 0.0	14.7 11.8 5.9 0.0	29.4 23.5 11.8 0.0	
--	--	1.0	1.0	2.5 2.0 1.0 0.0	7.4 5.9 3.0 0.0	14.9 11.9 5.9 0.0	29.7 23.8 11.9 0.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 11: The validity range of the "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk α_v vis-à-vis the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk α. The table is self-explanatory and all entries can be derived (not done here) with the help of equation (49) in combination with equations (28a), (44) and (47). The table serves as a guide for Table 12, where α_v values are calculated for the modified emission reduction targets δ_{mod} presented in Table 9.

δ_{mod}	$U =$	$\alpha =$	$U_v =$	$\alpha_v =$
Case 1: $\delta_{crit} \le \delta_{KP}$				
1 δ_{crit} δ_{KP}	The VT is $\le t_2 - t_1$, the maximal allowable VT. Equation (44), which permits to determine U for a given α or vice versa (knowing δ_{KP} and ρ), continues to stay valid.			
Case 2: $\delta_{crit} > \delta_{KP}$				
1	Reference (base year emissions)			
δ_{KP}	0	0.5	—	—
	Emission reductions have not yet reached $\delta_{mod} = \delta_{crit}$ (i.e., the initial or obligatory undershooting is not yet fulfilled). The risk α_v is only defined for $U_v \in \left[U_{Gap}, U_{v,max}\right]$.			
δ_{crit}	see U_v	$\frac{1}{2}\left\{1-\frac{U_{Gap}}{U_{max}}\right\}$	$U_{Gap} = \delta_{crit} - \delta_{KP}$	0.5
$\delta_{KP} +$ $(1-\delta_{KP})\rho$	$U_{max} = (1-\delta_{KP})\rho$	0	see U	$\frac{1}{2}\left\{1-\frac{U_{max}-U_{Gap}}{U_{v,max}}\right\}$
	Reducing emissions beyond $\delta_{mod} = \delta_{KP} + U_{max}$ involves no risk α, which is only defined for $U \in [0, U_{max}]$.			
$\delta_{crit} +$ $(1-\delta_{crit})\rho$	see U_v	—	$U_{v,max} = U_{Gap}$ $+(1-\delta_{crit})\rho$	0

Table 12: The Und&VT concept (equation (49)) applied to Annex I countries committed to emission reduction ($\delta_{KP} > 0$). The table lists "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk values α_v for the modified emission reduction targets δ_{mod} presented in Table 9. The table should be read as follows: Apply equation (32a) to calculate δ_{crit}. If $\delta_{crit} > \delta_{KP}$ (Case 2), the countries' emission reduction commitments are not detectable at t_2. As a consequence, the "$x_{t,2}$-greater-than-$(1-\delta_{KP})x_{t,1}$" risk α associated with a δ_{mod} value listed in Table 9 requires correction. The changed risk α_v derived with the help of equation (49) takes account of the initial or obligatory undershooting U_{Gap}, which is introduced so that the countries' emission signals become detectable. Table 11 shows that α_v cannot be specified if $U_v < U_{Gap}$ or, equivalently, $\delta_{mod} = \delta_{KP} + U_v < \delta_{crit}$ (i.e., $U_v \notin \left[U_{Gap}, U_{Gap} + (1-\delta_{crit})\rho\right]$). This case is referred to as "α_v n.d." (α_v not defined). If, however, $\delta_{crit} \le \delta_{KP}$ (Case 1), the countries' emission reduction commitments are detectable at t_2. In this case, the risk value α continues to stay relevant; it does not require correction. This case is referred to as "take α". In the last column, we assess the hypothetical situation that the Und&VT concept had been applied prior to/in negotiating the Kyoto Protocol. In Case 2 note that, as a consequence of the increase of δ_{KP} by U_{Gap} to reach δ_{crit}, α_v turns out to be greater than α.

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com. δ_{KP} %**	**Crit. Targ. δ_{crit} % for ρ = 2.5% 7.5% 15% 30%**	**Changed Risk α_v for ρ = 2.5%**	**7.5%**	**15%**	**30%**	**If the Und&VT Concept had been applied**
				and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
1a	20	8.0	2.4	take α	take α	**0.164**	0.229	Case (1): Inside the green-colored area ($\delta_{crit} \le \delta_{KP}$): No necessity for introducing U_{Gap}, i.e., the α values (here specified to be 0, 0.1, 0.3, 0.5) continue to stay relevant. Case (2) Outside the green-colored area ($\delta_{crit} > \delta_{KP}$): Overall: $\alpha_v > \alpha$. This is a consequence of the corrective increase of δ_{KP} by U_{Gap} to reach δ_{crit}. Part of the undershooting is used for this correction, with the result that the remainder of the undershooting, now referring to δ_{crit}, exhibits a greater risk α_v. (a) For given δ_{KP} and α: No monotonic relationship between ρ and the changed risk α_v, which replaces the constant-level risk α determined under the Und concept (see, e.g., fictitious country group for $\delta_{KP} = 4\%$: first line: α_v values for α = 0.0). (b) For given ρ and α: The smaller the δ_{KP}, the greater the changed risk α_v is that replaces the constant-level risk α determined under the Und concept (see, e.g., α_v values for ρ = 7.5% and α = 0.0).
1b	22		7.0	take α	take α	0.270	0.348	
1c	21		13.0	take α	take α	0.482	α_v n.d.	
1d	24		23.1	take α	take α	α_v n.d.	α_v n.d.	
2	20	7.0	2.4	take α	take α	**0.197**	0.244	
			7.0	take α	take α	0.304	0.365	
			13.0	take α	take α	α_v n.d.	α_v n.d.	
			23.1	take α	take α	α_v n.d.	α_v n.d.	
3a	20	6.0	2.4	take α	0.065	**0.230**	0.259	
3b	24		7.0	take α	0.166	0.338	0.381	
3c	22		13.0	take α	0.368	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
4	20	5.0	2.4	take α	0.131	**0.262**	0.274	
			7.0	take α	0.233	0.371	0.398	
			13.0	take α	0.437	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	4.0	2.4	take α	**0.197**	**0.295**	**0.289**	
			7.0	take α	0.301	0.405	0.414	
			13.0	take α	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	3.0	2.4	take α	0.264	**0.327**	0.305	
			7.0	take α	0.368	0.439	0.431	
			13.0	take α	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	2.0	2.4	0.088	0.330	**0.360**	0.320	
			7.0	0.188	0.435	0.473	0.447	
			13.0	0.389	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	α_v n.d.	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	1.0	2.4	0.288	0.396	**0.392**	0.335	
			7.0	0.389	α_v n.d.	α_v n.d.	0.464	
			13.0	α_v n.d.	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	α_v n.d.	α_v n.d.	α_v n.d.	α_v n.d.	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 13: The Und&VT concept (equation (46) in combination with equation (47)) applied to Annex I countries committed to emission reduction ($\delta_{\mathrm{KP}} > 0$). The table lists modified emission reduction targets δ_{mod} for all Annex I countries, where the "$x_{t,2}$-greater-than-$\left(1-\delta_{\mathrm{crit}}\right)x_{t,1}$" risk α_{v} is specified to be 0, 0.1, 0.3 and 0.5. In the last column, we assess the hypothetical situation that the Und&VT concept had been applied prior to/in negotiating the Kyoto Protocol. Green-colored fields: $\delta_{\mathrm{crit}} \leq \delta_{\mathrm{KP}}$ (Case 1). Note that the δ_{mod} values from Table 9 continue to stay valid. White fields: $\delta_{\mathrm{crit}} > \delta_{\mathrm{KP}}$ (Case 2). Note the uniform appearance of δ_{mod} for a given ρ and α_{v}, which results in the rectification of the Und concept (confer Table 9).

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com. δ_{KP} %**	**Crit. Targ. δ_{crit} % for ρ =** 2.5% 7.5% 15% 30%	**Modified Emission 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%** $a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	**If the Und&VT Concept had been applied**
1a	20	8.0	2.4	10.3	14.9	26.1	46.2	Case (1): Inside the green-colored area ($\delta_{\mathrm{crit}} \leq \delta_{\mathrm{KP}}$): No necessity for introducing U_{Gap}, i.e., the δ_{mod} values from Table 9 continue to stay valid. Case (2): Outside the green-colored area ($\delta_{\mathrm{crit}} > \delta_{\mathrm{KP}}$): Increase of δ_{KP} by U_{Gap} to reach δ_{crit}, the new relevant reference for undershooting, which only depends on ρ and α_{v} and not anymore on δ_{KP} (see equation (46) in combination with equation (47)). This explains why δ_{mod} appears uniform for a given ρ and α_{v}. Thus, the Und&VT concept rectifies the Und concept (see Table 9), where countries complying with a smaller δ_{KP} exhibit a small δ_{mod} while countries complying with a greater δ_{KP} exhibit a great δ_{mod}.
1b	22		7.0	9.8	13.5	23.5	41.5	
1c	21		13.0	8.9	10.8	18.3	32.3	
1d	24		23.1	8.0	8.0	13.0	23.1	
2	20	7.0	2.4	9.3	14.0	26.1	46.2	
			7.0	8.9	12.6	23.5	41.5	
			13.0	7.9	9.8	18.3	32.3	
			23.1	7.0	7.0	13.0	23.1	
3a **3b** **3c**	20 24 22	6.0	2.4	8.4	14.0	26.1	46.2	
			7.0	7.9	12.6	23.5	41.5	
			13.0	6.9	9.8	18.3	32.3	
			23.1	6.0	7.0	13.0	23.1	
4	20	5.0	2.4	7.4	14.0	26.1	46.2	
			7.0	6.9	12.6	23.5	41.5	
			13.0	6.0	9.8	18.3	32.3	
			23.1	5.0	7.0	13.0	23.1	
--	--	4.0	2.4	6.4	14.0	26.1	46.2	
			7.0	5.9	12.6	23.5	41.5	
			13.0	5.0	9.8	18.3	32.3	
			23.1	4.0	7.0	13.0	23.1	
--	--	3.0	2.4	5.4	14.0	26.1	46.2	
			7.0	4.9	12.6	23.5	41.5	
			13.0	4.0	9.8	18.3	32.3	
			23.1	3.0	7.0	13.0	23.1	
--	--	2.0	2.4	4.9	14.0	26.1	46.2	
			7.0	4.4	12.6	23.5	41.5	
			13.0	3.4	9.8	18.3	32.3	
			23.1	2.4	7.0	13.0	23.1	
--	--	1.0	2.4	4.9	14.0	26.1	46.2	
			7.0	4.4	12.6	23.5	41.5	
			13.0	3.4	9.8	18.3	32.3	
			23.1	2.4	7.0	13.0	23.1	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 14: The Und&VT concept (equation (47)) applied to Annex I countries committed to emission reduction ($\delta_{\mathrm{KP}} > 0$). The table lists the undershooting U_{v} contained in the modified emission reduction targets δ_{mod} listed in Table 13, where the "$\mathrm{x}_{\mathrm{t},2}$-greater-than-$(1-\delta_{\mathrm{crit}})\mathrm{x}_{\mathrm{t},1}$" risk α_{v} is specified to be 0, 0.1, 0.3 and 0.5. In the last column, we assess the hypothetical situation that the Und&VT concept had been applied prior to/in negotiating the Kyoto Protocol. Green-colored fields: $\delta_{\mathrm{crit}} \leq \delta_{\mathrm{KP}}$ (Case 1). Note that the U_{v} values from Table 10 continue to stay valid. White fields: $\delta_{\mathrm{crit}} > \delta_{\mathrm{KP}}$ (Case 2). Note the different behavior of U_{v} vis-à-vis U (confer Table 10).

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com. δ_{KP} %**	**Crit. Targ. δ_{crit} %**	**Undershooting U_v in % for ρ =**				**If the Und&VT Concept had been applied**
			for ρ = 2.5% 7.5% 15% 30%	**2.5%** **and** **a_v = 0.0 a_v = 0.1 a_v = 0.3 a_v = 0.5**	**7.5%** **and** **a_v = 0.0 a_v = 0.1 a_v = 0.3 a_v = 0.5**	**15%** **and** **a_v = 0.0 a_v = 0.1 a_v = 0.3 a_v = 0.5**	**30%** **and** **a_v = 0.0 a_v = 0.1 a_v = 0.3 a_v = 0.5**	
1a **1b** **1c** **1d**	20 22 21 24	8.0	2.4 7.0 13.0 23.1	2.3 1.8 0.9 0.0	6.9 5.5 2.8 0.0	18.1 15.5 10.3 5.0	38.2 33.5 24.3 15.1	Case (1): Inside the green-colored area ($\delta_{crit} \leq \delta_{KP}$): No necessity for introducing U_{Gap}, i.e., the U values from Table 10 continue to stay valid. Case (2): Outside the green-colored area ($\delta_{crit} > \delta_{KP}$): The new relevant reference for undershooting is δ_{crit} (see Table 13), which must be reached with the help of U_{Gap} so that the countries' emission signals become verifiable. $U_v = U_{Gap}$ for $\alpha_v = 0.5$. Similar to the undershooting U in Table 10, countries complying with a smaller δ_{KP} exhibit a great (U_{Gap}, thus) U_v while countries complying with a greater δ_{KP} exhibit a small (U_{Gap}, thus) U_v (see equation (47)). However, the introduction of U_{Gap} results in $U_v > U$ and a variation of U_v in dependence of δ_{KP} that is greater than that of U.
2	20	7.0	2.4 7.0 13.0 23.1	2.3 1.9 0.9 0.0	7.0 5.6 2.8 0.0	19.1 16.5 11.3 6.0	39.2 34.5 25.3 16.1	
3a **3b** **3c**	20 24 22	6.0	2.4 7.0 13.0 23.1	2.4 1.9 0.9 0.0	8.0 6.6 3.8 1.0	20.1 17.5 12.3 7.0	40.2 35.5 26.3 17.1	
4	20	5.0	2.4 7.0 13.0 23.1	2.4 1.9 1.0 0.0	9.0 7.6 4.8 2.0	21.1 18.5 13.3 8.0	41.2 36.5 27.3 18.1	
--	--	4.0	2.4 7.0 13.0 23.1	2.4 1.9 1.0 0.0	10.0 8.6 5.8 3.0	22.1 19.5 14.3 9.0	42.2 37.5 28.3 19.1	
--	--	3.0	2.4 7.0 13.0 23.1	2.4 1.9 1.0 0.0	11.0 9.6 6.8 4.0	23.1 20.5 15.3 10.0	43.2 38.5 29.3 20.1	
--	--	2.0	2.4 7.0 13.0 23.1	2.9 2.4 1.4 0.4	12.0 10.6 7.8 5.0	24.1 21.5 16.3 11.0	44.2 39.5 30.3 21.1	
--	--	1.0	2.4 7.0 13.0 23.1	3.9 3.4 2.4 1.4	13.0 11.6 8.8 6.0	25.1 22.5 17.3 12.0	45.2 40.5 31.3 22.1	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 13 (see last column) shows for $\delta_{\text{crit}} > \delta_{\text{KP}}$ (Case 2) that the Und&VT concept rectifies the Und concept, which we applied under the assumption that the emission limitation and reduction commitments δ_{KP} under the Kyoto Protocol were arbitrarily set. Here, we refer to the politically unfavorable situation under the Und concept, which arises when δ_{KP} is variable while ρ and α are kept constant. The result of this was that Annex I countries complying with a smaller δ_{KP} exhibit a small δ_{mod}, while countries complying with a greater δ_{KP} exhibit a great δ_{mod} (confer Table 9). This behavior is not apparent anymore with δ_{mod} being uniform for a given ρ and α_{v}. However, the undershooting U_{v} contained in δ_{mod} changes, as it depends on U_{Gap}, the initial or obligatory undershooting. Table 14 (see last column) shows for $\delta_{\text{crit}} > \delta_{\text{KP}}$ (Case 2) that $\text{U}_{\text{v}} > \text{U}$ and that the variation of U_{v} in dependence of δ_{KP} is greater than that of U (confer Table 10).

Appendix D presents tables similar to Tables 9, 10 and 12 to 14 by starting from inequalities (43a) and (45a) instead of their approximations (inequalities (43c) and (45c)).

Step 3: Initial or Obligatory Undershooting for $\delta_{KP} \leq 0$

Now δ_{KP} is ≤ 0 and, as shown in Figure 12, the countries' emission signals have to tunnel through an even greater non-detectability range during the undershooting process. We regard this as a direct consequence of the haphazard political negotiation process of the Kyoto Protocol.[25] Several possibilities exist to correct for this non-detectability drawback. Here, the idea is to continue making use of the initial or obligatory undershooting, irrespective of whether $\delta_{\text{crit}} < \delta_{\text{KP}}$ (Case 3) or $\delta_{\text{crit}} \geq \delta_{\text{KP}}$ (Case 4), and only then consider detectable reductions that might have already been realized in the case $\delta_{\text{crit}} \geq \delta_{\text{KP}}$. We consider this as being the most straightforward procedure.

Case 3: $\delta_{crit} < \delta_{KP}$. We start from inequality (43), which also holds for $\delta_{\text{KP}} \leq 0$:

$$\frac{\text{x}_2}{\text{x}_1} \leq (1-\delta_{\text{KP}})\frac{1}{1+(1-2\alpha)\rho} = (1-\delta_{\text{KP}})\frac{1-(1-2\alpha)\rho}{1-(1-2\alpha)^2\rho^2} \tag{43a,b}$$

$$\approx 1-\left\{\delta_{\text{KP}}+(1-2\alpha)(1-\delta_{\text{KP}})\rho\right\} \ , \tag{43c}$$

where

$$\delta_{\text{mod}} = \delta_{\text{KP}} + \text{U} \text{ and } \text{U} = (1-2\alpha)(1-\delta_{\text{KP}})\rho \ . \qquad \text{(28a), (44)}$$

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[25] However, this does not mean that we do not approve $\delta_{\text{KP}} \leq 0$ situations. On the contrary, but these must be rigorously based and result from a straightforward rule that applies equally to all countries.

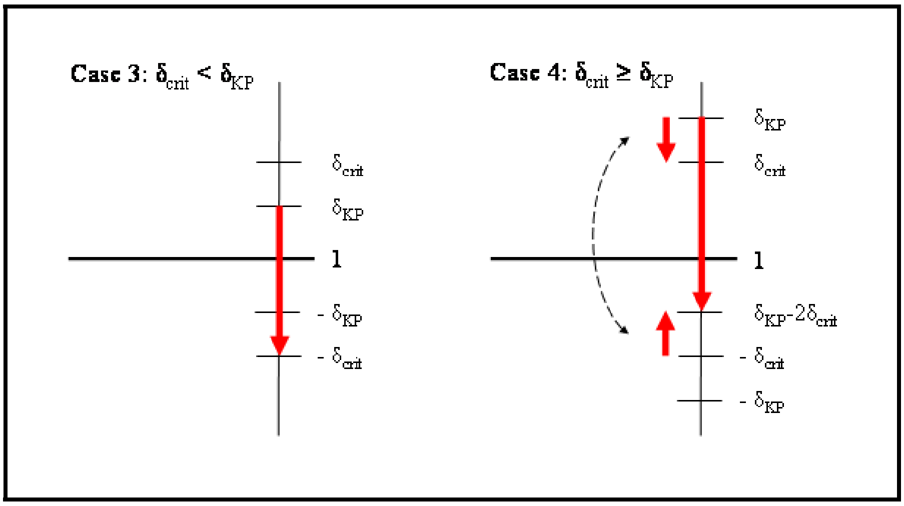

Figure 12: Initial or obligatory undershooting (indicated by the red arrows) for Annex I countries committed to emission limitation ($\delta_{KP} \le 0$). In the interval $[\delta_{crit}, -\delta_{crit}]$ emission signals are not detectable. Case 3: $\delta_{crit} < \delta_{KP}$. The reference for undershooting is $-\delta_{crit}$. Case 4: $\delta_{crit} \ge \delta_{KP}$. The reference for undershooting is $\delta_{KP} - 2\delta_{crit}$, which considers detectable emission reductions between δ_{KP} and δ_{crit}.

As before, we express inequality (43) correspondingly but with reference to $-\delta_{crit}$:

$$\frac{x_2}{x_1} \le (1+\delta_{crit})\frac{1}{1+(1-2\alpha_v)\rho} = (1+\delta_{crit})\frac{1-(1-2\alpha_v)\rho}{1-(1-2\alpha_v)^2\rho^2} \qquad (50a,b)$$

$$\approx 1-\left\{-\delta_{crit}+(1-2\alpha_v)(1+\delta_{crit})\rho\right\} = 1-\left\{\delta_{KP}+U_{Gap}+(1-2\alpha_v)(1+\delta_{crit})\rho\right\}\ , \qquad (50c,d)$$

where

$$\delta_{mod} = \delta_{KP} + U_v\ ,\ U_v = U_{Gap} + (1-2\alpha_v)(1+\delta_{crit})\rho\ , \qquad (46), (51)$$

$$U_{Gap} = -(\delta_{crit} + \delta_{KP})\ , \qquad (52)$$

and δ_{crit} is given by equation (32b). Continuing with the approximations and comparing inequalities (43c) and (50c), we thus find

$$\delta_{mod} = -\delta_{crit} + (1-2\alpha_v)(1+\delta_{crit})\rho \qquad (53)$$

or

$$\alpha_v = \frac{1}{2}\left\{1 - \frac{\delta_{mod}+\delta_{crit}}{(1+\delta_{crit})\rho}\right\}\ , \qquad (54)$$

respectively, where δ_{mod} is given (as before) by equation (28a) in combination with equation (44). However, as the intervals $\left[\delta_{\text{KP}}, \delta_{\text{KP}} + (1-\delta_{\text{KP}})\rho\right]$ and $\left[-\delta_{\text{crit}}, -\delta_{\text{crit}} + (1+\delta_{\text{crit}})\rho\right]$ do not overlap, corresponding risks $\alpha \leftrightarrow \alpha_{\text{v}}$ cannot be determined.[26]

Case 4: $\delta_{crit} \geq \delta_{KP}$. We adhere to the initial or obligatory undershooting which, however, we correct for detectable reductions between δ_{KP} and δ_{crit} (see Figure 12). Thus, we express inequality (43), which is still valid in combination with equations (28a) and (44), correspondingly but with reference to $-\delta'_{\text{crit}} = \delta_{\text{KP}} - 2\delta_{\text{crit}}$:

$$\frac{\mathrm{x}_2}{\mathrm{x}_1} \leq \left(1+\delta'_{\text{crit}}\right)\frac{1}{1+(1-2\alpha_{\text{v}})\rho} = \left(1+\delta'_{\text{crit}}\right)\frac{1-(1-2\alpha_{\text{v}})\rho}{1-(1-2\alpha_{\text{v}})^2\rho^2} \tag{55a,b}$$

$$\approx 1-\left\{-\delta'_{\text{crit}} + (1-2\alpha_{\text{v}})\left(1+\delta'_{\text{crit}}\right)\rho\right\} = 1-\left\{\delta_{\text{KP}} + \mathrm{U}_{\text{Gap}} + (1-2\alpha_{\text{v}})\left(1+\delta'_{\text{crit}}\right)\rho\right\}\ , \tag{55c,d}$$

where

$$\delta_{\text{mod}} = \delta_{\text{KP}} + \mathrm{U}_{\text{v}}\ ,\ \mathrm{U}_{\text{v}} = \mathrm{U}_{\text{Gap}} + (1-2\alpha_{\text{v}})\left(1+\delta'_{\text{crit}}\right)\rho\ , \tag{46), (56}$$

$$\mathrm{U}_{\text{Gap}} = -2\delta_{\text{crit}}\ ,\ -\delta'_{\text{crit}} = \delta_{\text{KP}} - 2\delta_{\text{crit}}\ , \tag{57), (58}$$

and δ_{crit} is given by equation (32b). Continuing with the approximations and comparing inequalities (43c) and (55c), we thus find

$$\delta_{\text{mod}} = -\delta'_{\text{crit}} + (1-2\alpha_{\text{v}})\left(1+\delta'_{\text{crit}}\right)\rho \tag{59}$$

or

$$\alpha_{\text{v}} = \frac{1}{2}\left\{1-\frac{\delta_{\text{mod}} + \delta'_{\text{crit}}}{\left(1+\delta'_{\text{crit}}\right)\rho}\right\}\ , \tag{60}$$

respectively, where δ_{mod} is given (as before) by equation (28a) in combination with equation (44). Again, as the intervals $\left[\delta_{\text{KP}}, \delta_{\text{KP}} + (1-\delta_{\text{KP}})\rho\right]$ and

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[26] The comparison of Tables 15 and 17 for $\delta_{\text{crit}} < \delta_{\text{KP}}$ (Case 3) shows that $\delta_{\text{mod}}\left(\text{equation } (28\text{a}): \alpha = 0\right)$ is always smaller than $\delta_{\text{mod}}\left(\text{Case 3}: \text{equation}(46): \alpha_{\text{v}} = 0.5\right)$ for all listed values of δ_{KP} and ρ. Mathematically, an overlap of intervals would require $\delta_{\text{mod}}\left(\text{equation}(28\text{a}): \alpha = 0\right) \geq \delta_{\text{mod}}\left(\text{Case 3}: \text{equation } (46): \alpha_{\text{v}} = 0.5\right)$ or, alternatively (after making use of equations (28a), (44), (46), (51), (52), and (32b)), $\delta_{\text{KP}} \geq \delta^2_{\text{crit}}$. This is not possible because $\delta_{\text{KP}} \leq 0$ and $\delta^2_{\text{crit}} > 0$ for $\rho > 0$.

$\left[-\delta'_{\mathrm{crit}}, -\delta'_{\mathrm{crit}} + \left(1+\delta'_{\mathrm{crit}}\right)\rho\right]$ do not overlap, corresponding risks $\alpha \leftrightarrow \alpha_{\mathrm{v}}$ cannot be determined.[27]

Tables 15 to 18 are the pendants to Tables 9, 10, 13 and 14, but now focusing on emission limitation ($\delta_{\mathrm{KP}} \le 0$). Tables 15 and 16 reflect the Und part of the Und&VT concept. They list, similar to Tables 7 and 8, modified emission reduction targets δ_{mod} (equation (28a) in combination with equation (44)) and the undershooting U contained in δ_{mod} (equation (44)) for Annex I countries, where the risk α is specified to be 0, 0.1, 0.3 and 0.5. Tables 17 and 18 reflect the application of the Und&VT concept. The two tables list the modified emission reduction targets δ_{mod}, i.e.,

$\delta_{\mathrm{crit}} < \delta_{\mathrm{KP}}$ (Case 3): equation (46) in combination with equations (51) and (52)

$\delta_{\mathrm{crit}} \ge \delta_{\mathrm{KP}}$ (Case 4): equation (46) in combination with equations (56)–(58),

and the undershooting $\mathrm{U_v}$ contained in δ_{mod}, i.e.,

$\delta_{\mathrm{crit}} < \delta_{\mathrm{KP}}$ (Case 3): equations (51) and (52);

$\delta_{\mathrm{crit}} \ge \delta_{\mathrm{KP}}$ (Case 4): equations (56)–(58)

for Annex I countries, where the "$\mathrm{x}_{\mathrm{t,2}}$-greater-than-$\left(1+\delta_{\mathrm{crit}}\right)\mathrm{x}_{\mathrm{t,1}}$" risk α_{v} (Case 3) and the "$\mathrm{x}_{\mathrm{t,2}}$-greater-than-$\left(1-\left(\delta_{\mathrm{KP}} - 2\delta_{\mathrm{crit}}\right)\right)\mathrm{x}_{\mathrm{t,1}}$" risk α_{v} (Case 4), respectively, are specified to be 0, 0.1, 0.3 and 0.5.

Case 3 ($\delta_{\mathrm{crit}} < \delta_{\mathrm{KP}}$) exhibits δ_{mod} and $\mathrm{U_v}$ values that behave similar to those achieved in Case 2 ($\delta_{\mathrm{crit}} > \delta_{\mathrm{KP}}$) of Step 2 above for Annex I countries committed to emission reduction. The uniform appearance of δ_{mod} for a given ρ and α_{v} results in the rectification of the Und concept (confer Tables 15 and 17: δ_{mod} appears uniform for a given ρ and α_{v}),[28] while the behavior of $\mathrm{U_v}$ is more pronounced than that of U (confer Table 16 and 18: $\mathrm{U_v} > \mathrm{U}$ and the variation of $\mathrm{U_v}$ in dependence of δ_{KP} is greater than that of U).

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[27] The comparison of Tables 15 and 17 for $\delta_{\mathrm{crit}} \ge \delta_{\mathrm{KP}}$ (Case 4) shows that $\delta_{\mathrm{mod}}\left(\text{equation } (28a): \alpha = 0\right)$ is always smaller than $\delta_{\mathrm{mod}}\left(\text{Case 4: equation (46)}: \alpha_{\mathrm{v}} = 0.5\right)$ for all listed values of δ_{KP} and ρ. Mathematically, an overlap of intervals would require $\delta_{\mathrm{mod}}\left(\text{equation}(28a): \alpha = 0\right) \ge \delta_{\mathrm{mod}}\left(\text{Case 4: equation } (46): \alpha_{\mathrm{v}} = 0.5\right)$ or, alternatively (after making use of equations (28a), (44), (46), (56), (57), and (32b)), $\left|\delta_{\mathrm{KP}}\right| \ge \dfrac{(1+\rho)^2}{1-\rho^2}$. This is not in accordance with reality because $\left|\delta_{\mathrm{KP}}\right|$ would have to be ≥ 1, the smallest value that the term on the right can take on for $\rho = 0$ ($\rho < 1$).

[28] It is noted that for $\delta_{\mathrm{KP}} \le 0$ the VT concept is rectified as an over/undershooting dissimilarity between countries committed to emission reduction ($\delta_{\mathrm{KP}} > 0$) and emission limitation ($\delta_{\mathrm{KP}} \le 0$) cannot occur any more (see Section 3.2).

Table 15: The Und part of the Und&VT concept (equation (28a) in combination with equation (44)) applied to Annex I countries committed to emission limitation ($\delta_{KP} \leq 0$). The table lists modified emission limitation targets δ_{mod} for all Annex I countries, where the “$x_{t,2}$-greater-than-$\left(1-\delta_{KP}\right)x_{t,1}$” risk α is specified to be 0, 0.1, 0.3 and 0.5. For further explanations confer to the caption of Table 7.

Country Group	Max. Allow. VT[a] t_2 - t_1 yr	KP Commit. δ_{KP} %	CRU ρ_{crit} %	Modified Emission Limitation Target δ_{mod} in % for ρ =				If the Und Concept had been applied
				2.5%	7.5%	15%	30%	
				and				
				α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	
5	20	0.0	0.0	2.5 2.0 1.0 0.0	7.5 6.0 3.0 0.0	15.0 12.0 6.0 0.0	30.0 24.0 12.0 0.0	See Und concept (Table 7).
6	20	-1.0	1.0	1.5 1.0 0.0 -1.0	6.6 5.1 2.0 -1.0	14.2 11.1 5.1 -1.0	29.3 23.2 11.1 -1.0	
--	--	-2.0	2.0	0.6 0.0 -1.0 -2.0	5.7 4.1 1.1 -2.0	13.3 10.2 4.1 -2.0	28.6 22.5 10.2 -2.0	
--	--	-3.0	2.9	-0.4 -0.9 -2.0 -3.0	4.7 3.2 0.1 -3.0	12.5 9.4 3.2 -3.0	27.9 21.7 9.4 -3.0	
--	--	-4.0	3.8	-1.4 -1.9 -3.0 -4.0	3.8 2.2 -0.9 -4.0	11.6 8.5 2.2 -4.0	27.2 21.0 8.5 -4.0	
--	--	-5.0	4.8	-2.4 -2.9 -4.0 -5.0	2.9 1.3 -1.9 -5.0	10.8 7.6 1.3 -5.0	26.5 20.2 7.6 -5.0	
--	--	-6.0	5.7	-3.4 -3.9 -4.9 -6.0	2.0 0.4 -2.8 -6.0	9.9 6.7 0.4 -6.0	25.8 19.4 6.7 -6.0	
--	--	-7.0	6.5	-4.3 -4.9 -5.9 -7.0	1.0 -0.6 -3.8 -7.0	9.1 5.8 -0.6 -7.0	25.1 18.7 5.8 -7.0	
7	20	-8.0	7.4	-5.3 -5.8 -6.9 -8.0	0.1 -1.5 -4.8 -8.0	8.2 5.0 -1.5 -8.0	24.4 17.9 5.0 -8.0	
--	--	-9.0	8.3	-6.3 -6.8 -7.9 -9.0	-0.8 -2.5 -5.7 -9.0	7.4 4.1 -2.5 -9.0	23.7 17.2 4.1 -9.0	
8	20	-10.0	9.1	-7.3 -7.8 -8.9 -10.0	-1.8 -3.4 -6.7 -10.0	6.5 3.2 -3.4 -10.0	23.0 16.4 3.2 -10.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 16: The Und part of the Und&VT concept (equation (44)) applied to Annex I countries committed to emission limitation ($\delta_{KP} \leq 0$). The table lists the undershooting U contained in the modified emission limitation targets δ_{mod} listed in Table 15, 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. For further explanations confer to the caption of Table 8.

Country Group	**Max. Allow. VT**[a] **t_2 - t_1 yr**	**KP Commit. δ_{KP} %**	**CRU ρ_{crit} %**	**Undershooting U in % for ρ = 2.5%**	**7.5%**	**15%**	**30%**	**If the Und Concept had been applied**
				and **α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
5	20	0.0	0.0	2.5	7.5	15.0	30.0	See Und concept (Table 8).
				2.0	6.0	12.0	24.0	
				1.0	3.0	6.0	12.0	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	2.5	7.6	15.2	30.3	
				2.0	6.1	12.1	24.2	
				1.0	3.0	6.1	12.1	
				0.0	0.0	0.0	0.0	
--	--	-2.0	2.0	2.6	7.7	15.3	30.6	
				2.0	6.1	12.2	24.5	
				1.0	3.1	6.1	12.2	
				0.0	0.0	0.0	0.0	
--	--	-3.0	2.9	2.6	7.7	15.5	30.9	
				2.1	6.2	12.4	24.7	
				1.0	3.1	6.2	12.4	
				0.0	0.0	0.0	0.0	
--	--	-4.0	3.8	2.6	7.8	15.6	31.2	
				2.1	6.2	12.5	25.0	
				1.0	3.1	6.2	12.5	
				0.0	0.0	0.0	0.0	
--	--	-5.0	4.8	2.6	7.9	15.8	31.5	
				2.1	6.3	12.6	25.2	
				1.0	3.2	6.3	12.6	
				0.0	0.0	0.0	0.0	
--	--	-6.0	5.7	2.7	8.0	15.9	31.8	
				2.1	6.4	12.7	25.4	
				1.1	3.2	6.4	12.7	
				0.0	0.0	0.0	0.0	
--	--	-7.0	6.5	2.7	8.0	16.1	32.1	
				2.1	6.4	12.8	25.7	
				1.1	3.2	6.4	12.8	
				0.0	0.0	0.0	0.0	
7	20	-8.0	7.4	2.7	8.1	16.2	32.4	
				2.2	6.5	13.0	25.9	
				1.1	3.2	6.5	13.0	
				0.0	0.0	0.0	0.0	
--	--	-9.0	8.3	2.7	8.2	16.4	32.7	
				2.2	6.5	13.1	26.2	
				1.1	3.3	6.5	13.1	
				0.0	0.0	0.0	0.0	
8	20	-10.0	9.1	2.8	8.3	16.5	33.0	
				2.2	6.6	13.2	26.4	
				1.1	3.3	6.6	13.2	
				0.0	0.0	0.0	0.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 17: The Und&VT concept applied to Annex I countries committed to emission limitation ($\delta_{KP} \leq 0$). Case 3 $\left(\delta_{crit} < \delta_{KP}\right)$: equation (46) in combination with equations (51) and (52); Case 4 $\left(\delta_{crit} \geq \delta_{KP}\right)$: equation (46) in combination with equations (56)–(58). The table lists modified emission limitation targets δ_{mod} for all Annex I countries, where the "$x_{t,2}$-greater-than-$\left(1+\delta_{crit}\right)x_{t,1}$" risk α_v (Case 3) and the "$x_{t,2}$-greater-than-$\left(1-\left(\delta_{KP}-2\delta_{crit}\right)\right)x_{t,1}$" risk α_v (Case 4), respectively, are specified to be 0, 0.1, 0.3 and 0.5. In the last column, we assess the hypothetical situation that the Und&VT concept had been applied prior to/in negotiating the Kyoto Protocol. White fields: $\delta_{crit} < \delta_{KP}$ (Case 3). Note the uniform appearance of δ_{mod} for a given ρ and α_v, which results in the rectification of the Und concept (confer Table 15). Orange-colored fields: $\delta_{crit} \geq \delta_{KP}$ (Case 4). Note that δ_{mod} is dependent on δ_{KP}, which is a consequence of how the undershooting is realized (detectable reductions are only considered after initial or obligatory undershooting). For the area in light orange confer to the caption of Table 18.

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com.** δ_{KP} **%**	**Crit. Targ.** δ_{crit} **% for** ρ **= 2.5% 7.5% 15% 30%**	**Modified Emission Limitation Target** δ_{mod} **in % for** ρ **=**				**If the Und&VT Concept had been applied**
				2.5%	**7.5%**	**15%**	**30%**	
				and				
				$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	
5	20	0.0	-2.6	5.0	15.0	30.0	60.0	Case (3): Outside the orange-colored area ($\delta_{crit} < \delta_{KP}$): Increase of δ_{KP} by U_{Gap} to reach $-\delta_{crit}$, the relevant reference for undershooting which only depends on ρ and α_v and not anymore on δ_{KP} (see equation (46) in combination with equations (51) and (52)). This explains why δ_{mod} appears uniform for a given ρ and α_v. Thus, the Und&VT concept rectifies the Und concept (see Table 15), where countries complying with a smaller δ_{KP} exhibit a small δ_{mod} while countries complying with a greater δ_{KP} exhibit a great δ_{mod}.
			-8.1	4.5	13.6	27.5	56.6	
			-17.6	3.5	10.9	22.6	49.7	
			-42.9	2.6	8.1	17.6	42.9	
6	20	-1.0	-2.6	5.0	15.0	30.0	60.0	
			-8.1	4.5	13.6	27.5	56.6	
			-17.6	3.5	10.9	22.6	49.7	
			-42.9	2.6	8.1	17.6	42.9	
--		-2.0	-2.6	5.0	15.0	30.0	60.0	
			-8.1	4.5	13.6	27.5	56.6	
			-17.6	3.5	10.9	22.6	49.7	
			-42.9	2.6	8.1	17.6	42.9	
--		-3.0	-2.6	4.6	15.0	30.0	60.0	
			-8.1	4.1	13.6	27.5	56.6	
			-17.6	3.1	10.9	22.6	49.7	
			-42.9	2.1	8.1	17.6	42.9	
--		-4.0	-2.6	3.6	15.0	30.0	60.0	
			-8.1	3.1	13.6	27.5	56.6	
			-17.6	2.1	10.9	22.6	49.7	
			-42.9	1.1	8.1	17.6	42.9	
--		-5.0	-2.6	2.6	15.0	30.0	60.0	
			-8.1	2.1	13.6	27.5	56.6	
			-17.6	1.1	10.9	22.6	49.7	Case (4): Inside the orange-colored area ($\delta_{crit} \geq \delta_{KP}$): Increase of δ_{KP} by U_{Gap} to reach $\delta_{KP} - 2\delta_{crit}$, the relevant reference for undershooting which, in contrast to the case $\delta_{crit} < \delta_{KP}$ above, still depends on δ_{KP} (see equation (46) in combination with equations (56)–(58)). This is a consequence of how the undershooting is realized (detectable reductions are only considered after initial or obligatory undershooting). The area in light orange indicates where $\left\|\delta_{KP} - \delta_{crit}\right\|$ is actually greater than and could thus compensate any realized undershooting U (see Table 18).
			-42.9	0.1	8.1	17.6	42.9	
--	--	-6.0	-2.6	1.7	15.0	30.0	60.0	
			-8.1	1.1	13.6	27.5	56.6	
			-17.6	0.1	10.9	22.6	49.7	
			-42.9	- 0.9	8.1	17.6	42.9	
--	--	-7.0	-2.6	0.7	15.0	30.0	60.0	
			-8.1	0.2	13.6	27.5	56.6	
			-17.6	-0.9	10.9	22.6	49.7	
			-42.9	-1.9	8.1	17.6	42.9	
7	20	-8.0	-2.6	-0.3	15.0	30.0	60.0	
			-8.1	-0.8	13.6	27.5	56.6	
			-17.6	-1.8	10.9	22.6	49.7	
			-42.9	-2.9	8.1	17.6	42.9	
--	--	-9.0	-2.6	-1.3	14.2	30.0	60.0	
			-8.1	-1.8	12.8	27.5	56.6	
			-17.6	-2.8	10.0	22.6	49.7	
			-42.9	-3.9	7.2	17.6	42.9	
8	20	-10.0	-2.6	-2.3	13.3	30.0	60.0	
			-8.1	-2.8	11.8	27.5	56.6	
			-17.6	-3.8	9.0	22.6	49.7	
			-42.9	-4.9	6.2	17.6	42.9	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table 18: The Und&VT concept applied to Annex I countries committed to emission limitation ($\delta_{\text{KP}} \leq 0$). Case 3 $\left(\delta_{\text{crit}} < \delta_{\text{KP}}\right)$**:** equations (51) and (52); Case 4 $\left(\delta_{\text{crit}} \geq \delta_{\text{KP}}\right)$**:** equations (56)–(58). The table lists the undershooting U_{v} contained in the modified emission limitation targets δ_{mod} listed in Table 17, where the "$\mathrm{x}_{\mathrm{t},2}$-greater-than-$\left(1+\delta_{\text{crit}}\right)\mathrm{x}_{\mathrm{t},1}$" risk α_{v} (Case 3) and the "$\mathrm{x}_{\mathrm{t},2}$-greater-than-$\left(1-\left(\delta_{\text{KP}}-2\delta_{\text{crit}}\right)\right)\mathrm{x}_{\mathrm{t},1}$" risk α_{v} (Case 4), respectively, are specified to be 0, 0.1, 0.3 and 0.5. In the last column, we assess the hypothetical situation that the Und&VT concept had been applied prior to/in negotiating the Kyoto Protocol. White fields: $\delta_{\text{crit}} < \delta_{\text{KP}}$ (Case 3). Note the different behavior of U_{v} vis-à-vis U (confer Table 16). Orange-colored fields: $\delta_{\text{crit}} \geq \delta_{\text{KP}}$ (Case 4). Note that U_{v} is independent of δ_{KP}, which is a consequence of how the undershooting is realized (detectable reductions are only considered after initial or obligatory undershooting). The area in light orange indicates where $\left|\delta_{\text{KP}}-\delta_{\text{crit}}\right|$ is actually greater than and could thus compensate the specified undershooting U (confer Table 16).

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com. δ**	**Crit. Targ. δ_{crit} % for ρ =** **2.5%** **7.5%** **15%** **30%**	**Undershooting U_v in % for ρ =**				**If the Und&VT Concept had been applied**
				2.5%	**7.5%**	**15%**	**30%**	
				and				
				$a_v = 0.0$ **$a_v = 0.1$** **$a_v = 0.3$** **$a_v = 0.5$**	**$a_v = 0.0$** **$a_v = 0.1$** **$a_v = 0.3$** **$a_v = 0.5$**	**$a_v = 0.0$** **$a_v = 0.1$** **$a_v = 0.3$** **$a_v = 0.5$**	**$a_v = 0.0$** **$a_v = 0.1$** **$a_v = 0.3$** **$a_v = 0.5$**	
5	20	0.0	-2.6	5.0	15.0	30.0	60.0	(I) Outside the orange-colored area ($\delta_{\text{crit}} < \delta_{\text{KP}}$): The relevant reference for undershooting is $-\delta_{\text{crit}}$ (see Table 17), which must be reached with the help of U_{Gap} so that the countries' emission signals become detectable. $\mathrm{U}_{\mathrm{v}} = \mathrm{U}_{\text{Gap}}$ for $\alpha_{\mathrm{v}} = 0.5$. Similar to the undershooting U in Table 16, countries complying with a smaller δ_{KP} exhibit a great (U_{Gap}, thus) U_{v} while countries complying with a greater δ_{KP} exhibit a small (U_{Gap}, thus) U_{v} see equations (51) and (52). However, the introduction of U_{Gap} results in $\mathrm{U}_{\mathrm{v}} > \mathrm{U}$ and a variation of U_{v} in dependence of δ_{KP} that is greater than that of U.
			-8.1	4.5	13.6	27.5	56.6	
			-17.6	3.5	10.9	22.6	49.7	
			-42.9	2.6	8.1	17.6	42.9	
6	20	-1.0	-2.6	6.0	16.0	31.0	61.0	
			-8.1	5.5	14.6	28.5	57.6	
			-17.6	4.5	11.9	23.6	50.7	
			-42.9	3.6	9.1	18.6	43.9	
--		-2.0	-2.6	7.0	17.0	32.0	62.0	
			-8.1	6.5	15.6	29.5	58.6	
			-17.6	5.5	12.9	24.6	51.7	
			-42.9	4.6	10.1	19.6	44.9	
--		-3.0	-2.6	7.6	18.0	33.0	63.0	
			-8.1	7.1	16.6	30.5	59.6	
			-17.6	6.1	13.9	25.6	52.7	
			-42.9	5.1	11.1	20.6	45.9	
--		-4.0	-2.6	7.6	19.0	34.0	64.0	
			-8.1	7.1	17.6	31.5	60.6	
			-17.6	6.1	14.9	26.6	53.7	
			-42.9	5.1	12.1	21.6	46.9	
--		-5.0	-2.6	7.6	20.0	35.0	65.0	
			-8.1	7.1	18.6	32.5	61.6	
			-17.6	6.1	15.9	27.6	54.7	
			-42.9	5.1	13.1	22.6	47.9	
--	--	-6.0	-2.6	7.7	21.0	36.0	66.0	(II) Inside the orange-colored area ($\delta_{\text{crit}} \geq \delta_{\text{KP}}$): The relevant reference for undershooting is $\delta_{\text{KP}} - 2\delta_{\text{crit}}$ (see Table 17), which is to be reached with the help of U_{Gap}. $\mathrm{U}_{\mathrm{v}} = \mathrm{U}_{\text{Gap}}$ for $\alpha_{\mathrm{v}} = 0.5$. Unlike δ_{mod}, U_{v} mainly depends on ρ and α_{v} and only slightly on δ_{KP} (see equations (56)–(58)). This is a consequence of how the undershooting is realized (detectable reductions are only considered after initial or obligatory undershooting). Still, $\mathrm{U}_{\mathrm{v}} > \mathrm{U}$. The area in light orange indicates where $\left|\delta_{\text{KP}} - \delta_{\text{crit}}\right|$ is actually greater than and could thus compensate the specified undershooting U (confer Table 16).
			-8.1	7.1	19.6	33.5	62.6	
			-17.6	6.1	16.9	28.6	55.7	
			-42.9	5.1	14.1	23.6	48.9	
--	--	-7.0	-2.6	7.7	22.0	37.0	67.0	
			-8.1	7.2	20.6	34.5	63.6	
			-17.6	6.1	17.9	29.6	56.7	
			-42.9	5.1	15.1	24.6	49.9	
7	20	-8.0	-2.6	7.7	23.0	38.0	68.0	
			-8.1	7.2	21.6	35.5	64.6	
			-17.6	6.2	18.9	30.6	57.7	
			-42.9	5.1	16.1	25.6	50.9	
--	--	-9.0	-2.6	7.7	23.2	39.0	69.0	
			-8.1	7.2	21.8	36.5	65.6	
			-17.6	6.2	19.0	31.6	58.7	
			-42.9	5.1	16.2	26.6	51.9	
8	20	-10.0	-2.6	7.8	23.3	40.0	70.0	
			-8.1	7.2	21.8	37.5	66.6	
			-17.6	6.2	19.0	32.6	59.7	
			-42.9	5.1	16.2	27.6	52.9	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Case 4 ($\delta_{\text{crit}} \geq \delta_{\text{KP}}$) exhibits δ_{mod} and U_{v} values that behave the other way around: δ_{mod} is now dependent on and U_{v} is (not independent of but) only slightly dependent on δ_{KP} (with U_{v} still $> U$). This is a consequence of how the undershooting is realized (detectable reductions are only considered after initial or obligatory undershooting) and what we consider as being the most straightforward procedure of dealing with the non-detectability of emission signals in the interval $[\delta_{\text{crit}}, -\delta_{\text{crit}}]$.

Appendix D presents tables similar to Tables 15 to 18 by starting from inequalities (43a), (50a) and (55a) instead of their approximations (inequalities (43c), (50c) and (55c)).

4 Conclusions

The conclusions of our study are grouped according to their relevance to (I) verification, (II) the detection of emission signals, and (III) the detection of stock signals. The conclusions are preceded by an overview that facilitates the general classification of our study.

Overview

In our study we address the detection of uncertain GHG emission signals under the Kyoto Protocol. The question to be probed is *how well do we need to know net emissions if we want to detect a specified emission signal after a given time?* No restrictions exist as to what concerns the net emitter, which may be any GHG source or sink, e.g., a fossil-fuel powered plant, a terrestrial biospheric system or any part of it, or even a combination of anthropogenic and terrestrial biospheric systems as envisaged under the Kyoto Protocol. However, 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. Another restriction concerns the exclusion of emissions/removals due to LUCF as the reporting of their uncertainties is only soon becoming standard practice. Therefore, we narrow the focus of our study to the countries' anthropogenic GHG emissions, i.e., excluding CO_2 emissions/removals due to LUCF, when we refer to the detection of their emission signals.

Our study centers on the preparatory detection of emission signals (which should have been applied prior to/in negotiating the Kyoto Protocol), while midway signal detection (which should be applied, e.g., in 2005) and signal detection in retrospect (which should be applied, e.g., in 2008–2012) will be dealt with in follow-up studies. Rigorous preparatory signal detection has not yet been carried out, neither prior to the negotiations of the Kyoto Protocol nor afterwards. The same is true for midway signal detection. The starting point for preparatory signal detection is that the Annex I countries under the Kyoto Protocol comply with their emission limitation or reduction commitments.

Uncertainties are already monitored, e.g., are they extracted as 95% confidence intervals from the national inventory reports of the EU Member States (ranging between 5–10%

and above rather than below, excluding emissions/removals due to LUCF). However, monitored emissions and uncertainties are still dealt with in isolation. A connection between emission and uncertainty estimates for the purpose of an advanced country evaluation has not yet been established.

We use relative uncertainties of 2.5, 7.5, 15 and 30% when we evaluate Annex I countries in the context of our preparatory signal detection concepts. These values are understood as the median values of relative uncertainty classes following a suggestion by Jonas and Nilsson (2001), who recommended in their earlier study the application of relative uncertainty classes as a common good practice measure. (The authors used the relative uncertainty classes $[0, 5]$, $[5, 10]$, $[10, 20]$, $[20, 40]$ and $> 40\%$.) The classes constitute a robust means to get an effective grip on uncertainties in light of the numerous data limitations and intra and inter-country inconsistencies, which do not justify the reporting of exact relative uncertainties.

(I) Verification

- The Kyoto Protocol can only be verified on the basis of bottom-up/top-down (consistent or dual-constrained) FCA, where the biosphere must be treated as one system and must not be split up into a *Kyoto* and a *non-Kyoto biosphere* (that is, the subsystems of a system can only be verified if they can be discriminated).
- Signal detection does not imply verification. Verification of emissions, in turn, does not imply, as a consequence of uncertainty, the detectability of emission signals. Therefore, the verification of emissions and the detection of emission signals must go hand-in-hand. We consider merging the two as a major research challenge, which needs to be taken up if the Kyoto Protocol is to be put on a sound basis.
- Bottom up–top down verification strongly suggests favoring total uncertainty over trend uncertainty. Total uncertainty matters as long as bottom up–top down verification is not in place and the accuracy of mean emission values is an issue. By contrast, 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 emission change is detectable.

(II) Detection of Emission Signals

- We applied four preparatory signal detection techniques by using Annex I countries as an example. These are the CRU concept; its generalization, the VT concept; the Und concept; and the Und and VT concepts combined, termed Und&VT concept. All of the techniques identify an emission signal and consider the total uncertainty that underlies the countries' emissions, either in the commitment year/period or in both the base year and the commitment year/period. The techniques follow a hierarchical order in terms of complexity permitting to explore their robustness. The most complex technique, the Und&VT concept, considers in addition to uncertainty (1) the dynamics of the signal itself permitting to ask for the verification time, the time when the signal is outstripping total uncertainty; (2) the risk (probability) that the countries' true emissions in the commitment year/period are above (below) their true emission limitation or reduction commitments; (3) the undershooting that is needed to reduce this risk to a prescribed level; and (4) a corrected undershooting/risk that accounts for detectability, i.e., that fulfills a given commitment period/maximal allowable verification time. Table 19 summarizes the results of the four detection techniques, while Table 20 lists the techniques' major pros and cons as well as our major findings.

- This preparatory signal detection exercise exemplifies that the negotiations for the Kyoto Protocol were imprudent because they did not consider the consequences of uncertainty, i.e., (1) the risk that the countries' true emissions in the commitment year/period are above their true emission limitation or reduction commitments (Und, Und&VT); and (2) detectable targets (CRU, VT, Und&VT). Based on Tables 19 and 20, the following overall conclusion can be drawn:

  Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, both the CRU concept and VT concept show that it is virtually impossible for most of the Annex I countries to meet the condition that their overall relative uncertainties are smaller than their CRUs or, equivalently, that their VTs are smaller than their maximal allowable verification times.

  In the case of the Und concept, the modified emission limitation or reduction targets δ_{mod} of the countries require considerable undershooting of their committed Kyoto targets 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.

  The situation for the Und&VT concept is similar. In this case the modified emission limitation or reduction targets δ_{mod} of the countries also require considerable undershooting of their Kyoto-compatible, but detectable, targets if one wants to keep the risk low ($\alpha_{\mathrm{v}} \approx 0.1$) that the countries' true emissions in the commitment year/period are above the true equivalents of these targets.

- The amount by which a country undershoots its Kyoto target (Und) or its Kyoto-compatible, but detectable, target (Und&VT) can be traded. Towards installing a successful trading regime, countries may want to also price the risk associated with this amount. We anticipate that the evaluation of the countries' emission signals in terms of risk and detectability will become reality.

- The IPCC also suggests assessing total uncertainties. However, a connection between monitored emission and uncertainty estimates for the purpose of an advanced country evaluation, which considers the aforementioned risk as well as detectable targets, has not yet been established. The IPCC has to take up this challenge.

(III) Detection of Stock Signals

- The Und concept is well-suited for building the bridge to "stocks". (We referred to soil carbon as a general example.) Our notion of risk introduced by the Und concept is in line with the soil communities' (type-I-error) thinking in terms of statistical significance. However, in contrast to the soil community, which is typically trying to estimate the minimum detectable difference with a specified sample size or the number of measurements needed to detect a specified difference with a specified power, we assess risk in terms of true (but unknown) emissions and in relation to committed targets, and by how much these are undershot, where the undershooting can be corrected to account for the detectability of the targets.

- Although the detection of uncertain emission changes (emission signals) and stock changes (stock signals) is similar, the signal-versus-uncertainty understanding differs among the scientific communities concerned. A rigorous attempt has not yet been made to unify their understanding and to address this issue. We see a clear need for the development of a unified signal-versus-uncertainty understanding across "flux" and "stock communities" under the Kyoto Protocol. This task needs to be tackled, ideally under the umbrella of the IPCC, and also consider the risk associated with not undershooting specified stock targets as well as the detectability of these targets.

Table 19: Summary of results: The four signal detection techniques (CRU, VT, Und, Und&VT) applied to Annex I countries. The table is compiled from Tables 6, B1 and D4 (in Appendices B and D) and lists the countries' CRUs, their normalized VTs as well as their modified emission limitation or reduction targets δ_{mod}. The latter consider undershooting committed or detectable targets to prescribed levels, thus reducing the risk (α and α_{v}, respectively) that the countries' true emissions in the commitment year/period are above the true equivalents of these targets.

			CRU Concept	**VT Concept**			
Country Group	**Max. Allow. VT**[a] **t_2 - t_1** **yr**	**KP Commit. δ_{KP}**[b] **%**	**CRU ρ_{crit}** **%**	**Normalized VTs if Countries report with ρ =**			
				2.5%	**7.5%**	**15%**	**30%**
1a	20	8.0	8.7	0.3	0.9	1.6	2.9
1b	22						
1c	21						
1d	24						
2	20	7.0	7.5	0.3	< 1.0	1.9	3.3
3a	20	6.0	6.4	0.4	1.2	2.2	3.8
3b	24						
3c	22						
4	20	5.0	5.3	0.5	1.4	2.6	4.6
5	20	0.0	0.0	infinite			
6	20	-1.0	1.0	2.6	8.1	17.6	42.9
7	20	-8.0	7.4	0.3	> 1.0	2.2	5.4
8	20	-10.0	9.1	0.3	0.8	1.8	4.3

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{\text{KP}} > 0$ – emission reduction; $\delta_{\text{KP}} \leq 0$ – emission limitation.

Table 19: continued.

		Und Concept				Und&VT Concept			
Country Group	Critical Target δ_{crit}	Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ =				Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ =			
	%	2.5%	7.5%	15%	30%	2.5%	7.5%	15%	30%
	for ρ =	and				and			
	2.5% 7.5% 15% 30%	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$
1a **1b** **1c** **1d**	2.4	12.5	20.8	32.0	50.5	10.2	14.4	24.4	40.8
	7.0	11.6	18.4	27.7	43.6	9.8	13.2	22.4	38.0
	13.0	9.8	13.4	18.4	27.7	8.9	10.7	18.0	31.3
	23.1	8.0	8.0	8.0	8.0	8.0	8.0	13.0	23.1
2	2.4	11.5	20.0	31.3	49.9	9.3	13.5	24.4	40.8
	7.0	10.6	17.5	26.9	43.0	8.8	12.3	22.4	38.0
	13.0	8.8	12.4	17.5	26.9	7.9	9.7	18.0	31.3
	23.1	7.0	7.0	7.0	7.0	7.0	7.0	13.0	23.1
3a **3b** **3c**	2.4	10.6	19.1	30.5	49.4	8.3	13.5	24.4	40.8
	7.0	9.7	16.6	26.1	42.4	7.8	12.2	22.4	38.0
	13.0	7.9	11.5	16.6	26.1	6.9	9.7	18.0	31.3
	23.1	6.0	6.0	6.0	6.0	6.0	7.0	13.0	23.1
4	2.4	9.6	18.3	29.8	48.8	7.3	13.5	24.4	40.8
	7.0	8.7	15.8	25.4	41.8	6.9	12.2	22.4	38.0
	13.0	6.9	10.5	15.8	25.4	5.9	9.7	18.0	31.3
	23.1	5.0	5.0	5.0	5.0	5.0	7.0	13.0	23.1
5	-2.6	4.9	14.0	26.1	46.2	4.9	14.5	28.4	56.0
	-8.1	3.9	11.3	21.4	38.7	4.5	13.3	26.5	53.9
	-17.6	2.0	5.8	11.3	21.4	3.5	10.8	22.3	49.0
	-42.9	0.0	0.0	0.0	0.0	2.6	8.1	17.6	42.9
6	-2.6	3.9	13.1	25.3	45.6	4.9	14.5	28.4	56.0
	-8.1	3.0	10.4	20.6	38.1	4.5	13.3	26.5	53.9
	-17.6	1.0	4.9	10.4	20.6	3.5	10.8	22.3	49.0
	-42.9	-1.0	-1.0	-1.0	-1.0	2.6	8.1	17.6	42.9
7	-2.6	-2.7	7.1	20.2	41.8	-0.4	14.5	28.4	56.0
	-8.1	-3.8	4.2	15.1	33.8	-0.9	13.3	26.5	53.9
	-17.6	-5.9	-1.7	4.2	15.1	-1.9	10.8	22.3	49.0
	-42.9	-8.0	-8.0	-8.0	-8.0	-2.9	8.1	17.6	42.9
8	-2.6	-4.6	5.3	18.7	40.8	-2.3	12.8	28.4	56.0
	-8.1	-5.7	2.5	13.6	32.6	-2.8	11.5	26.5	53.9
	-17.6	-7.8	-3.6	2.5	13.6	-3.8	8.9	22.3	49.0
	-42.9	-10.0	-10.0	-10.0	-10.0	-4.9	6.2	17.6	42.9

Table 20: This table complements Table 19. It lists the techniques' major characteristics, pros and cons as well as our interpretation of the results.

Concept	Major Characteristics, including Pros and Cons	Major Findings
CRU Section 3.1	The CRU concept implicitly addresses the issue of signal detection in a temporal context. The emission signal is compared with the total uncertainty that underlies the emissions in the commitment year/period. The uncertainty is treated as statistically independent. The CRU concept exhibits an over/ undershooting dissimilarity between countries committed to emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \le 0$).	Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, it is virtually impossible for most of the countries in groups 1–8 to meet the condition that their overall relative uncertainties are smaller than their CRUs ($\rho < \rho_{crit}$).
VT Section 3.2	The VT concept explicitly addresses the issue of signal detection in a temporal context. The emission signal is compared with the total uncertainty that underlies the emissions in the commitment year/period. The uncertainty is treated as statistically independent. The VT concept exhibits an over/ undershooting dissimilarity between countries committed to emission reduction ($\delta_{KP} > 0$) and emission limitation ($\delta_{KP} \le 0$).	Normalized VTs equal to or smaller than 1 (see green fields for emission reduction and orange fields for emission limitation) are compatible with the Kyoto Protocol, i.e., countries report with $\rho \le \rho_{crit}$; normalized VTs greater than 1 (see red fields) are not, i.e., countries report with $\rho > \rho_{crit}$. Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, it is virtually impossible for most of the countries in groups 1–8 to meet the condition $\rho < \rho_{crit}$ or, equivalently, achieve normalized VTs ≤ 1.
Und Section 3.3	Total uncertainties of base year and commitment year/period emissions are combined. (Their correlation can only be considered in the stochastic generalization of the Und concept.) With the help of the combined uncertainty, modified emission limitation or reduction targets δ_{mod} can be specified, which consider the risk that the countries' true, but unknown, emissions are above their limitation or reduction commitments agreed upon under the Kyoto Protocol. The modified targets depend on the undershooting that is needed to reduce this risk to a prescribed level. As a consequence of arbitrarily agreed-upon, nonuniform emission limitation or reduction commitments δ_{KP} , a politically unfavorable situation arises that is not in line with the spirit of the Kyoto Protocol. 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} (they exhibit a small δ_{mod}) are better off than countries that must comply with a greater δ_{KP} (they exhibit a great δ_{mod}). Toward the development of a unified signal-versus-uncertainty understanding across "flux" and "stock communities" under the Kyoto Protocol, the Und concept is well-suited for building a bridge. Its notion of risk is in line with the stock communities' (type-I-error) thinking in terms of statistical significance.	Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, the modified emission limitation or reduction targets δ_{mod} of the countries require considerable undershooting of their committed Kyoto targets if one wants to keep the risk low ($\alpha \approx 0.1$) that the countries' emissions in the commitment year/period are above these targets in terms of true, but unknown, emissions.

Table 20: continued.

Und&VT Section 3.4	The Und&VT concept takes advantage of the introduction of risk as the strength of the Und concept and the explicit consideration of time in detecting an emission signal as the strength of the VT concept. Like in the VT concept, the emission signal is compared with the total uncertainty, which underlies the emissions in the commitment year/period and which is treated as statistically independent.	All modified emission limitation or reduction targets δ_{mod} are detectable and are thus compatible with the Kyoto Protocol. Under compliance, countries would report with $\rho \le \rho_{\text{crit}}$ or, equivalently, with normalized VTs equal to or smaller than 1. Emission reduction: No correction in the form of an initial or obligatory undershooting is necessary in the case of the green fields as δ_{crit} is $\le \delta_{\text{KP}}$. Emission limitation: The concept of an initial or obligatory undershooting is unconditionally applied although δ_{crit} can be $\ge \delta_{\text{KP}}$ (see orange fields) and before detectable reductions that countries might have already realized (see light orange fields) are considered. Expecting that Annex I countries exhibit relative uncertainties in the range of 5–10% and above rather than below, excluding emissions/removals due to LUCF, the countries' modified emission limitation or reduction targets require considerable undershooting of their Kyoto-compatible, but detectable, targets if one wants to keep the risk low ($\alpha_{\text{v}} \approx 0.1$) that the countries' emissions in the commitment year/period are above these targets in terms of true, but unknown, emissions.

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Acronyms and Nomenclature

COP	Conference of the Parties
CRU	Critical Relative Uncertainty
C&C	Contraction and Convergence
EU	European Union
DTI	Distance-to-Target Indicator
FCA	Full Carbon Accounting
FF	Fossil Fuels
FCCC	Framework Convention on Climate Change
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KP	Kyoto Protocol
KT	Kyoto Target
LUCF	Land-Use Change and Forestry
MDD	Minimum Detectable Difference
MS	Member State
P	Probability
PCA	Partial Carbon Accounting
PDF	Probability Distribution Function
RC	Reduction Commitment
RME	Reliable Minimum Estimate
U	Uncertainty
Und	Undershooting
Und&VT	Undershooting and Verification Time
UNFCCC	United Nations Framework Convention on Climate Change
VT	Verification Time
crit	critical
low	lower
n.d.	not defined
mod	modified
t	true
upp	upper
v	verifiable

ISO Country Code

AT	Austria
AU	Australia
BE	Belgium
BG	Bulgaria
CA	Canada
CH	Switzerland
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
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
UA	Ukraine
UK	United Kingdom
US	United States

Appendix A: A Note to Sections 3.1 and 3.2 on the Independence of Uncertainties

The CRU (Section 3.1) as well as the VT concept (Section 3.2) require further discussion as to how the emission signal is linked with uncertainty (see inequalities (3) and (7)) and because the notion of statistical independence is used (see inequality (8)).

To elucidate, we distinguish between GHG fluxes, carbon stocks and carbon stock changes explicitly interpreted as net fluxes:

GHG Fluxes

Assume that the emissions (x_i) of a specific GHG source have been derived at times t_i with the knowledge of the respective activity (A_i) and corresponding emission factor (EF_i). Emission calculations have been carried out at t_1 and t_2 ($i = 1, 2$), where we assume that the activities A_1 and A_2 have been assessed independently, while our knowledge of the emission factor has not changed, which can be considered typical for inventorying GHG emissions.[29] Thus, we can write for the emissions and the difference in emissions:

$$x_1 = A_1 EF \ , \ x_2 = A_2 EF \qquad \text{(A1), (A2)}$$

$$\Delta x_2 := x_1 - x_2 = \left(A_1 - A_2\right) EF \ , \qquad \text{(A3a,b)}$$

and for their uncertainties following the law of uncertainty (error) propagation:

$$\varepsilon_1^2 = EF^2 \varepsilon_{A_1}^2 + A_1^2 \varepsilon_{EF}^2 \quad \Leftrightarrow \quad \frac{\varepsilon_1^2}{x_1^2} = \frac{\varepsilon_{A1}^2}{A_1^2} + \frac{\varepsilon_{EF}^2}{EF^2} \qquad \text{(A4), (A5)}$$

$$\varepsilon_2^2 = EF^2 \varepsilon_{A_2}^2 + A_2^2 \varepsilon_{EF}^2 \quad \Leftrightarrow \quad \frac{\varepsilon_2^2}{x_2^2} = \frac{\varepsilon_{A2}^2}{A_2^2} + \frac{\varepsilon_{EF}^2}{EF^2} \qquad \text{(A6), (A7)}$$

$$\varepsilon_{\Delta x,2}^2 = EF^2 \left(\varepsilon_{A_1}^2 + \varepsilon_{A_2}^2\right) + \left(A_1 - A_2\right)^2 \varepsilon_{EF}^2 = \varepsilon_1^2 + \varepsilon_2^2 - 2A_1 A_2 \varepsilon_{EF}^2 \ , \qquad \text{(A8a,b)}$$

or ($A_1 \neq A_2$):

$$\frac{\varepsilon_{\Delta x,2}^2}{\Delta x^2} = \frac{\varepsilon_{A1}^2 + \varepsilon_{A2}^2}{\left(A_1 - A_2\right)^2} + \frac{\varepsilon_{EF}^2}{EF^2} \ . \qquad \text{(A9)}$$

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[29] In this context, two remarks need to be made: (1) in general, the emission assessments at t_1 and t_2 are singular (i.e., they cannot be repeated as frequently as desired) and reflect the best expert knowledge available; and (2) a number of activities may also be dependent (or correlated) at t_1 and t_2 as the same activity data may be used to estimate more than one emission source (e.g., in the agricultural sector) or pollutant (e.g., in the case of energy emissions).

To graphically visualize the emissions x_i (equations (A1) and (A2)) and the absolute change in emissions $|\Delta x_i|$ (equation (A3)) in the context of their uncertainties, equation (A8) needs to be developed further. In accordance with Sections 3.1 and 3.2, we specify the ratio of activities with the help of δ_{KP}:

$$\frac{x_2}{x_1} = \frac{A_2}{A_1} = 1 - \delta_{KP} \qquad \text{(A10), (2)}$$

and consider the case $EF^2 \varepsilon_{A_i}^2 << A_i^2 \varepsilon_{EF}^2$ or, equivalently, $\frac{\varepsilon_{A_i}^2}{A_i^2} << \frac{\varepsilon_{EF}^2}{EF^2}$ (i = 1, 2) (see also Table A1). Here, we refer to a situation that we consider typical or close to typical for industrialized Annex I countries. CO_2 activities related to the combustion of fossil fuels (including fugitive emissions) are less precisely known than their corresponding emission factors. However, it is the opposite situation if we also consider CH_4 and N_2O resulting from fossil fuel combustion activities (including fugitive emissions) and industrial processes, as well as from natural sources. For these gases, activities are typically known more precisely than their corresponding emission factors. We consider the latter situation also representative if CO_2, CH_4 and N_2O are combined and aggregated in the form of CO_2-equivalent emissions (Winiwarter, 2004). Thus:

$$\varepsilon_{\Delta x,2}^2 \approx A_1^2 \varepsilon_{EF}^2 + A_2^2 \varepsilon_{EF}^2 - 2A_1 A_2 \varepsilon_{EF}^2 = \left(A_1 - A_2\right)^2 \varepsilon_{EF}^2 \,, \qquad \text{(A11a,b)}$$

from which we can derive with the help of equations (A10) and (2)

$$\varepsilon_{\Delta x,2}^2 \approx \left(1 - \left(1 - \delta_{KP}\right)\right)^2 A_1^2 \varepsilon_{EF}^2 \approx \delta_{KP}^2 \varepsilon_1^2 < \varepsilon_1^2 \qquad \text{(A12a,b), (A13)}$$

and/or

$$\varepsilon_{\Delta x,2}^2 \approx \left(\frac{1}{1 - \delta_{KP}} - 1\right)^2 A_2^2 \varepsilon_{EF}^2 \approx \left(\frac{\delta_{KP}}{1 - \delta_{KP}}\right)^2 \varepsilon_2^2 < \varepsilon_2^2 \qquad \text{(A14a,b), (A15)}$$

for δ_{KP} ranging between –0.1 and 0.08 (see, e.g., Table 5).

Moreover, the uncertainty $\varepsilon_{\Delta x,2}^2$ can be assessed in relation to $|x_1 - x_2| = |\delta_{KP}| x_1$ (confer equation (2)). For instance, from approximation (A12b) in combination with equation (1a) we can conclude that

$$\varepsilon_{\Delta x,2}^2 \approx \delta_{KP}^2 \varepsilon_1^2 = \delta_{KP}^2 \rho^2 x_1^2 < \delta_{KP}^2 x_1^2 \qquad \text{(A12b,c), (A16)}$$

if $\rho^2 \leq 1$ (see also Table A1).[30]

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[30] Making use of approximation (A14b) in combination with equations (1b) and (2) leads to the same result.

Table A1: Assessment of the uncertainty $\varepsilon^2_{\Delta x,2}$ in relation to ε^2_1, ε^2_2 and $\left|x_1 - x_2\right| = \left|\delta_{KP}\right| x_1$.

<table>
<tr><th>Case</th><th>Approximation of $\varepsilon^2_{\Delta x,2}$
(cf. equation (A8))</th><th>Comparison of $\varepsilon^2_{\Delta x,2}$ with $\left|x_1 - x_2\right| = \left|\delta_{KP}\right| x_1$
(cf. equation (2))</th></tr>
<tr><td>$\frac{\varepsilon^2_{A_i}}{A_i^2} << \frac{\varepsilon^2_{EF}}{EF^2}$</td><td>$\varepsilon^2_{\Delta x,2} \approx \delta^2_{KP}\varepsilon^2_1$
$\varepsilon^2_{\Delta x,2} \le \varepsilon^2_1$ for $\delta^2_{KP} \le 1$

$\varepsilon^2_{\Delta x,2} \approx \left(\frac{\delta_{KP}}{1-\delta_{KP}}\right)^2 \varepsilon^2_2$
$\varepsilon^2_{\Delta x,2} \le \varepsilon^2_2$ for $\delta_{KP} \le \frac{1}{2}$</td><td>$\varepsilon^2_{\Delta x,2} \le \left|x_1 - x_2\right|^2$ for $\rho^2 \le 1$</td></tr>
<tr><td>$\frac{\varepsilon^2_{A_i}}{A_i^2} \approx \frac{\varepsilon^2_{EF}}{EF^2}$</td><td>$\varepsilon^2_{\Delta x,2} \approx \left(1-\delta_{KP}+\delta^2_{KP}\right)\varepsilon^2_1$
$\varepsilon^2_{\Delta x,2} \le \varepsilon^2_1$ for $0 \le \delta_{KP} \le 1$
$\varepsilon^2_{\Delta x,2} > \varepsilon^2_1$ for $\delta_{KP} < 0$, $\delta_{KP} > 1$

$\varepsilon^2_{\Delta x,2} \approx \frac{1-\delta_{KP}+\delta^2_{KP}}{\left(1-\delta_{KP}\right)^2}\varepsilon^2_2$
$\varepsilon^2_{\Delta x,2} \le \varepsilon^2_2$ for $\delta_{KP} \le 0$
$\varepsilon^2_{\Delta x,2} > \varepsilon^2_2$ for $\delta_{KP} > 0$</td><td>$\varepsilon^2_{\Delta x,2} \le \left|x_1 - x_2\right|^2$ for $\rho^2 \le \frac{\delta^2_{KP}}{1-\delta_{KP}+\delta^2_{KP}}$
<table>
<tr><th>δ_{KP} in %</th><th>$\left\{\delta^2_{KP}/\left(1-\delta_{KP}+\delta^2_{KP}\right)\right\}^{0.5}$ in %</th></tr>
<tr><td>8.0</td><td>8.3</td></tr>
<tr><td>7.0</td><td>7.2</td></tr>
<tr><td>6.0</td><td>6.2</td></tr>
<tr><td>5.0</td><td>5.1</td></tr>
<tr><td>0.0</td><td>0.0</td></tr>
<tr><td>-1.0</td><td>1.0</td></tr>
<tr><td>-8.0</td><td>7.7</td></tr>
<tr><td>-10.0</td><td>9.5</td></tr>
</table></td></tr>
<tr><td>$\frac{\varepsilon^2_{A_i}}{A_i^2} >> \frac{\varepsilon^2_{EF}}{EF^2}$</td><td>$\varepsilon^2_{\Delta x,2} \approx \varepsilon^2_1 + \varepsilon^2_2$
$\varepsilon^2_{\Delta x,2} \ge \varepsilon^2_1$ for any δ_{KP}

$\varepsilon^2_{\Delta x,2} \approx \varepsilon^2_1 + \varepsilon^2_2$
$\varepsilon^2_{\Delta x,2} \ge \varepsilon^2_2$ for any δ_{KP}</td><td>$\varepsilon^2_{\Delta x,2} \le \left|x_1 - x_2\right|^2$ for $\rho^2 \le \frac{\delta^2_{KP}}{1+\left(1-\delta_{KP}\right)^2}$
<table>
<tr><th>δ_{KP} in %</th><th>$\left\{\delta^2_{KP}/\left(1+\left(1-\delta_{KP}\right)^2\right)\right\}^{0.5}$ in %</th></tr>
<tr><td>8.0</td><td>5.9</td></tr>
<tr><td>7.0</td><td>5.1</td></tr>
<tr><td>6.0</td><td>4.4</td></tr>
<tr><td>5.0</td><td>3.6</td></tr>
<tr><td>0.0</td><td>0.0</td></tr>
<tr><td>-1.0</td><td>0.7</td></tr>
<tr><td>-8.0</td><td>5.4</td></tr>
<tr><td>-10.0</td><td>6.7</td></tr>
</table></td></tr>
</table>

Figure A1 illustrates, in a simplified fashion, for the case $\frac{\varepsilon_{A_i}}{A_i^2} << \frac{\varepsilon^2_{EF}}{EF^2}$ the emissions x_i (equations (A1) and (A2)) and the absolute change in emissions $\left|\Delta x_i\right|$ (equation (A3)) as well as their uncertainties ε_i and $\varepsilon_{\Delta x,i}$ (equations (A4), (A6) and (A8)) within a temporal context.[31] Both the emissions and the (absolute) emission signal are shown at

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[31] Note that $\varepsilon_{\Delta x}$ at t_1 is zero (i.e., $\varepsilon_{\Delta x,1} = 0$). This can be shown (but not done here) with the help of the general law of uncertainty propagation.

t_1 and t_2. They are surrounded by their respective uncertainties, which — when connected (in line with preparatory signal detection) by straight lines — provide uncertainty bands.

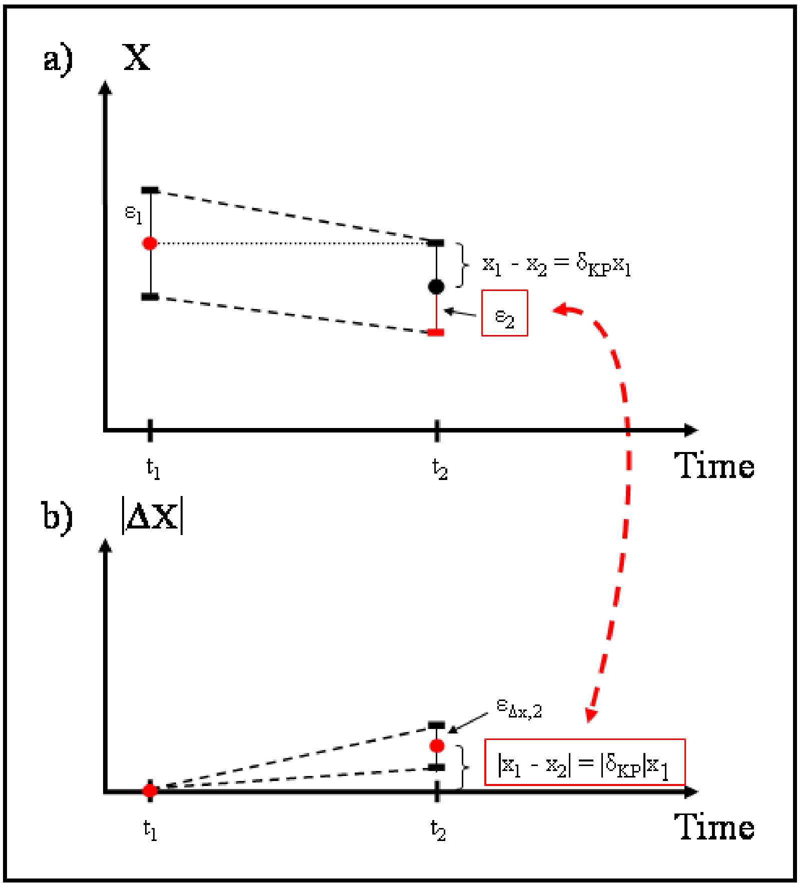

Figure A1: a) Emissions x_i and b) (absolute) emission signal $|\Delta x_i|$ at t_i, together with their respective uncertainties ε_i and $\varepsilon_{\Delta x,i}$ (i =1, 2). To address the question of when the emission signal outstrips uncertainty, the emission signal is compared with the uncertainty that underlies the emissions, not the emission signal (see red link). In the figure (without restricting generality): $\rho = \rho_{\mathrm{crit}}$ (see Sections 3.1 and 3.2).

However, the equations underlying Figure A1 do not yet reflect this temporal context. They do not yet permit addressing the issue of signal detection, i.e., the question of when an emission signal outstrips uncertainty. To overcome this fundamental shortcoming, we need to make the step from a one or one-by-one to a (here) two-points-in-time view (i.e., make use of the dynamics of the emissions or the emission signal), and thus introduce time. The CRU as well as the VT concept make this step — the CRU concept implicitly, the VT concept explicitly. In these concepts, the emission signal is compared with the uncertainty that underlies the emissions, not the emission signal (see, e.g., inequality (7)):

$$\left|\Delta x\left(t_2\right)\right| > \varepsilon\left(t_2\right) \ ; \qquad (7)$$

under the VT concept $\left|\Delta x\left(t_2\right)\right|$ is then expressed temporally by extracting the (absolute) rate of change of the emission signal (see inequality (8)). (Under the CRU concept inequality (7) is assumed to be fulfilled at t_2.) In inequality (7), we treat $\varepsilon\left(t_i\right) = \varepsilon_i$ as statistically independent (similar to white noise). That is, in the commitment year/period t_2 we ask 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). This is in accordance with the concept of bottom up–top down verification (see Box 1 in Section 2.3), which strongly suggests that it is the total uncertainty that matters as long as we are still searching for the accurate mean emission values.

Carbon Stocks

To potentially also deal with carbon stocks under the CRU as well as the VT concept, the issue of physical units and the issue of correlation have to be addressed.

(a) The Issue of Physical Units. So far, both the CRU concept and the VT concept had been applied at the level of fluxes and their uncertainties. However, they can formally also be applied at the level of stocks and their uncertainties. To these ends, equations (3) and (7) as well as their successor equations only need to be shifted in terms of physical units, i.e., from $\mathrm{Mt\,C\,yr^{-1}}$ to $\mathrm{Mt\,C}$, as shown in Table A2.

(b) The Issue of Correlation. Measurements of stocks might be correlated over time, e.g., if forests are inventoried using permanent plots or if soils are resampled in a paired sample mode.[32] Here, the same argument is put forward as under the flux approach above: In order to temporally detect a stock signal (instead of an emission signal) — again, in accordance with the concept of bottom up–top down verification — the stock signal has to be linked with the uncertainty, which underlies the stock measurements (not the stock signal) and which is also treated as statistically independent. This is just the characteristic modus of how the CRU and the VT concept address the issue of detecting emission and/or stock signals over time. This mere investigation of when a stock signal has outstripped its underlying total uncertainty is in contrast to the case below where a carbon stock change is the mathematical object to be explicitly dealt with, e.g., when interpreted as a net flux in accordance with the principle of conservation of matter. This mathematical interpretation requires considering the issue of correlation.

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[32] However, soil scientists concomitantly point out that, as variability among samples can be high even at small spatial scales, the statistical concept of paired samples, even if collected only centimeters apart, cannot be reliably employed (Shoch *et al.*, 2003).

Table A2: CRU and VT concept: The issue of physical units in dependence of the approach followed (flux or a stock approach).

Equation	**Quantity**	**Flux Approach Units**	**Stock Approach Units**
(3)	$\left\|x_1 - x_2\right\|$	$\mathrm{Mt\,C\,yr^{-1}}$	$\mathrm{Mt\,C}$
	ε_2	$\mathrm{Mt\,C\,yr^{-1}}$	$\mathrm{Mt\,C}$
(7)	$\left\|\Delta x(t_2)\right\|$	$\mathrm{Mt\,C\,yr^{-1}}$	$\mathrm{Mt\,C}$
	$\varepsilon(t_2)$	$\mathrm{Mt\,C\,yr^{-1}}$	$\mathrm{Mt\,C}$
(9)	Δt	yr	yr
	$\left\|\frac{dx}{dt}\right\|_{t_1}$	$\frac{\mathrm{Mt\,C\,yr^{-1}}}{\mathrm{yr}}$	$\frac{\mathrm{Mt\,C}}{\mathrm{yr}}$
	$\varepsilon(t_1)$	$\mathrm{Mt\,C\,yr^{-1}}$	$\mathrm{Mt\,C}$
	$\left(\frac{d\varepsilon}{dt}\right)_{t_1}$	$\frac{\mathrm{Mt\,C\,yr^{-1}}}{\mathrm{yr}}$	$\frac{\mathrm{Mt\,C}}{\mathrm{yr}}$

Carbon Stock Changes Explicitly Interpreted as Net Fluxes

Articles 3.3 and 3.4 of the Kyoto Protocol stipulate that human activities related to LUCF since 1990 can also be used to meet 2008–2012 commitments (see Section 2.2). The *net changes in carbon emissions by sources and removals by sinks* resulting from these activities have to be measured as changes in carbon stocks either between 2012 and 2008 or 2008/12 and 1990 (FCCC, 1998:Articles 3.3, 3.4; 1999:Decision 9/CP.4; 2002:Annex to Draft decision -/CMP.1). However, considering a carbon stock at two points in time and interpreting its change as a net flux permits us to only derive one net flux value as well as only one uncertainty value. As a consequence, the issue of temporal signal detection cannot be addressed. (Nevertheless, in the case that carbon stock estimates are available at more than two points in time, carbon stock changes that are interpreted as net fluxes can also be put into a temporal context as described above.)

To conclude, it is recalled that the way of how both the CRU concept and the VT concept assess uncertainty differs from that recommended by the IPCC and envisaged under the Kyoto Protocol (see Section 2.3). The CRU and VT concepts assess uncertainty in connection with the temporal detection of an emission signal; the IPCC and the Kyoto Protocol do not do this.

Appendix B: A Note to Section 3.3 on the Not Approximated Undershooting Concept

In this appendix we apply the Und concept without approximations. To these ends, we write inequality (26a) in the form

$$\frac{x_2}{x_1} \le \left(1-\delta_{KP}\right)\frac{1-(1-2\alpha)\rho}{1+(1-2\alpha)\rho} = 1-\delta_{mod} \ . \qquad \text{(26a), (B1)}$$

Thus, the modified emission limitation or reduction target δ_{mod} is given by:

$$\delta_{mod} = 1-\left(1-\delta_{KP}\right)\frac{1-(1-2\alpha)\rho}{1+(1-2\alpha)\rho} \ , \qquad \text{(B2)}$$

where δ_{mod} is still linked with U according to

$$\delta_{mod} = \delta_{KP} + U \ . \qquad \text{(B3)}$$

Resolving for U:

$$U = 2\left(1-\delta_{KP}\right)\frac{(1-2\alpha)\rho}{1+(1-2\alpha)\rho} \ . \qquad \text{(B4)}$$

Equation (B2) allows calculating the accurate modified emission limitation or reduction targets δ_{mod} and equation (B4) the accurate undershooting U contained in δ_{mod} for all Annex 1 countries. Tables B1 and B2 lists their δ_{mod} and U values, where the "$x_{t,2}$-greater-than-$\left(1-\delta_{KP}\right)x_{t,1}$" risk α is specified, like in Tables 7 and 8 to be 0, 0.1, 0.3 and 0.5.

The comparison with Tables 7 and 8 shows (1) that δ_{mod} and U are reasonably well approximated over the entire range of δ_{KP} values except for those combinations, in which ρ exhibits values in the order of 0.15 and beyond and α approaches zero; and (2) that our conclusions of Section 3.3 are not impaired.

Table B1: The Und concept (equation (B2)) applied to Annex I countries. The table lists modified emission limitation or reduction targets δ_{mod} for all Annex 1 countries, where the "$x_{t,2}$-greater-than-$(1-\delta_{\text{KP}})x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5. For further explanations confer to the caption of Table 7.

Country Group	**Max. Allow. VT**^{a} **t_2 - t_1 yr**	**KP Commit. δ_{KP}**^{b} **%**	**CRU ρ_{crit} %**	**Modified Emission Limitation or Reduction Targets δ_{mod} in % for ρ =**				**If the Und Concept had been applied**
				2.5%	**7.5%**	**15%**	**30%**	
				and				
				α = 0.0 **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
1a	20	8.0	8.7	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	See Und concept (Table 7).
1b	22							
1c	21							
1d	24							
2	20	7.0	7.5	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	20	6.0	6.4	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	
3b	24							
3c	22							
4	20	5.0	5.3	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	4.2	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	3.1	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	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	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 B1: continued.

5	20	0.0	0.0	4.9	14.0	26.1	46.2	See Und concept (Table 7).
				3.9	11.3	21.4	38.7	
				2.0	5.8	11.3	21.4	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	3.9	13.1	25.3	45.6	
				3.0	10.4	20.6	38.1	
				1.0	4.9	10.4	20.6	
				-1.0	-1.0	-1.0	-1.0	
--	--	-2.0	2.0	3.0	12.2	24.6	45.1	
				2.0	9.5	19.9	37.5	
				0.0	3.9	9.5	19.9	
				-2.0	-2.0	-2.0	-2.0	
--	--	-3.0	2.9	2.0	11.4	23.9	44.5	
				1.0	8.7	19.1	36.9	
				-1.0	3.0	8.7	19.1	
				-3.0	-3.0	-3.0	-3.0	
--	--	-4.0	3.8	1.1	10.5	23.1	44.0	
				0.1	7.8	18.3	36.3	
				-1.9	2.1	7.8	18.3	
				-4.0	-4.0	-4.0	-4.0	
--	--	-5.0	4.8	0.1	9.7	22.4	43.5	
				-0.9	6.9	17.5	35.6	
				-2.9	1.1	6.9	17.5	
				-5.0	-5.0	-5.0	-5.0	
--	--	-6.0	5.7	-0.8	8.8	21.7	42.9	
				-1.8	6.0	16.7	35.0	
				-3.9	0.2	6.0	16.7	
				-6.0	-6.0	-6.0	-6.0	
--	--	-7.0	6.5	-1.8	7.9	20.9	42.4	
				-2.8	5.1	15.9	34.4	
				-4.9	-0.8	5.1	15.9	
				-7.0	-7.0	-7.0	-7.0	
7	20	-8.0	7.4	-2.7	7.1	20.2	41.8	
				-3.8	4.2	15.1	33.8	
				-5.9	-1.7	4.2	15.1	
				-8.0	-8.0	-8.0	-8.0	
--	--	-9.0	8.3	-3.7	6.2	19.4	41.3	
				-4.7	3.3	14.4	33.2	
				-6.8	-2.7	3.3	14.4	
				-9.0	-9.0	-9.0	-9.0	
8	20	-10.0	9.1	-4.6	5.3	18.7	40.8	
				-5.7	2.5	13.6	32.6	
				-7.8	-3.6	2.5	13.6	
				-10.0	-10.0	-10.0	-10.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Table B2: The Und concept (equation (B4)) applied to Annex I countries. The table lists the undershooting U contained in the modified emission limitation and reduction targets δ_{mod} listed in Table B1, 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. For further explanations confer to the caption of Table 7.

Country Group	Max. Allow. VT^a t_2 - t_1 yr	KP Commit. δ_{KP}^{b} %	CRU ρ_{crit} %	Undershooting U in % for ρ =				If the Und Concept had been applied
				2.5%	7.5%	15%	30%	
				and				
				α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	α = 0.0 α = 0.1 α = 0.3 α = 0.5	
1a **1b** **1c** **1d**	20 22 21 24	8.0	8.7	4.5 3.6 1.8 0.0	12.8 10.4 5.4 0.0	24.0 19.7 10.4 0.0	42.5 35.6 19.7 0.0	See Und concept (Table 8).
2	20	7.0	7.5	4.5 3.6 1.8 0.0	13.0 10.5 5.4 0.0	24.3 19.9 10.5 0.0	42.9 36.0 19.9 0.0	
3a **3b** **3c**	20 24 22	6.0	6.4	4.6 3.7 1.9 0.0	13.1 10.6 5.5 0.0	24.5 20.1 10.6 0.0	43.4 36.4 20.1 0.0	
4	20	5.0	5.3	4.6 3.7 1.9 0.0	13.3 10.8 5.5 0.0	24.8 20.4 10.8 0.0	43.8 36.8 20.4 0.0	
--	--	4.0	4.2	4.7 3.8 1.9 0.0	13.4 10.9 5.6 0.0	25.0 20.6 10.9 0.0	44.3 37.2 20.6 0.0	
--	--	3.0	3.1	4.7 3.8 1.9 0.0	13.5 11.0 5.7 0.0	25.3 20.8 11.0 0.0	44.8 37.5 20.8 0.0	
--	--	2.0	2.0	4.8 3.8 1.9 0.0	13.7 11.1 5.7 0.0	25.6 21.0 11.1 0.0	45.2 37.9 21.0 0.0	
--	--	1.0	1.0	4.8 3.9 2.0 0.0	13.8 11.2 5.8 0.0	25.8 21.2 11.2 0.0	45.7 38.3 21.2 0.0	

Table B2: continued.

5	20	0.0	0.0	4.9	14.0	26.1	46.2	See Und concept (Table 8).
				3.9	11.3	21.4	38.7	
				2.0	5.8	11.3	21.4	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	4.9	14.1	26.3	46.6	
				4.0	11.4	21.6	39.1	
				2.0	5.9	11.4	21.6	
				0.0	0.0	0.0	0.0	
--	--	-2.0	2.0	5.0	14.2	26.6	47.1	
				4.0	11.5	21.9	39.5	
				2.0	5.9	11.5	21.9	
				0.0	0.0	0.0	0.0	
--	--	-3.0	2.9	5.0	14.4	26.9	47.5	
				4.0	11.7	22.1	39.9	
				2.0	6.0	11.7	22.1	
				0.0	0.0	0.0	0.0	
--	--	-4.0	3.8	5.1	14.5	27.1	48.0	
				4.1	11.8	22.3	40.3	
				2.1	6.1	11.8	22.3	
				0.0	0.0	0.0	0.0	
--	--	-5.0	4.8	5.1	14.7	27.4	48.5	
				4.1	11.9	22.5	40.6	
				2.1	6.1	11.9	22.5	
				0.0	0.0	0.0	0.0	
--	--	-6.0	5.7	5.2	14.8	27.7	48.9	
				4.2	12.0	22.7	41.0	
				2.1	6.2	12.0	22.7	
				0.0	0.0	0.0	0.0	
--	--	-7.0	6.5	5.2	14.9	27.9	49.4	
				4.2	12.1	22.9	41.4	
				2.1	6.2	12.1	22.9	
				0.0	0.0	0.0	0.0	
7	20	-8.0	7.4	5.3	15.1	28.2	49.8	
				4.2	12.2	23.1	41.8	
				2.1	6.3	12.2	23.1	
				0.0	0.0	0.0	0.0	
--	--	-9.0	8.3	5.3	15.2	28.4	50.3	
				4.3	12.3	23.4	42.2	
				2.2	6.3	12.3	23.4	
				0.0	0.0	0.0	0.0	
8	20	-10.0	9.1	5.4	15.3	28.7	50.8	
				4.3	12.5	23.6	42.6	
				2.2	6.4	12.5	23.6	
				0.0	0.0	0.0	0.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Appendix C: A Note to Section 3.3 on the Stochastic Generalization of the Undershooting Concept

The Und concept can be generalized stochastically with respect to both GHG fluxes and carbon stocks. In this note, we explain in more general terms the conditions underlying the generalization of the Und concept and its notion of risk. We found building this interdisciplinary bridge necessary when communicating with experts from various scientific communities involved in monitoring and estimating GHG fluxes and carbon stocks over time.

GHG Fluxes

In general, emission estimates of large emitters (countries, sectors, etc.) are unique in the sense that they can be carried out independently from each other only once in a certain manner for a given point in time. They cannot be repeatedly realized as specified. In practice, repetitions are carried out if improved knowledge becomes available that is used as input for an emission estimate, e.g., more correct activity data or emission factors. As a consequence, improved emission estimates cannot be considered as independent repetitions of the initial estimate.

It is common practice to interpret a singular emission estimate as the best estimate that is identical, or sufficiently close, to the mean value of a hypothetical probability distribution function (PDF) that one would find if emission estimates could be repeatedly realized independently of each other. In addition, experts try to also specify the uncertainty that surrounds this mean emission estimate (which is the situation underlying Appendix A) as well as the type of PDF which, they believe, reflects this emission estimate best. Typically, PDFs are chosen to be normal. However, in some cases, they are also assumed to be uniform and even lognormal or triangular (see, e.g., Winiwarter and Orthofer, 2000:Table 6; Winiwarter and Rypdal, 2001:Table 2).

Nahorski *et al.* (2003) have generalized the Und concept stochastically with respect to emissions. The authors also specify the PDF that is assumed to underlie x_i (i = 1, 2).

The true (but unknown) emissions $x_{t,i}$ are assumed to satisfy

$$E(x_i) = x_{t,i} \ , \tag{C1}$$

where $E(x_i)$ denotes the expectation value of the random variable x_i with ε_i as its (finite) standard deviation. With a view on inequalities (19)–(22), the combined PDF of the random variable $\left\{(1-\delta_{KP})x_1 - x_2\right\}$ is considered. This PDF can be arbitrary provided it exhibits $\left\{(1-\delta_{KP})x_{t,1} - x_{t,2}\right\}$ as its median. The risk α that $\left\{(1-\delta_{KP})x_1 - x_2\right\}$ is equal to or greater than $\left\{(1-\delta_{KP})x_{t,1} - x_{t,2}\right\} + q_{1-\alpha}\varepsilon_{12}$, or, alternatively, the standardized difference $\left\{\left((1-\delta_{KP})x_1 - x_2\right) - \left((1-\delta_{KP})x_{t,1} - x_{t,2}\right)\right\}$ is equal to or greater than $q_{1-\alpha}$, can be expressed as the probability (P) of

$$P\left(\frac{\left\{\left(1-\delta_{KP}\right)x_1-x_2\right\}-\left\{\left(1-\delta_{KP}\right)x_{t,1}-x_{t,2}\right\}}{\varepsilon_{12}}\geq q_{1-\alpha}\right)=\alpha \ , \tag{C2}$$

where $\varepsilon_{12}=f\left(\varepsilon_1,\varepsilon_2\right)$ is the standard deviation of the random variable $\left\{\left(1-\delta_{KP}\right)x_1-x_2\right\}$ (ε_1 and ε_2 can correlate); $q_{1-\alpha}$ is the $\left(1-\alpha\right)^{th}$ quantile of the PDF of the corresponding standardized variable; and $0\leq\alpha\leq0.5$. Due to the standardization, $q_{0.5}=0$. Equation (C2) contains the condition that needs to be satisfied with respect to α:

$$x_2\leq\left(1-\delta_{KP}\right)x_1+\left\{x_{t,2}-\left(1-\delta_{KP}\right)x_{t,1}\right\}-q_{1-\alpha}\varepsilon_{12} \ . \tag{C3}$$

To study the case $x_{t,2}-\left(1-\delta_{KP}\right)x_{t,1}\geq0$ (cf. Section 3.3), it is sufficient to consider $x_{t,2}-\left(1-\delta_{KP}\right)x_{t,1}=0$, i.e., inequality

$$x_2\leq\left(1-\delta_{KP}\right)x_1-q_{1-\alpha}\varepsilon_{12} \ , \tag{C4a}$$

because inequality (C4a) implies inequality (C3). All of the terms of inequality (C4a) are known or can be determined. It permits calculating the risk α associated with $x_{t,2}-\left(1-\delta_{KP}\right)x_{t,1}\geq0$. Similar to the Und concept based on interval uncertainties, inequality (C4a) or

$$x_2-\left(1-\delta_{KP}\right)x_1\leq-q_{1-\alpha}\varepsilon_{12} \tag{C4b}$$

also requires $Dx=x_2-\left(1-\delta_{KP}\right)x_1\leq0$.

Carbon Stocks

Here, we refer to soil carbon as a general example. For soil or non-forest vegetation, in contrast to forests, the same soil or plant sample cannot be monitored over time. Instead, on each sample collection, the sampled unit is destroyed for the analysis of its relevant components. Here, we interpret x_i as the arithmetic mean over a number of soil carbon measurements (collectively called a sample in statistics) within a given spatial unit at time t_i and $x_{t,i}$ as the unknown expectation value of the population from which the sample came (i = 1, 2).

Soil scientists typically apply the t statistics as their samples are limited (consisting of less than 30 measurements per spatial unit) and the populations from which they came can be assumed to be normally distributed. In Table C1, we present a general overview on typical t statistical applications in soil sciences. The generalized Und concept outlined above is in accordance with the concept of statistical significance in combination with the testing of hypotheses. In the particular case here, it is the accordance with the two-(independent or dependent) samples t test (where the "t_1 sample" is multiplied with $\left(1-\delta_{KP}\right)$) to test the null hypothesis that the difference of two population means is = 0 or ≤ 0. (That is, the alternate hypotheses are that this difference is ≠ or > 0.) The risk α addressed by the generalized Und concept is identical with the situation that the test comes to a significant result (rejection of the null hypothesis), commonly also called type I error.

Table C1: General overview on typical t statistical applications in soil sciences. Sources: Dawkins (1957); Sokal and Rohlf (1981); MacDicken (1997); Bleymüller *et al.* (1998); Zar (1999); Shoch *et al.* (2003).

Applied t Statistics	**Sampling Available at**		**Issues Addressed in the t Test Modus**
	t_1	**t_2**	
One-sample t test	✓		1. Estimating the confidence intervals for the population mean, the minimum value of which is also referred to as reliable minimum estimate (RME). 2. Estimating the minimum detectable difference (MDD) with a sample of specified size, or the number of measurements needed to detect a specified difference with a specified power.
Two-independent samples t test (unpaired sampling)	✓	✓	1. Estimating the confidence interval for the difference of two population means. A modification is the quantification of the (two-sided) RME. 2. Testing the null hypothesis that the difference of two population means is = 0 or ≤ 0. (To avoid the Behrens-Fisher problem, the variances of the two populations are assumed to be equal.)
Two-dependent samples t test (paired sampling)[32]	✓	✓	1. Quantifying the (two-sided) RME. 2. Testing the null hypothesis that the difference of two population means is = 0 or ≤ 0.

Appendix D: A Note to Section 3.4 on the Not Approximated Undershooting–Verification Time Concept

In this appendix we apply the Und&VT concept without approximations.

(I) Initial or Obligatory Undershooting for $\delta_{KP} > 0$

Case 1: $\delta_{crit} \le \delta_{KP}$. The emission reduction commitments of the Annex I countries are detectable at t_2. An initial or obligatory undershooting does not need to be introduced.

Case 2: $\delta_{crit} > \delta_{KP}$. We compare inequality (43a) with reference to δ_{KP}:

$$\frac{x_2}{x_1} \le \left(1-\delta_{\mathrm{KP}}\right)\frac{1}{1+\left(1-2\alpha\right)\rho} = 1-\delta_{\mathrm{mod}} \ , \qquad \text{(43a), (B1)}$$

where

$$\delta_{\mathrm{mod}} = 1-\left(1-\delta_{\mathrm{KP}}\right)\frac{1}{1+\left(1-2\alpha\right)\rho} = \delta_{\mathrm{KP}} + \mathrm{U} \qquad \text{(D1), (B3)}$$

$$\mathrm{U} = \left(1-\delta_{\mathrm{KP}}\right)\frac{\left(1-2\alpha\right)\rho}{1+\left(1-2\alpha\right)\rho} \ ; \qquad \text{(D2)}$$

and inequality (45a) with reference to δ_{crit}:

$$\frac{x_2}{x_1} \le \left(1-\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = 1-\delta_{\mathrm{mod}} \ , \qquad \text{(45a), (B1)}$$

where

$$\delta_{\mathrm{mod}} = 1-\left(1-\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = \delta_{\mathrm{KP}} + \mathrm{U}_{\mathrm{v}} \qquad \text{(D3a,b)}$$

$$\mathrm{U}_{\mathrm{v}} = \mathrm{U}_{\mathrm{Gap}} + \left(1-\delta_{\mathrm{crit}}\right)\frac{\left(1-2\alpha_{\mathrm{v}}\right)\rho}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} \qquad \text{(D4)}$$

and δ_{crit} and $\mathrm{U}_{\mathrm{Gap}}$ are given, as before, by equations (32a) and (42b), respectively. Thus:

$$1-\delta_{\mathrm{mod}} = \left(1-\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} \ . \qquad \text{(D5)}$$

Solving for α_{v}, we find

$$\alpha_{\mathrm{v}} = \frac{1}{2}\left\{1 - \frac{\delta_{\mathrm{mod}} - \delta_{\mathrm{crit}}}{\left(1-\delta_{\mathrm{mod}}\right)\rho}\right\} , \tag{D6}$$

where δ_{mod} is given by equation (D1).

(II) Initial or Obligatory Undershooting for $\delta_{KP} \leq 0$

Case 3: $\delta_{crit} < \delta_{KP}$. We compare inequality (43a) with reference to δ_{KP} (as above) and inequality (50a) with reference to $-\delta_{\mathrm{crit}}$:

$$\frac{\mathrm{x}_2}{\mathrm{x}_1} \leq \left(1+\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = 1-\delta_{\mathrm{mod}} , \qquad \text{(50a), (B1)}$$

where

$$\delta_{\mathrm{mod}} = 1-\left(1+\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = \delta_{\mathrm{KP}} + \mathrm{U}_{\mathrm{v}} \qquad \text{(D7a,b)}$$

$$\mathrm{U}_{\mathrm{v}} = \mathrm{U}_{\mathrm{Gap}} + \left(1+\delta_{\mathrm{crit}}\right)\frac{\left(1-2\alpha_{\mathrm{v}}\right)\rho}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} \tag{D8}$$

and δ_{crit} and $\mathrm{U}_{\mathrm{Gap}}$ are given, as before, by equations (32b) and (52), respectively. Thus:

$$1-\delta_{\mathrm{mod}} = \left(1+\delta_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} . \tag{D9}$$

Solving for α_{v}, we find

$$\alpha_{\mathrm{v}} = \frac{1}{2}\left\{1 - \frac{\delta_{\mathrm{mod}} + \delta_{\mathrm{crit}}}{\left(1-\delta_{\mathrm{mod}}\right)\rho}\right\} , \tag{D10}$$

where δ_{mod} is given by equation (D1). However, as the intervals $\left[\delta_{\mathrm{KP}}, \delta_{\mathrm{KP}} + \left(1-\delta_{\mathrm{KP}}\right)\frac{\rho}{1+\rho}\right]$ and $\left[-\delta_{\mathrm{crit}}, -\delta_{\mathrm{crit}} + \left(1+\delta_{\mathrm{crit}}\right)\frac{\rho}{1+\rho}\right]$ do not overlap, corresponding risks $\alpha \leftrightarrow \alpha_{\mathrm{v}}$ cannot be determined.[33]

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[33] The comparison of Tables D1 and D4 for $\delta_{\mathrm{crit}} < \delta_{\mathrm{KP}}$ (Case 3) shows that $\delta_{\mathrm{mod}}\left(\text{equation }\left(\mathrm{D1}\right): \alpha = 0\right)$ is always smaller than $\delta_{\mathrm{mod}}\left(\text{Case 3: equation }\left(\mathrm{D7a}\right): \alpha_{\mathrm{v}} = 0.5\right)$ for all listed values of δ_{KP} and ρ. Mathematically, an overlap of intervals would require $\delta_{\mathrm{mod}}\left(\text{equation}\left(\mathrm{D1}\right): \alpha = 0\right) \geq \delta_{\mathrm{mod}}\left(\text{Case 3: equation }\left(\mathrm{D7a}\right): \alpha_{\mathrm{v}} = 0.5\right)$ or, alternatively (after making use of equations (D1), (D7a) and (32b)), $\delta_{\mathrm{KP}} \geq 2\left(1-\rho\right)\delta_{\mathrm{crit}}^{2}$. This is not possible because $\delta_{\mathrm{KP}} \leq 0$ and the right sight > 0 for $\rho < 1$.

Case 4: $\delta_{crit} \geq \delta_{KP}$. We compare inequality (43a) with reference to δ_{KP} (as above) and inequality (55a) with reference to $-\delta'_{\mathrm{crit}} = \delta_{\mathrm{KP}} - 2\delta_{\mathrm{crit}}$:

$$\frac{\mathrm{x}_2}{\mathrm{x}_1} \leq \left(1+\delta'_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = 1-\delta_{\mathrm{mod}} \ , \qquad \text{(55a), (B1)}$$

where

$$\delta_{\mathrm{mod}} = 1-\left(1+\delta'_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} = \delta_{\mathrm{KP}} + \mathrm{U}_{\mathrm{v}} \qquad \text{(D11a,b)}$$

$$\mathrm{U}_{\mathrm{v}} = \mathrm{U}_{\mathrm{Gap}} + \left(1+\delta'_{\mathrm{crit}}\right)\frac{\left(1-2\alpha_{\mathrm{v}}\right)\rho}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} \qquad \text{(D12)}$$

and δ_{crit}, $\mathrm{U}_{\mathrm{Gap}}$ and δ'_{crit} are given, as before, by equations (32b), (57) and (58), respectively. Thus:

$$1-\delta_{\mathrm{mod}} = \left(1+\delta'_{\mathrm{crit}}\right)\frac{1}{1+\left(1-2\alpha_{\mathrm{v}}\right)\rho} \ . \qquad \text{(D13)}$$

Solving for α_{v}, we find

$$\alpha_{\mathrm{v}} = \frac{1}{2}\left\{1-\frac{\delta_{\mathrm{mod}}+\delta'_{\mathrm{crit}}}{\left(1-\delta_{\mathrm{mod}}\right)\rho}\right\} \ , \qquad \text{(D14)}$$

where δ_{mod} is given by equation (D1). Again, as the intervals $\left[\delta_{\mathrm{KP}}, \delta_{\mathrm{KP}} + \left(1-\delta_{\mathrm{KP}}\right)\frac{\rho}{1+\rho}\right]$ and $\left[-\delta'_{\mathrm{crit}}, -\delta'_{\mathrm{crit}} + \left(1+\delta'_{\mathrm{crit}}\right)\frac{\rho}{1+\rho}\right]$ do not overlap, corresponding risks $\alpha \leftrightarrow \alpha_{\mathrm{v}}$ cannot be determined.[34]

The comparison with Tables 9, 10 and 12 to 14 shows (1) that δ_{mod} and U, α_{v}, and δ_{mod} and U_{v} are reasonably well approximated over the entire range of δ_{KP} values except for those combinations, in which ρ exhibits values in the order of 0.15 and beyond and α approaches zero; and (2) that our conclusions of Section 3.4 are not impaired.

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[34] The comparison of Tables 15 and 17 for $\delta_{\mathrm{crit}} \geq \delta_{\mathrm{KP}}$ (Case 4) shows that $\delta_{\mathrm{mod}}\left(\text{equation}\left(\mathrm{D1}\right): \alpha = 0\right)$ is always smaller than $\delta_{\mathrm{mod}}\left(\text{Case 4: equation (D11a)}: \alpha_{\mathrm{v}} = 0.5\right)$ for all listed values of δ_{KP} and ρ. Mathematically, an overlap of intervals would require $\delta_{\mathrm{mod}}\left(\text{equation}\left(\mathrm{D1}\right): \alpha = 0\right) \geq \delta_{\mathrm{mod}}\left(\text{Case 4: equation }\left(\mathrm{D11a}\right): \alpha_{\mathrm{v}} = 0.5\right)$ or, alternatively (after making use of equations (D1), (D11a),(58), and (32b)), $\left|\delta_{\mathrm{KP}}\right| \geq \frac{1+3\rho}{1-\rho}$. This is not in accordance with reality because $\left|\delta_{\mathrm{KP}}\right|$ would have to be ≥ 1, the smallest value that the term on the right can take on for $\rho = 0$ ($\rho < 1$).

Table D1: The Und part of the Und&VT concept (equation (D1)) applied to Annex I countries. The table lists modified emission limitation or reduction targets δ_{mod} for all Annex I countries, where the "$x_{t,2}$-greater-than-$\left(1-\delta_{\text{KP}}\right)x_{t,1}$" risk α is specified to be 0, 0.1, 0.3 and 0.5. For further explanations confer to the captions of Tables 9 and 15.

Country Group	**Max. Allow. VT**[a] **t_2 - t_1 yr**	**KP Commit. δ_{KP}**[b] **%**	**CRU ρ_{crit} %**	**Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ =**				**If the Und Concept had been applied**
				2.5%	**7.5%**	**15%**	**30%**	
				and				
				α = 0.0 **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
1a	20	8.0	8.7	10.2 9.8 8.9 8.0	14.4 13.2 10.7 8.0	20.0 17.9 13.2 8.0	29.2 25.8 17.9 8.0	See Und&VT concept (Table 9).
1b	22							
1c	21							
1d	24							
2	20	7.0	7.5	9.3 8.8 7.9 7.0	13.5 12.3 9.7 7.0	19.1 17.0 12.3 7.0	28.5 25.0 17.0 7.0	
3a	20	6.0	6.4	8.3 7.8 6.9 6.0	12.6 11.3 8.7 6.0	18.3 16.1 11.3 6.0	27.7 24.2 16.1 6.0	
3b	24							
3c	22							
4	20	5.0	5.3	7.3 6.9 5.9 5.0	11.6 10.4 7.8 5.0	17.4 15.2 10.4 5.0	26.9 23.4 15.2 5.0	
--	--	4.0	4.2	6.3 5.9 5.0 4.0	10.7 9.4 6.8 4.0	16.5 14.3 9.4 4.0	26.2 22.6 14.3 4.0	
--	--	3.0	3.1	5.4 4.9 4.0 3.0	9.8 8.5 5.8 3.0	15.7 13.4 8.5 3.0	25.4 21.8 13.4 3.0	
--	--	2.0	2.0	4.4 3.9 3.0 2.0	8.8 7.5 4.9 2.0	14.8 12.5 7.5 2.0	24.6 21.0 12.5 2.0	
--	--	1.0	1.0	3.4 2.9 2.0 1.0	7.9 6.6 3.9 1.0	13.9 11.6 6.6 1.0	23.8 20.2 11.6 1.0	

Table D1: continued.

5	20	0.0	0.0	2.4	7.0	13.0	23.1	See Und&VT concept (Table 15).
				2.0	5.7	10.7	19.4	
				1.0	2.9	5.7	10.7	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	1.5	6.0	12.2	22.3	
				1.0	4.7	9.8	18.5	
				0.0	1.9	4.7	9.8	
				-1.0	-1.0	-1.0	-1.0	
--	--	-2.0	2.0	0.5	5.1	11.3	21.5	
				0.0	3.8	8.9	17.7	
				-1.0	1.0	3.8	8.9	
				-2.0	-2.0	-2.0	-2.0	
--	--	-3.0	2.9	-0.5	4.2	10.4	20.8	
				-1.0	2.8	8.0	16.9	
				-2.0	0.0	2.8	8.0	
				-3.0	-3.0	-3.0	-3.0	
--	--	-4.0	3.8	-1.5	3.3	9.6	20.0	
				-2.0	1.9	7.1	16.1	
				-3.0	-1.0	1.9	7.1	
				-4.0	-4.0	-4.0	-4.0	
--	--	-5.0	4.8	-2.4	2.3	8.7	19.2	
				-2.9	0.9	6.3	15.3	
				-4.0	-1.9	0.9	6.3	
				-5.0	-5.0	-5.0	-5.0	
--	--	-6.0	5.7	-3.4	1.4	7.8	18.5	
				-3.9	0.0	5.4	14.5	
				-5.0	-2.9	0.0	5.4	
				-6.0	-6.0	-6.0	-6.0	
--	--	-7.0	6.5	-4.4	0.5	7.0	17.7	
				-4.9	-0.9	4.5	13.7	
				-5.9	-3.9	-0.9	4.5	
				-7.0	-7.0	-7.0	-7.0	
7	20	-8.0	7.4	-5.4	-0.5	6.1	16.9	
				-5.9	-1.9	3.6	12.9	
				-6.9	-4.9	-1.9	3.6	
				-8.0	-8.0	-8.0	-8.0	
--	--	-9.0	8.3	-6.3	-1.4	5.2	16.2	
				-6.9	-2.8	2.7	12.1	
				-7.9	-5.8	-2.8	2.7	
				-9.0	-9.0	-9.0	-9.0	
8	20	-10.0	9.1	-7.3	-2.3	4.3	15.4	
				-7.8	-3.8	1.8	11.3	
				-8.9	-6.8	-3.8	1.8	
				-10.0	-10.0	-10.0	-10.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Table D2: The Und part of the Und&VT concept (equation (D2)) applied to Annex I countries. The table lists the undershooting U contained in the modified emission limitation or reduction targets δ_{mod} listed in Table D1, 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. For further explanations confer to the captions of Tables 10 and 16.

Country Group	**Max. Allow. VT**[a] **t_2 - t_1 yr**	**KP Commit. δ_{KP}**[b] **%**	**CRU ρ_{crit} %**	**Undershooting U in % for ρ =**				**If the Und Concept had been applied**
				2.5%	**7.5%**	**15%**	**30%**	
				and				
				α = 0.0 **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	**α = 0.0** **α = 0.1** **α = 0.3** **α = 0.5**	
1a	20	8.0	8.7	2.2 1.8 0.9 0.0	6.4 5.2 2.7 0.0	12.0 9.9 5.2 0.0	21.2 17.8 9.9 0.0	See Und&VT concept (Table 10).
1b	22							
1c	21							
1d	24							
2	20	7.0	7.5	2.3 1.8 0.9 0.0	6.5 5.3 2.7 0.0	12.1 10.0 5.3 0.0	21.5 18.0 10.0 0.0	
3a	20	6.0	6.4	2.3 1.8 0.9 0.0	6.6 5.3 2.7 0.0	12.3 10.1 5.3 0.0	21.7 18.2 10.1 0.0	
3b	24							
3c	22							
4	20	5.0	5.3	2.3 1.9 0.9 0.0	6.6 5.4 2.8 0.0	12.4 10.2 5.4 0.0	21.9 18.4 10.2 0.0	
--	--	4.0	4.2	2.3 1.9 1.0 0.0	6.7 5.4 2.8 0.0	12.5 10.3 5.4 0.0	22.2 18.6 10.3 0.0	
--	--	3.0	3.1	2.4 1.9 1.0 0.0	6.8 5.5 2.8 0.0	12.7 10.4 5.5 0.0	22.4 18.8 10.4 0.0	
--	--	2.0	2.0	2.4 1.9 1.0 0.0	6.8 5.5 2.9 0.0	12.8 10.5 5.5 0.0	22.6 19.0 10.5 0.0	
--	--	1.0	1.0	2.4 1.9 1.0 0.0	6.9 5.6 2.9 0.0	12.9 10.6 5.6 0.0	22.8 19.2 10.6 0.0	

Table D2: continued.

5	20	0.0	0.0	2.4	7.0	13.0	23.1	See Und&VT concept (Table 16).
				2.0	5.7	10.7	19.4	
				1.0	2.9	5.7	10.7	
				0.0	0.0	0.0	0.0	
6	20	-1.0	1.0	2.5	7.0	13.2	23.3	
				2.0	5.7	10.8	19.5	
				1.0	2.9	5.7	10.8	
				0.0	0.0	0.0	0.0	
--	--	-2.0	2.0	2.5	7.1	13.3	23.5	
				2.0	5.8	10.9	19.7	
				1.0	3.0	5.8	10.9	
				0.0	0.0	0.0	0.0	
--	--	-3.0	2.9	2.5	7.2	13.4	23.8	
				2.0	5.8	11.0	19.9	
				1.0	3.0	5.8	11.0	
				0.0	0.0	0.0	0.0	
--	--	-4.0	3.8	2.5	7.3	13.6	24.0	
				2.0	5.9	11.1	20.1	
				1.0	3.0	5.9	11.1	
				0.0	0.0	0.0	0.0	
--	--	-5.0	4.8	2.6	7.3	13.7	24.2	
				2.1	5.9	11.3	20.3	
				1.0	3.1	5.9	11.3	
				0.0	0.0	0.0	0.0	
--	--	-6.0	5.7	2.6	7.4	13.8	24.5	
				2.1	6.0	11.4	20.5	
				1.0	3.1	6.0	11.4	
				0.0	0.0	0.0	0.0	
--	--	-7.0	6.5	2.6	7.5	14.0	24.7	
				2.1	6.1	11.5	20.7	
				1.1	3.1	6.1	11.5	
				0.0	0.0	0.0	0.0	
7	20	-8.0	7.4	2.6	7.5	14.1	24.9	
				2.1	6.1	11.6	20.9	
				1.1	3.1	6.1	11.6	
				0.0	0.0	0.0	0.0	
--	--	-9.0	8.3	2.7	7.6	14.2	25.2	
				2.1	6.2	11.7	21.1	
				1.1	3.2	6.2	11.7	
				0.0	0.0	0.0	0.0	
8	20	-10.0	9.1	2.7	7.7	14.3	25.4	
				2.2	6.2	11.8	21.3	
				1.1	3.2	6.2	11.8	
				0.0	0.0	0.0	0.0	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP} , the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Table D3: The Und&VT concept (equation (D6)) applied to Annex I countries committed to emission reduction $(\delta_{KP} > 0)$. The table lists "$x_{t,2}$-greater-than-$(1-\delta_{crit})x_{t,1}$" risk values α_v for the modified emission reduction targets δ_{mod} presented in Table D1. For further explanations confer to the caption of Table 12.

Country Group	**Max. Allow. VT**[a] $t_2 - t_1$ **yr**	**KP Com. δ**	**Crit. Targ. δ_{crit} % for ρ = 2.5% 7.5% 15% 30%**	**Changed Risk α_v for ρ = 2.5% and α = 0.0 α = 0.1 α = 0.3 α = 0.5**	**Changed Risk α_v for ρ = 7.5% and α = 0.0 α = 0.1 α = 0.3 α = 0.5**	**Changed Risk α_v for ρ = 15% and α = 0.0 α = 0.1 α = 0.3 α = 0.5**	**Changed Risk α_v for ρ = 30% and α = 0.0 α = 0.1 α = 0.3 α = 0.5**	**If the Und&VT Concept had been applied**
1a **1b** **1c** **1d**	20 22 21 24	8.0	2.4	take α	take α	0.210	0.355	See Und&VT concept (Table 12).
			7.0	take α	take α	0.305	0.439	
			13.0	take α	take α	0.494	α_v n.d.	
			23.1	take α	take α	α_v n.d.	α_v n.d.	
2	20	7.0	2.4	take α	take α	0.249	0.375	
			7.0	take α	take α	0.343	0.457	
			13.0	take α	take α	α_v n.d.	α_v n.d.	
			23.1	take α	take α	α_v n.d.	α_v n.d.	
3a **3b** **3c**	20 24 22	6.0	2.4	take α	0.074	0.287	0.394	
			7.0	take α	0.173	0.380	0.475	
			13.0	take α	0.371	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
4	20	5.0	2.4	take α	0.149	0.325	0.412	
			7.0	take α	0.247	0.416	0.493	
			13.0	take α	0.443	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	4.0	2.4	take α	0.222	0.361	0.431	
			7.0	take α	0.319	0.452	α_v n.d.	
			13.0	take α	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	3.0	2.4	take α	0.294	0.397	0.448	
			7.0	take α	0.390	0.487	α_v n.d.	
			13.0	take α	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	take α	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	2.0	2.4	0.092	0.364	0.432	0.466	
			7.0	0.191	0.459	α_v n.d.	α_v n.d.	
			13.0	0.390	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	α' n.d.	α_v n.d.	α_v n.d.	α_v n.d.	
--	--	1.0	2.4	0.298	0.433	0.466	0.483	
			7.0	0.397	α_v n.d.	α_v n.d.	α_v n.d.	
			13.0	α_v n.d.	α_v n.d.	α_v n.d.	α_v n.d.	
			23.1	α_v n.d.	α_v n.d.	α_v n.d.	α_v n.d.	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

Table D4: The Und&VT concept (equations (D3a), (D7a) and (D11a)) applied to Annex I countries. The table lists modified emission limitation or reduction targets δ_{mod} for all Annex I countries, where the "$x_{t,2}$-greater-than-$(1-|\delta_{\text{crit}}|)x_{t,1}$" risk α_v (Cases 2, 3) and the "$x_{t,2}$-greater-than-$(1-(\delta_{\text{KP}}-2\delta_{\text{crit}}))x_{t,1}$" risk α_v (Case 4), respectively, are specified to be 0, 0.1, 0.3 and 0.5. For the green-colored fields $\delta_{\text{KP}} > 0$: $\delta_{\text{crit}} \le \delta_{\text{KP}}$ (Case 1), i.e., the δ_{mod} values are taken from Table D1. For further explanations confer to the captions of Tables 13 and 17.

Country Group	Max. Allow. VT[a] $t_2 - t_1$ yr	KP Com. δ_{KP}[b] %	Crit. Targ. δ_{crit} %	Modified Emission Limitation or Reduction Target δ_{mod} in % for ρ =				If the Und&VT Concept had been bpplied
				2.5%	7.5%	15%	30%	
			for ρ =	and				
			2.5% 7.5% 15% 30%	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	$a_v = 0.0$ $a_v = 0.1$ $a_v = 0.3$ $a_v = 0.5$	
1a **1b** **1c** **1d**	20 22 21 24	8.0	2.4 7.0 13.0 23.1	10.2 9.8 8.9 8.0	14.4 13.2 10.7 8.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	See Und&VT concept (Table 13).
2	20	7.0	2.4 7.0 13.0 23.1	9.3 8.8 7.9 7.0	13.5 12.3 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
3a **3b** **3c**	20 24 22	6.0	2.4 7.0 13.0 23.1	8.3 7.8 6.9 6.0	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
4	20	5.0	2.4 7.0 13.0 23.1	7.3 6.9 5.9 5.0	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
--	--	4.0	2.4 7.0 13.0 23.1	6.3 5.9 5.0 4.0	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
--	--	3.0	2.4 7.0 13.0 23.1	5.4 4.9 4.0 3.0	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
--	--	2.0	2.4 7.0 13.0 23.1	4.8 4.4 3.4 2.4	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	
--	--	1.0	2.4 7.0 13.0 23.1	4.8 4.4 3.4 2.4	13.5 12.2 9.7 7.0	24.4 22.4 18.0 13.0	40.8 38.0 31.3 23.1	

Table D4: continued.

5	20	0.0	-2.6 -8.1 -17.6 -42.9	4.9 4.5 3.5 2.6	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	See Und&VT concept (Table 17).
6	20	-1.0	-2.6 -8.1 -17.6 -42.9	4.9 4.5 3.5 2.6	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--		-2.0	-2.6 -8.1 -17.6 -42.9	4.9 4.5 3.5 2.6	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--		-3.0	-2.6 -8.1 -17.6 -42.9	4.5 4.0 3.1 2.1	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--		-4.0	-2.6 -8.1 -17.6 -42.9	3.5 3.1 2.1 1.1	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--		-5.0	-2.6 -8.1 -17.6 -42.9	2.6 2.1 1.1 0.1	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--	--	-6.0	-2.6 -8.1 -17.6 -42.9	1.6 1.1 0.1 -0.9	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--	--	-7.0	-2.6 -8.1 -17.6 -42.9	0.6 0.1 -0.9 -1.9	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
7	20	-8.0	-2.6 -8.1 -17.6 -42.9	-0.4 -0.9 -1.9 -2.9	14.5 13.3 10.8 8.1	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
--	--	-9.0	-2.6 -8.1 -17.6 -42.9	-1.3 -1.8 -2.8 -3.9	13.7 12.5 9.9 7.2	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	
8	20	-10.0	-2.6 -8.1 -17.6 -42.9	-2.3 -2.8 -3.8 -4.9	12.8 11.5 8.9 6.2	28.4 26.5 22.3 17.6	56.0 53.9 49.0 42.9	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.

Table D5: The Und&VT concept (equations (D4), (D8) and (D12)) applied to Annex I countries. The table lists the undershooting U_v contained in the modified emission limitation or reduction targets δ_{mod} listed in Table D4, where the "$x_{t,2}$-greater-than-$\left(1-\left|\delta_{crit}\right|\right)x_{t,1}$" risk α_v (Cases 2, 3) and the "$x_{t,2}$-greater-than-$\left(1-\left(\delta_{KP}-2\delta_{crit}\right)\right)x_{t,1}$" risk α_v (Case 4), respectively, are specified to be 0, 0.1, 0.3 and 0.5. For the green-colored fields $\delta_{KP}>0$: $\delta_{crit}<\delta_{KP}$ (Case 1), i.e., the U values are taken from Table D2. For further explanations confer to the captions of Tables 14 and 18.

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%**	**Undershooting U_v 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	**If the Und&VT Concept had been applied**
1a **1b** **1c** **1d**	20 22 21 24	8.0	2.4 7.0 13.0 23.1	2.2 1.8 0.9 0.0	6.4 5.2 2.7 0.0	16.4 14.4 10.0 5.0	32.8 30.0 23.3 15.1	See Und&VT concept (Table 14).
2	20	7.0	2.4 7.0 13.0 23.1	2.3 1.8 0.9 0.0	6.5 5.3 2.7 0.0	17.4 15.4 11.0 6.0	33.8 31.0 24.3 16.1	
3a **3b** **3c**	20 24 22	6.0	2.4 7.0 13.0 23.1	2.3 1.8 0.9 0.0	7.5 6.2 3.7 1.0	18.4 16.4 12.0 7.0	34.8 32.0 25.3 17.1	
4	20	5.0	2.4 7.0 13.0 23.1	2.3 1.9 0.9 0.0	8.5 7.2 4.7 2.0	19.4 17.4 13.0 8.0	35.8 33.0 26.3 18.1	
--	--	4.0	2.4 7.0 13.0 23.1	2.3 1.9 1.0 0.0	9.5 8.2 5.7 3.0	20.4 18.4 14.0 9.0	36.8 34.0 27.3 19.1	
--	--	3.0	2.4 7.0 13.0 23.1	2.4 1.9 1.0 0.0	10.5 9.2 6.7 4.0	21.4 19.4 15.0 10.0	37.8 35.0 28.3 20.1	
--	--	2.0	2.4 7.0 13.0 23.1	2.8 2.4 1.4 0.4	11.5 10.2 7.7 5.0	22.4 20.4 16.0 11.0	38.8 36.0 29.3 21.1	
--	--	1.0	2.4 7.0 13.0 23.1	3.8 3.4 2.4 1.4	12.5 11.2 8.7 6.0	23.4 21.4 17.0 12.0	39.8 37.0 30.3 22.1	

Table D5: continued.

5	20	0.0	-2.6	4.9	14.5	28.4	56.0	See Und&VT concept (Table 18).
			-8.1	4.5	13.3	26.5	53.9	
			-17.6	3.5	10.8	22.3	49.0	
			-42.9	2.6	8.1	17.6	42.9	
6	20	-1.0	-2.6	5.9	15.5	29.4	57.0	
			-8.1	5.5	14.3	27.5	54.9	
			-17.6	4.5	11.8	23.3	50.0	
			-42.9	3.6	9.1	18.6	43.9	
--		-2.0	-2.6	6.9	16.5	30.4	58.0	
			-8.1	6.5	15.3	28.5	55.9	
			-17.6	5.5	12.8	24.3	51.0	
			-42.9	4.6	10.1	19.6	44.9	
--		-3.0	-2.6	7.5	17.5	31.4	59.0	
			-8.1	7.0	16.3	29.5	56.9	
			-17.6	6.1	13.8	25.3	52.0	
			-42.9	5.1	11.1	20.6	45.9	
--		-4.0	-2.6	7.5	18.5	32.4	60.0	
			-8.1	7.1	17.3	30.5	57.9	
			-17.6	6.1	14.8	26.3	53.0	
			-42.9	5.1	12.1	21.6	46.9	
--		-5.0	-2.6	7.6	19.5	33.4	61.0	
			-8.1	7.1	18.3	31.5	58.9	
			-17.6	6.1	15.8	27.3	54.0	
			-42.9	5.1	13.1	22.6	47.9	
--	--	-6.0	-2.6	7.6	20.5	34.4	62.0	
			-8.1	7.1	19.3	32.5	59.9	
			-17.6	6.1	16.8	28.3	55.0	
			-42.9	5.1	14.1	23.6	48.9	
--	--	-7.0	-2.6	7.6	21.5	35.4	63.0	
			-8.1	7.1	20.3	33.5	60.9	
			-17.6	6.1	17.8	29.3	56.0	
			-42.9	5.1	15.1	24.6	49.9	
7	20	-8.0	-2.6	7.6	22.5	36.4	64.0	
			-8.1	7.1	21.3	34.5	61.9	
			-17.6	6.2	18.8	30.3	57.0	
			-42.9	5.1	16.1	25.6	50.9	
--	--	-9.0	-2.6	7.7	22.7	37.4	65.0	
			-8.1	7.2	21.5	35.5	62.9	
			-17.6	6.2	18.9	31.3	58.0	
			-42.9	5.1	16.2	26.6	51.9	
8	20	-10.0	-2.6	7.7	22.8	38.4	66.0	
			-8.1	7.2	21.5	36.5	63.9	
			-17.6	6.2	18.9	32.3	59.0	
			-42.9	5.1	16.2	27.6	52.9	

[a] The maximal allowable VT is calculated for each country group as the difference between 2010 (as the temporal mean over the commitment period 2008–2012) and its base year or mean base year, respectively (as specified in Table 5).

[b] The countries' emission limitation and reduction commitments under the Kyoto Protocol are expressed with the help of δ_{KP}, the normalized change in emissions between t_1 and t_2: $\delta_{KP} > 0$ – emission reduction; $\delta_{KP} \leq 0$ – emission limitation.