Uncertainty in an emissions-constrained world

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Abstract Our study focuses on uncertainty in greenhouse gas (GHG) emissions from anthropogenic sources, including land use and land-use change activities. We aim to understand the relevance of diagnostic (retrospective) and prognostic (prospective) uncertainty in an emissions-temperature setting that seeks to constrain global warming and to link uncertainty consistently across temporal scales. We discuss diagnostic and prognostic uncertainty in a systems setting that allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term context. Cumulative emissions are not only constrained and globally binding but exhibit quantitative uncertainty; and whether or not compliance with an agreed temperature target will be achieved is also uncertain. To facilitate discussions, we focus on two countries, the USA and China. While our study addresses whether or not future increase in global temperature can be kept below 2, 3, or 4 °C targets, its primary aim is to use those targets to demonstrate the relevance of both diagnostic and prognostic uncertainty. We show how to combine diagnostic and prognostic uncertainty to take more educated (precautionary) decisions for reducing emissions toward an agreed temperature target; and how to perceive combined diagnostic and prognostic uncertainty-related risk. Diagnostic uncertainty is the uncertainty contained in inventoried emission estimates and relates to the risk that true GHG emissions are greater than inventoried emission estimates reported in a specified year; prognostic uncertainty refers to cumulative emissions between a start year and a future target year, and relates to the risk that an agreed temperature target is exceeded.

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1 Introduction

This study focuses on the uncertainty in estimates of anthropogenic greenhouse gas (GHG) emissions, including land use and land-use change activities. It aims to provide an overview of how to perceive uncertainty in a systems context seeking to constrain global warming.

It focuses on understanding uncertainty across temporal scales and on reconciling short-term GHG emission commitments with long-term efforts to meet average global temperature targets in 2050 and beyond. The discussion is a legacy of the 2nd International Workshop on Uncertainty in Greenhouse Gas Inventories, which concluded:

> the consequence of including inventory uncertainty in policy analysis has not been quantified to date. The benefit would be both short-term and long-term, for example, an improved understanding of compliance … or of the sensitivity of climate stabilization goals to the range of possible emissions, given a single reported emissions inventory" (Jonas et al. 2010a).

It addresses a fundamental problem: how to combine diagnostic (retrospective) and prognostic (prospective) uncertainty. Current (and historic) GHG emission inventories contain uncertainty in relation to our ability to estimate emissions (Lieberman et al. 2007; White et al. 2011). Diagnostic uncertainty results from grasping emissions accurately but imprecisely (our initial assumption). It can be related to the risk that true GHG emissions are greater than inventoried estimates reported at a given time point (Jonas et al. 2010b: Tab. 3). (The opposite case, true emissions being smaller than inventoried estimates, is not relevant from a precautionary perspective.)

Diagnostic uncertainty, our ability to estimate current emissions, stays with us also in the future. Assuming that compliance with an agreed emissions target is met in a target year allows prognostic uncertainty to be eliminated entirely. How this target was reached is irrelevant; only our real diagnostic capabilities of estimating emissions in the target year matter. This is how experts proceeded, e.g., when they evaluated ex ante the impact of uncertainty in the case of compliance with the Kyoto Protocol (KP) in 2008–2012, the Protocol's commitment period (Jonas et al. 2010b).

Emissions accounting in a target year can involve constant, increased or decreased uncertainty compared with the start (reference) year, depending on whether or not our knowledge of emission-generating activities and emission factors becomes more precise. The typical approach to date has been to assume that, in relative terms, our knowledge of uncertainty in the target year will be the same as it was in the start year.

However, uncertainty under a prognostic scenario always increases with time. The further we look into the future, the greater the uncertainty. This important difference suggests that diagnostic and prognostic uncertainty are independent. This differs from how prognostic modelers usually argue. A prevalent approach is to realize a number of scenarios and grasp prognostic uncertainty by means of the spread in these scenarios over time—which increases with increasing uncertainty in the starting conditions built into their models. However, this approach nullifies diagnostic uncertainty once a target (future) is reached.

To stabilize Earth's climate within 2 °C of historic levels, treaty negotiations have pursued mechanisms that reduce GHG emissions globally and lead to sustainable management of the atmosphere at a "safe," steady-state level. In recent years, international climate policy has increasingly focused on limiting temperature rise as opposed to achieving GHG concentration–related objectives (Rogelj et al. 2011). A promising and robust methodology for adhering to a long-term global warming target appears to be to constrain cumulative GHG emissions in the future (WBGU 2009; Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; Zickfeld

et al. (2009); Raupach et al. 2011). Cumulative emissions, defined by the area under an emissions scenario path, are a good predictor for the expected temperature rise. The concept of cumulative emissions began influencing climate policymaking after the 2009 climate conference in Copenhagen, where it was first discussed broadly and publicly. The emission reductions required from the fossil-fuel and land-use sectors to comply with the concept of constraining cumulative emissions until 2050 to limit global warming to 2 °C in 2050 and beyond are daunting: 50–85 % below the 1990 global annual emissions, with even greater reductions for industrialized countries (Fisher et al. 2007; Jonas et al. 2010a).

The cumulative emissions concept is particularly suited to linking diagnostic and prognostic uncertainty because it allows compliance with both emissions and temperature targets to be investigated at a selected future time point. Here, we employ Meinshausen et al.'s (2009) global-scale research, which centers on limiting the increase in average global temperature to 2 °C from its pre-industrial level. Meinshausen et al. express compliance with this temperature target in terms of constraining cumulative CO_2 or CO_2 equivalent (CO_2-eq) emissions between 2000 and 2049 while accounting for a multitude of model-based, forward-looking emission-climate change scenarios. Thus, the relationship between cumulative emissions and the risk of exceeding the 2 °C target—an S-shaped curve broadening between its end points (see Fig. 3 and S1a in Meinshausen et al.)—is not unequivocal. For a given cumulative emissions value, multiple emission pathways per modeling exercise are conceivable that comply, or not, with the 2 °C target, thus allowing the risk of exceedance pertinent to this cumulative emissions value to be defined. The risk value translates into an interval, if many modeling exercises are considered.

The broadened S-curve shows that a sharp cumulative emissions value translates into a risk interval for exceeding 2 °C; vice versa, a sharp risk value translates into a cumulative emissions interval. The latter interval comprises all cumulative emissions allowing at least one emissions pathway that exhibits this risk. These intervals can be interpreted in terms of (prognostic) uncertainty, subsuming our lack of knowledge in toto (from the climate system and its key characteristics through to model representation). Here, we employ the two extreme alternatives—sharp cumulative emissions versus uncertain risk, and uncertain cumulative emissions versus sharp risk—without further investigating the two uncertainties' interdependence.

We discuss diagnostic and prognostic uncertainty in an emissions-temperature setting that allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term context. In this systems context, cumulative emissions are constrained and globally binding but exhibit quantitative uncertainty (i.e., they can be estimated only imprecisely); and whether or not compliance with an agreed temperature target will be achieved is also uncertain. Because more data are available, we focus on the 2 °C temperature target, disregarding the current dispute about the achievability of this target (Victor 2009). Later in the analysis we consider higher temperature targets (3 and 4 °C), our objective being to understand the relevance of diagnostic and prognostic uncertainty in a global emissions-temperature context and across temporal scales. Although our mode of bridging uncertainty across temporal scales still relies on discrete points in time and is not yet continuous, it provides a valuable first step toward that objective.

Our study is structured as follows: Section 2 links to the data, techniques, and models we employ; it provides the methodological overview and describes the steps taken to establish the systems context. It prepares the basis for addressing our objective—in Section 3—where we present uncertainty in the elaborated emissions-temperature context for selected countries. Findings and conclusions are summarized in Section 4.

2 Methodology

We use publicly available emission and other data (Supplementary Information [henceforth "SI"]: Tab. S1). The time period 1990–2008/09 is the diagnostic part (D) of our study (although some data to 2008/09 are lacking). The time period 2008/09 and beyond is its prognostic part (P).

In establishing the emissions-temperature-uncertainty context for countries, we also employ a number of techniques and models that are publicly available and/or described in the scientific literature. Table S2 in SI provides an overview of the techniques and models, their mode of application, and how their output is used.

2.1 Global emission constraints

The notion of constraining cumulative emissions gained momentum with a number of publications in 2009, among them Meinshausen et al. and the German Advisory Council on Global Change (WBGU). WBGU in 1995 raised the idea of determining an upper limit for the tolerable increase of the mean global temperature and deriving a global CO_2 reduction target through an inverse approach (i.e., a backward calculation [WBGU 1995]). The budget concept (WBGU 2009) is the further development of this idea.

To limit atmospheric warming, total anthropogenic CO_2 emitted to the atmosphere must be constrained. Concerning 2 °C, WBGU (2009) proposed adoption of a binding upper limit for the total CO_2 emitted from fossil-fuel sources up to 2050 and allocation of the defined amount of emissions among countries, subject to negotiation but based on various principles, among them "polluter-pays," precautionary principle, and the principle of equality.

WBGU thus separated the global emissions budget into national emissions budgets based on an equal per capita (p/c) basis. The budget concept contains four political (i.e., negotiable) parameters: (i) the start year and (ii) end year for the total budget period; (iii) the cumulative emissions constraint or, equivalently, the probability of exceeding the 2 °C temperature target; and (iv) the reference year for global population. Our choices for the four parameters—(i) 1990 (to conform with the KP) and 2000 (to study the impact of a different start year on national emission budgets); (ii) 2050; (iii) alternative combinations of uncertainty in both cumulative emissions and risk of exceeding temperature targets ranging from 2 to 4 °C; and (iv) 2050—differ from the options investigated by WBGU.[1] We also assess both alternative and imperative global emission reduction concepts. These are linked, e.g., to reducing emission intensity for technospheric emissions and to achieving sustainability across total land use and land-use change (LU) activities. Costs of mitigation measures (and the uncertainty in costs resulting from emissions uncertainty) can be expressed as marginal costs and p/c costs. Here we refer to p/c costs.

2.2 From global to national: per capita emissions equity in 2050

We apply a "contraction & convergence" approach as an initial reference approach (GCI 2012). This allows establishment of global linear target paths for 1990–2050 (from 36.8 Pg CO_2-eq in 1990 to 25.9 Pg CO_2-eq in 2050) and for 2000–2050 (from 39.5 Pg CO_2-eq in 2000 to 20.5 Pg CO_2-eq in 2050), and derivation of global emission targets for 2050 (Fig. 1 and SI:

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[1] The four parameters in WBGU's "historical responsibility" approach are (i) 1990, (ii) 2050, (iii) 25 %, and (iv) 1990; and (i) 2010, (ii) 2050, (iii) 33 %, and (iv) 2010 in its "future responsibility" approach. In both approaches, the probability of exceeding the 2 °C temperature target refers to cumulative emission constraints for 2000–2049.
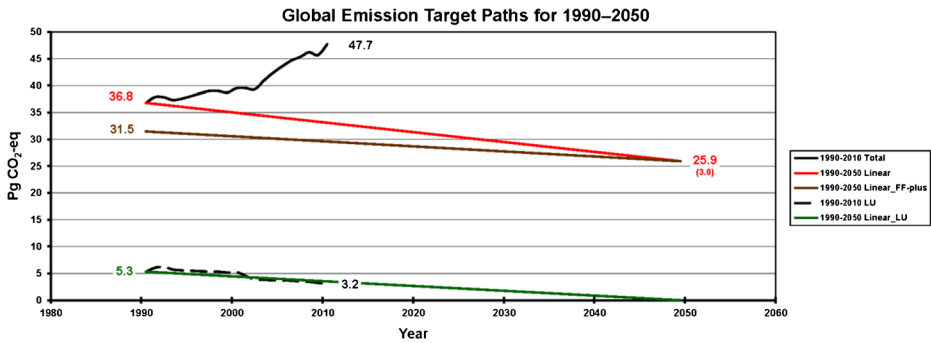
Fig. 1 Global linear emission target paths for 1990–2050 and global emission targets (global emissions equity, GEE, in parentheses) for 2050 (see also SI: Tab. S3). Emissions between 2000 and 2050 are constrained by 1500 Pg CO_2-eq. Emissions are in Pg CO_2-eq (GEE in t CO_2-eq/cap). The global target paths are for (i) total GHG emissions (*solid red line*); (ii) total emission excluding emissions from land use and land-use change (LU), i.e., emissions from fossil-fuel burning and cement production and for technospheric GHGs other than CO_2 ("FF-plus": *solid brown line*); and (iii) emissions from LU (*solid green line*). The 2050 global targets for total GHG emissions and FF-plus emissions are identical (25.9 Pg CO_2-eq and 3.0 t CO_2-eq/cap, respectively) because the 2050 global target for LU emissions is set to zero. The *solid black and dashed black curves* show actual estimates of total GHG emissions and LU emissions

Tab. S3). In conformity with Meinshausen et al. (2009) we apply an emissions constraint of 1500 Pg CO_2-eq for the period 2000–2049 (2050 is hereafter the "end year") to which we add the CO_2-eq emissions emitted cumulatively between 1990 and 1999 if we choose 1990 as start year. We also stipulate that the emission targets derived for 2050 are exclusively available for technospheric emissions. The imperative we follow for net emissions from LU activities is that these will be reduced linearly to zero by 2050; that is, we assume that deforestation and other LU mismanagement will cease and that net emissions balance. Our underlying assumptions are that (i) the remainder of the biosphere (including oceans) stays in or returns to an emissions balance—which must be questioned (Canadell et al. 2007); (ii) this return, which refers to CO_2-C, implies in turn that emissions and removals of CH_4, N_2O, etc. also return to an emissions balance; and (iii) these returns happen without systemic surprises of the terrestrial biosphere.

To achieve universally applicable global emissions equity (GEE) by 2050, we divide the aforementioned global emission targets by the global population we expect by 2050—estimated as ranging between 7.5 and 10.2 10^9 with a best estimate of 8.8 10^9 and a confidence interval (CI) of 95 %.[2] We find 2050 GEE values of 3.0 and 2.3 t CO_2-eq/cap for 1990–2050 and 2000–2050, respectively (Fig. 1 and SI: Tab. S3).

2.3 Uncertainty in cumulative emissions and risk of exceeding 2 °C in 2050

Figure 3 of Meinshausen et al. (2009) and Figure S1a in their supplementary information show that a sharp cumulative CO_2 (or CO_2-eq) emissions value for 2000–2050 translates into a risk interval of exceeding 2 °C in 2050 and beyond; vice versa, a sharp risk value translates into a cumulative emissions interval. We interpret these intervals in terms of prognostic uncertainty and apply the 2 °C Check Tool of Meinshausen et al. (SI: Tab. S2) to derive the two extreme alternatives: sharp cumulative emissions versus uncertain risk (min/max) and uncertain cumulative emissions versus sharp risk (max/min). If we choose 1990 as start year, the cumulative

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[2] IIASA's World Population Program reports 7.8 and 9.9 for the 10th and 90th percentiles.

CO_2-eq emissions for 1990–1999 are added to the cumulative CO_2-eq emissions for 2000–2050, but the risk and the uncertainty in the risk do not change.

The 2000–2050 constraint of 1500 Pg CO_2-eq entails a risk ranging from 10 to 43 % of exceeding 2 °C, with its center at 26 % (SI: Tab. S4; see also Tab. 1 in Meinshausen et al.). For comparison, we ran the 2 °C Check Tool (in a repetitive, trial-and-error mode) to determine the upper and lower CO_2-eq constraints for keeping the risk of exceeding 2 °C constant at 26 %, we found 1189 and 1945 Pg CO_2-eq cumulative emissions, respectively; acknowledging that the 2 °C Check Tool does not allow insertion of cumulative constraints for 2000–2050 below 1189 Pg CO_2-eq (see also Fig. S1a in Meinshausen et al.).

The uncertainty in cumulative emissions of 1189–1945 Pg CO_2-eq for 2000–2050 translates into an uncertainty in GEE values in 2050 that depends on start year choice (1990 or 2000). For 1990, we find a GEE interval of 1.8–4.7 with its center at 3.0 t CO_2-eq/cap; for 2000, we find a GEE interval of 0.9–4.4 with its center at 2.3 t CO_2-eq/cap. Considering, in addition, the uncertainty in the 2050 population estimate, we find 1.5–5.4 t CO_2-eq/cap for 1990–2050 and 0.8–5.1 t CO_2-eq/cap for 2000–2050 (Table 1: column "1500 Pg CO_2-eq").

Finally, we tweak the min-max uncertainty combination. The case of no uncertainty in the cumulative emissions constraint (1500 Pg CO_2-eq) is impacted, if expressed on a p/c basis, by the uncertainty in the population estimate. The respective GEE intervals are 2.5–3.5 t CO_2-eq/cap for 1990–2050 and 2.0–2.7 t CO_2-eq/cap for 2000–2050 (these adjusted GEE intervals are reported in Table 1). We did not reapply the 2 °C Check Tool to adjust the uncertainty in the risk of exceeding 2 °C.

2.4 Uncertainty in cumulative emissions and risk of exceeding 3 and 4 °C in 2050

In this section we translate the min/max and max/min uncertainty combinations for cumulative emissions and risk from 2 to 3 and 4 °C. This translation is graphically based and approximate but sufficient for present purposes. The stepwise release of the global temperature target for 2050 and beyond from 2 to 4 °C translates into a stepwise increase of the 2050 GEE values. The crucial question is whether these values can still be distinguished from each other given the underlying uncertainties in cumulative emissions and risk.

The translation is realized with the help of Figures 33 and 34 in Meinshausen (2005), which quantify the risk of overshooting global mean equilibrium warming ranging from 1.5 to 4 °C for different stabilization levels of CO_2-eq concentration. The details are outlined in SI (Note 5).

With this translation to hand and supported by the 2 °C Check Tool, we can explore the min/max and max/min uncertainty combinations investigated in Section 2.3 for: (i) cumulative emission constraints for 2000–2050 other than 1500 Pg CO_2-eq and (ii) temperature targets for 2050 and beyond other than 2 °C. In the first step, we keep the temperature target at 2 °C and expand our investigation of the min/max and max/min uncertainty combinations over a range of cumulative emission constraints that is well covered by the 2 °C Check Tool, here to constraints of 1800, 2100, and 2400 Pg CO_2-eq. In the next step we translate the risk contained in these min/max and max/min uncertainty combinations into the risk of exceeding 3 and 4 °C. Table 1 summarizes the expansion and translation process.

Prudence is needed, however. The assumptions underlying this expansion and translation process are that (i) the risk of overshooting is comparatively stable and independent of the particular warming situation, equilibrium or transient, when going from, e.g., 2 to 3 °C; and (ii) deviations from this assumption are minor compared to the considerable change in risk when going from 2 to 3 °C under either warming, equilibrium or transient.

Table 1 should be read as follows: the cumulative GHG emissions constraint for 2000–2050 of 1800 Gt CO_2-eq with reference to start year 1990 (Table 1a) results in a risk of between 20 and 58 % of exceeding the 2 °C temperature target if the p/c emissions (GEE) in 2050 center at 4.1 t CO_2-eq within the interval from 3.5 to 4.8 t CO_2-eq. If the latter interval is increased to 2.1–6.3 t CO_2-eq, the risk interval of exceeding the 2 °C temperature target decreases to about 38 %.[3] The two examples result in lower risks ranging between 5 and 26 % and 12–17 %, respectively, if the 1800 Gt CO_2-eq constraint is interpreted with regard to exceeding the 3 °C temperature target.

The comparison of the min/max uncertainty combinations—i.e., minimal uncertainty in GEE in 2050 and maximal uncertainty in the risk of exceeding 2, 3, or 4 °C in 2050 and beyond—across cumulative emission constraints for 2000–2050 ranging from 1500 to 2400 Pg CO_2-eq (or for GEE in 2050 ranging from 3.0 to 6.4 t CO_2-eq/cap) shows that the GEE values increasingly overlap. That is, distinguishing GEE values from each other for the various cumulative emission constraints becomes increasingly difficult. For example, with regard to exceeding the 4 °C temperature target: for the cumulative emissions constraint of 2100 Gt CO_2-eq the GEE uncertainty range goes from 4.5 to 6.1 t CO_2-eq/cap (with its center at 5.2 t CO_2-eq/cap). For comparison, for the cumulative emissions constraint of 2400 Gt CO_2-eq the GEE uncertainty range goes from 5.5 to 7.4 t CO_2-eq/cap (with its center at 6.4 t CO_2-eq/cap) (columns "2100 Pg CO_2-eq" and "2400 Pg CO_2-eq" in Table 1a).

Comparison of Table 1a (start year 1990) with Table 1b (start year 2000) also indicates uncertainty becoming too large for cumulative emission constraints for 2000–2050 above ~2100 Gt CO_2-eq. GEE values in 2050 can no longer be properly distinguished. We are at the limits in resolution terms of our graphical-based approach. Uncertainty overshadows differences in the GEE values resulting from differences in both cumulative emissions and start year.

2.5 Uncertainty in inventoried emissions

In this section we introduce diagnostic uncertainty which is related to the risk that true GHG emissions are greater than inventoried emission estimates reported at given time points. We are interested in the order of magnitude involved in correcting cumulative emission constraints so that this diagnostic uncertainty-related risk vanishes.

Analyzing uncertainty is an important tool for improving emission inventories containing uncertainty for various reasons (Lieberman et al. 2007, White et al. 2011). Jonas et al. (2010b) describe six techniques to analyze uncertain emission changes (signals) and we apply two of those techniques here: the undershooting (Und) and the combined undershooting and verification time concept (Und&VT). The two techniques differ, but common to them is that they apply undershooting to limit, or even reduce, the risk that true emissions are greater than agreed emissions in a target year—from 50 % (no undershooting: ignoring uncertainty altogether) to 0 % (with undershooting: the undershooting needed to make the diagnostic uncertainty-related risk vanish can be calculated).

The Und concept accounts for the trend uncertainty in the emission estimates between any two time points, e.g., start year and target year, and correlates uncertainty between these. The Und&VT concept also allows undershooting but accounts for the linear dynamics of the emission signal between start and target year, and the total uncertainty in the latter.

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[3] Note that applying the 2 °C Check Tool as described in Section 2.3 but to a cumulative emissions constraint for 2000–2050 of 1800, instead of 1500 Pg CO_2-eq, does not encounter any limitations, which is why the risk interval is minimal for maximal uncertainty in p/c emissions and consists of a single value only.

Table 1 Interpreting the global cumulative GHG emission constraints for 2000–2050 of 1500 to 2400 Pg CO_2-eq with reference to start year **a)** 1990 and **b)** 2000; and in terms of uncertainty in both p/c emissions (GEE) in 2050 and risk of exceeding a temperature target in 2050 and beyond ranging between 2 and 4 °C. The table lists min/max and max/min combinations of these two uncertainties

a) Start year 1990 (1990–2050):

T	Uncertainty min/max – max/min	in 2050 under a cumulative GHG emissions constraint for 2000–2050 of			
		1500 Pg CO_2-eq	1800 Pg CO_2-eq	2100 Pg CO_2-eq	2400 Pg CO_2-eq
°C	Uncertainty in emissions Uncertainty in risk	t CO_2-eq/cap %	t CO_2-eq/cap %	t CO_2-eq/cap %	t CO_2-eq/cap %
2	in emissions	3.0 [2.5 – 3.5]	4.1 [3.5 – 4.8]		
	in risk of exceeding 2 °C	10 – 43	20 – 58		
	in emissions	1.5 – 5.4	2.1 – 6.3		
	in risk of exceeding 2 °C	26 – 31	38		
3	in emissions		4.1 [3.5 – 4.8]	5.2 [4.5 – 6.1]	
	in risk of exceeding 3 °C		5 – 26	11 – 40	
	in emissions		2.1 – 6.3	3.5 – 7.8	
	in risk of exceeding 3 °C		12 – 17	21 – 26	
4	in emissions			5.2 [4.5 – 6.1]	6.4 [5.5 – 7.4]
	in risk of exceeding 4 °C			4 – 21	8 – 36
	in emissions			3.5 – 7.8	4.5 – 9.5
	in risk of exceeding 4 °C			9 – 13	17 – 21

b) Start year 2000 (2000–2050):

T	Uncertainty min/max – max/min	in 2050 under a cumulative GHG emissions constraint for 2000–2050 of			
		1500 Pg CO_2-eq	1800 Pg CO_2-eq	2100 Pg CO_2-eq	2400 Pg CO_2-eq
°C	Uncertainty in emissions Uncertainty in risk	t CO_2-eq/cap %	t CO_2-eq/cap %	t CO_2-eq/cap %	t CO_2-eq/cap %
2	in emissions	2.3 [2.0 – 2.7]	3.7 [3.2 – 4.3]		
	in risk of exceeding 2 °C	10 – 43	20 – 58		
	in emissions	0.8 – 5.1	1.5 – 6.2		
	in risk of exceeding 2 °C	26 – 31	38		
3	in emissions		3.7 [3.2 – 4.3]	5.1 [4.4 – 5.9]	
	in risk of exceeding 3 °C		5 – 26	11 – 40	
	in emissions		1.5 – 6.2	3.2 – 7.9	
	in risk of exceeding 3 °C		12 – 17	21 – 26	
4	in emissions			5.1 [4.4 – 5.9]	6.5 [5.5 – 7.5]
	in risk of exceeding 4 °C			4 – 21	8 – 36
	in emissions			3.2 – 7.9	4.4 – 10.0
	in risk of exceeding 4 °C			9 – 13	17 – 21

SI (Note 6) illustrates the combining of diagnostic and prognostic uncertainty graphically. We find a downward shift for representative values of both diagnostic uncertainty (10 % constant in relative terms) and correlation in diagnostic uncertainty (0.75) of global emissions between start and target year, from 36.8 to 24.6 Pg CO_2-eq (Und technique) and from 36.8 to 23.5 Pg CO_2-eq

(Und&VT technique), respectively, between 1990 and 2050 (see also Fig. 1). This translates into a downward shift of about 2–5 % of the 1500 Pg CO_2-eq cumulative constraint for 2000–2050. GEE in 2050 are then 2.8 and 2.7 t CO_2-eq/cap, respectively. That is, to nullify the diagnostic uncertainty-related risk, the GEE intervals listed in the column "1500 Pg CO_2-eq" of Table 1a would need to be shifted downward by an additional 0.2 or 0.3 t CO_2-eq/cap, while the prognostic uncertainty-related risk of exceeding 2 °C is unimpaired.

2.6 Land use and land-use change until 2050

In this section we explain how we deal with emissions from LU activities, which are included in the model-based, global emission-climate change scenarios of Meinshausen et al. (2009). The cumulative CO_2 emissions from land-use activities range from -35 to 248 Pg CO_2 (80 % interval range) over the 2007–2050 period, with a median of 24 Pg CO_2. Cumulative emissions of 24 Pg CO_2 translate into an average of 0.56 Pg CO_2/yr.

Net emissions from LU activities are the least certain in our current understanding of anthropogenic changes in the global carbon cycle (Peters et al. 2011a). They are about 3.3 ± 2.6 Pg CO_2 in 2010 and have apparently declined on average, from 5.5 Pg CO_2/yr during 1990–1999 to 4.0 Pg CO_2/yr during 2000–2009 (http://www.globalcarbonproject.org/carbonbudget/10/hl-full.htm, available via archive-org.com; and Pan et al. 2011). The net atmospheric carbon flux from 1850 to 2010 is modeled as a function of documented land-use change and changes in above- and belowground carbon from land-use change, with unmanaged ecosystems not considered (Houghton 2008).

Country-level LU emissions are equally difficult to deal with (IIASA 2007; Jonas et al. 2010c, 2011; Salk et al. 2013) and have at least comparable uncertainty.

As no fundamental analysis of the future state of terrestrial biospheric carbon stocks exists, we consider the case that the emission targets derived for 2050 are exclusively available for technospheric emissions and that deforestation and other LU mismanagement will cease by 2050, when we require net emissions from LU activities to balance at zero.

We consider this case unrealistic; however, it does allow us to evaluate the challenge of reducing technospheric GHG emissions globally under the assumption that the terrestrial biosphere behaves deterministically (without surprises and unknown feedbacks).

2.7 Accounting for known CO_2 emission transfers

Accounting for emissions can be viewed from both production and consumption perspectives. Historical emission estimates from a consumption perspective are becoming available, but not their uncertainties.

Under the KP, mitigation policy takes place at the country level and applies only to GHG emissions and removals within the country's national or offshore territorial jurisdiction. This territorial-based approach (production perspective) does not consider emission transfers between countries from international trade and may give a misleading interpretation of factors driving emission trends and therefore mitigation policies (EC 2011). To account for international CO_2 transfers, we employ the trade-linked global database for CO_2 emissions of Peters et al. (2011b). This covers 113 countries and/or regions and 57 economic sectors through time (1990–2008; see also Tab. S1 in the SI: the Global Carbon Project (GCP) provides updated data up to 2010) while excluding emissions from LU.

Grasping the spatial disconnect between biomass production and consumption is less advanced. Erb et al. (2009b) use the concept of embodied human appropriation of net primary production (HANPP) to map the global pattern of net-producing and net-consuming regions in

2000 (see also Haberl et al. 2007; Erb et al. 2009a). HANPP measures the extent to which "human activities affect NPP (net primary production) and its availability in the ecosystem as a source of nutritional energy and other ecosystem processes."[4] In contrast, embodied HANPP (eHANPP) is defined as "the NPP appropriated in the course of biomass production, encompassing losses along the production chain as well as productivity changes induced through land conversion or harvest. By making the pressure exerted on ecosystems associated with imports and exports visible, eHANPP allows for the analysis of teleconnections between producing and consuming regions" (Haberl et al. 2009: 119, 121). According to Erb et al. (2009b), international net transfers of eHANPP amount to 6.2 Pg CO_2 in 2000 and are thus of global significance.

Reducing emissions from LU to zero requires discussion of the state of sustainability (including the uncertainties involved) that the terrestrial biosphere will assumely attain in 2050 under a 2, 3 or 4 °C temperature target. Although the intention behind developing the HANPP concept was different at the time, we consider it useful for tracking sustainability (SI: Note 7).

We employ HANPP embodied in biomass trade to estimate the fraction of global LU emissions traded. This side-step is necessary given the current problematic situation of LU data. Net emissions from LU for 1850–2010 (GCP's carbon budget 2010; Peters et al. 2011a), currently resolve only large regions/continents, not large countries. We preserve GCP's previous set of global LU emission data because, although it only lists emissions until 2005, it does resolve a small number of large countries or units of countries (Canada, China, the USA, and Europe as a whole). Their emission estimates can show considerable discrepancies when compared to the land use, land-use change, and forestry (LULUCF) emission estimates reported by these countries under the UNFCCC (United Nations Framework Convention on Climate Change). These discrepancies are also noted by the World Resources Institute, whose Climate Analysis Indicators Tool (CAIT) employs additional land-use change and forestry data from the 2010 *World Development Report* to resolve the 25 largest emissions contributors for 1990–2005 (WRI 2011).

We consider LU and LULUCF emissions data—which typically disagree with each other and also underestimate real emissions as observed top-down by the "atmosphere"—as sufficiently good to indicate whether the directly human-impacted part of a country's terrestrial biosphere is a net source or net sink. We also use HANPP embodied in biomass trade (eTrade$_{NPP}$=ImpNPP−ExpNPP) to indicate whether a country is a net importer or net exporter of biomass (SI: Note 8).

We apply a globally averaged approach to link eTrade$_{NPP}$ with national LU emissions. This assumes that HANPP and LU emissions refer to the same directly human-impacted part of the terrestrial biosphere. A direct consequence of our approach is that the human appropriation of biomass results in a positive flux to the atmosphere. We use the ratio of net transfer of embodied HANPP to total HANPP to specify the fraction of global LU emissions traded (eTrade$_{LU}$) by country.[5] Traded LU emissions are added to a country's national LU (or LULUCF) emissions, thereby switching from a production to a consumption perspective. Net transfers of LU emissions balance when globally summed. This approach is simple and straightforward, and the calculation of national plus traded emissions is unambiguous.

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[4] Ito (2011) provides a historical meta-analysis of global NPP (1860s–2000s) which allows Haberl and Erb's HANPP concept with reference to 2000 to be put into a long-term temporal perspective.
[5] Haberl et al. (2007: Tab. 1) estimate total HANPP in 2000 to be 57.2 Pg CO_2 (including human-induced fires), of which about 6.2 Pg CO_2 is internationally transferred (net transfer) according to Erb et al. (2009b: Tab. 2) (about 7.2 Pg CO_2 according to the data communicated to us).

2.8 Additional insights from models

We employ two types of models that are prognostic or run in a prognostic mode to help bridge reference concepts and norms (SI: Tab. S2). The first type encompasses IIASA's GAINS (Greenhouse gas – Air pollution INteractions and Synergies) model. GAINS allows broadening of the applied contraction & convergence approach by making the step from emissions p/c to costs p/c in the context of discussing Annex I countries' mitigation pledges for 2020.[6]

The second model type encompasses the class of large-scale, energy-economic, and integrated assessment models, from which we selected three illustrative scenarios to 2100 that stabilize atmospheric GHG concentrations at low levels. The scenarios help us deviate from the contraction & convergence reference approach by making the step from emissions p/c to emission intensities measured as emissions per GDP (gross domestic product) in the context of discussing emission reduction scenarios to 2100. We discuss the models in SI (Note 3). In Section 3 below we apply them with the focus on technospheric emissions and exclude CO_2 emissions from land use and land-use change.

3 Results

For illustration, we present uncertainty in the elaborated emissions-temperature systems context for two selected countries, the USA and China. A third example, Austria, is included in SI (Note 9). We select 1990 as start year.

3.1 USA, a data-rich country with high total and p/c emissions

Figure 2a (see also Table 2) shows that to meet global cumulative emission constraints between 1500 and 2400 Pg CO_2-eq for 2000–2050, each individual within the USA must reduce his/her production-based GHG emissions on average by between 88 % and 74 % from 1990 to 2050. The dark- and light-gray lines (solid and broken) indicate the target paths emissions must follow to achieve universal p/c targets between 3.0 and 6.4 t CO_2-eq. Countries currently emitting p/c quantities above these lines will need to compensate by emitting below the gray lines before 2050 to ensure targets are reached.

As explained in Sections 2.3 and 2.4, the emission target paths can be interpreted in terms of min/max and max/min combinations of uncertainty in both p/c emissions in 2050 and risk of exceeding a specified temperature target in the 2–4 °C range in 2050 and beyond. Table 1a reproduces these min/max uncertainty combinations (see below).

The thick solid black curve in Fig. 2a shows the technosperic emissions of the six Kyoto GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6[7]; excluding CO_2 emissions from land use and land-use change) between 1990 and 2009 as reported by the USA to the UNFCCC; the thin solid black curve additionally considers fossil-fuel emissions embodied in trade, indicating that the USA turned from net exporter to net importer between 1994 and 1998. Comparison with the aforementioned emission target paths shows the USA to be operating beyond a 4 °C global warming. The USA's technospheric emissions are far above the uppermost emission target path, which satisfies a cumulative emissions constraint of 2400 Pg CO_2-eq for 2000–2050 and

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[6] See http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php for Annex I countries to the UNFCCC.
[7] Respectively, carbon dioxide, methane, nitrous oxide, hydrofluorocarbon, sulfur hexafluoride, perfluorocarbon

a

United States of America

b

United States of America

c

China

d

China
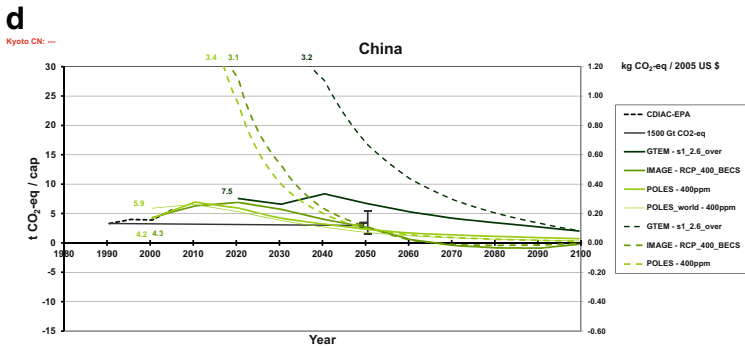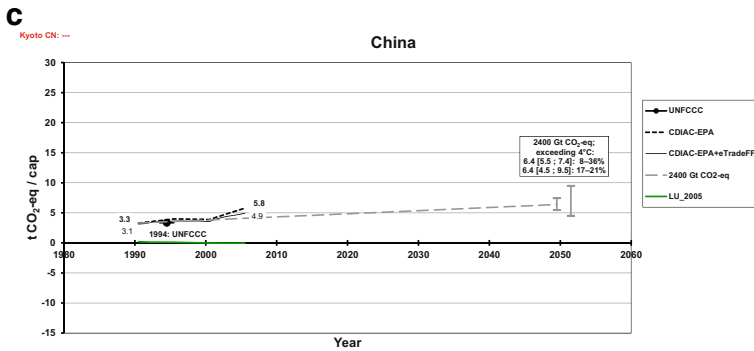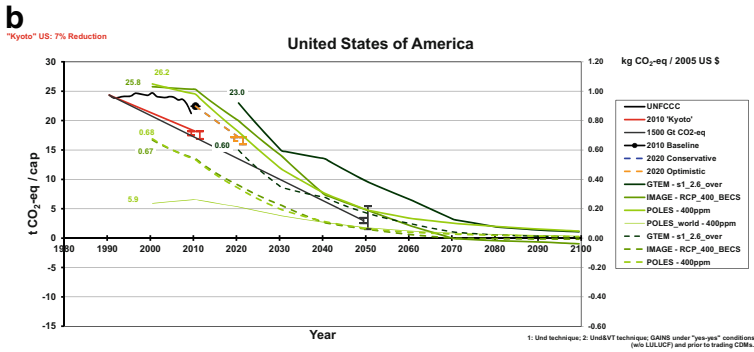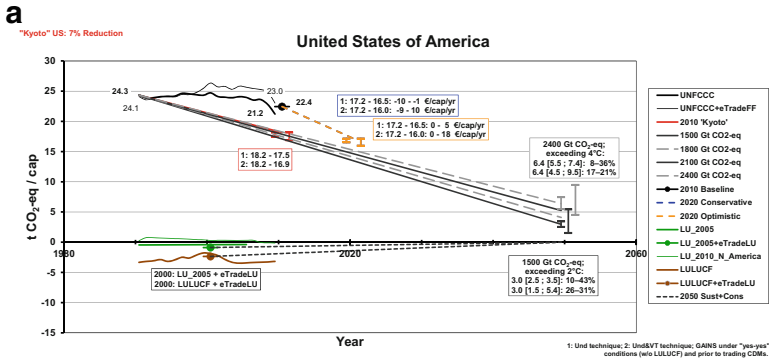
◀ **Fig. 2 a** USA (1990–2050): National GHG emissions and removals and near-term mitigation policies and measures in a globally consistent and long-term GHG emissions-temperature-uncertainty context. Technospheric emissions are budget-constrained globally for 2000–2050 but exhibit quantitative uncertainty; while emissions from land use and land-use change (LU and LULUCF) reduce to zero, global temperature targets for 2050 and beyond range between 2 and 4 °C, and compliance with an agreed temperature target is uncertain and entails a risk of exceedance. For further explanations see text. **b** USA (1990–2050): The figure takes over relevant technospheric emission entries of Fig. 2a. In addition, the figure shows three globally-embedded, long-term emission reduction scenarios as realized by GTEM, IMAGE and POLES for the USA. They allow switching between emission reduction perspectives, here from emission reduction p/c (*thick solid, dark to light, green lines*; in t CO_2-eq/cap) to emission reduction per GDP (*thick broken, dark to light, green lines*; in kg CO_2-eq per 2005 US $). The additional thin solid, light green line also belongs to POLES. It shows how POLES performs globally (in t CO_2-eq/cap). It allows the effectiveness of the USA's emission reduction to be put into a global perspective. **c** China (1990–2050): See caption to Fig. 2a and text. **d** China (1990–2050): See caption to Fig. 2b and text

which, as Table 1a indicates, must preferably be interpreted with reference to 4 °C (and higher) temperatures in 2050 and beyond.

Underneath, the (hardly visible) red line shows what p/c emission levels the USA would have committed to in 2010 had it ratified the Kyoto Protocol which stipulates a 7 % emission reduction. Per capita emissions would have practically followed the 2400 Pg CO_2-eq constraint.

The solid black dot shows estimated production-based emissions for 2010 according to IIASA's GAINS model.

The broken blue and orange lines (the latter covers the first) show expected p/c emission reductions for 2010–2020 according to the USA's conservative and optimistic pledges in 2010 (the two pledges—17 % reduction until 2020 relative to 2005—are identical in the case of the USA). The costs for achieving these pledges by applying known mitigation techniques are mentioned in the blue- and orange-framed boxes (GAINS output). The conservative and optimistic pledges to reduce emissions until 2020 are not necessarily identical for the other Annex I countries. IIASA's GAINS model is run in a mode that allows emissions exchange among Annex I countries, and between Annex I and developing countries (i.e., "with Annex I trading" and "with CDM measures"). The conservative and optimistic pledges of the other Annex I countries do not affect the USA's pledge to reduce emissions but do impact the costs of achieving these reductions. The costs differ depending on whether GAINS applies conservative or optimistic country pledges. Negative costs mean that implemented emission reduction measures pay back during their lifetime.

The ranges shown numerically in the red, blue, and orange boxes and graphically by the "I" shape at the end of the red, blue, and orange lines reflect the current range of diagnostic uncertainty (0.7–1.3 t CO_2-eq/cap) in estimating emissions; or, alternatively, the undershooting required to reduce the risk from 50 to 0 % that true emissions are greater than agreed targets or pledges. The uncertainty ranges take into account: (i) uncertainty in GHG inventories in both start and target year; and (ii) uncertainty in the GHG inventory in only the target year.[8] They are derived by applying the two emission change-uncertainty analysis techniques mentioned in Section 2.5. Adjusting the pledges of a country for undershooting—in the USA's case from 17.2 to 16.5 t CO_2-eq/cap according to the Und concept and from 17.2 to 16.0 t CO_2-eq/cap according to the Und&VT concept and reapplying GAINS allows the uncertainty in mitigation costs to be specified (see blue and orange boxes).

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[8] We employ a total uncertainty in relative terms of 7.5 % (representing the median of the relative uncertainty class 5–10 %) for reporting the emissions of the six Kyoto GHGs excluding emissions from land use and land-use change in both reference and target year; and 0.75 for the correlation in these uncertainties (Jonas et al. 2010b).

Table 2 P/c GHG emissions (excluding CO_2 emissions from land use and land-use change) globally and by country in 1990 and for 2050 required to meet global cumulative emission constraints for 2000–2050 ranging between 1500 and 2400 Pg CO_2-eq. Percentage emission reductions refer to 1990–2050 (negative reduction = increase)

Global / Country	1990 Emissions	2050 GEE target under a cumulative emissions constraint for 2000–2050 of			
		1500 Pg CO_2-eq	1800 Pg CO_2-eq	2100 Pg CO_2-eq	2400 Pg CO_2-eq
	t CO_2-eq/cap	t CO_2-eq/cap 3.0	t CO_2-eq/cap 4.1	t CO_2-eq/cap 5.2	t CO_2-eq/cap 6.4
		1990–2050 emission reduction			
		% / cap	% / cap	% / cap	% / cap
Global[a]	5.9	50	30	11	−8
USA[b]	24.3	88	83	78	74
China[c]	3.3	11	−24	−59	−93
Austria[b]	10.2	71	60	48	37

[a] POLES

[b] UNFCCC

[c] CDIAC, EPA, and UN POP

   Diagnostic uncertainty has not been introduced and combined with the prognostic uncertainties which we show (in gray) for the lowest and highest GEE targets in 2050 (3.0 and 6.4 t CO_2-eq/cap, respectively). Reducing diagnostic uncertainty to 0 % results in a downward shift of the prognostic uncertainty intervals (and the respective target paths). For instance, the min/max interval, [2.5 ; 3.5], around the lowest GEE target (3.0 t CO_2-eq/cap), by an additional 0.2 or 0.3 t CO_2-eq/cap, dependent on emission change-uncertainty analysis technique applied. This downward shift will not impair the prognostic-uncertainty related risk of exceeding the agreed temperature targets (SI: Note 6).

   Both the solid green line and the solid brown line show p/c emissions from land use and land-use change within US territory, the first LU emissions for 1990–2005 (from GCP's LU emissions for 1850–2005) and the second LULUCF emissions for 1990–2009 (reported by the USA under the UNFCCC). The difference between the two is considerable. For comparison, the thin solid green line shows LU emissions for 1990–2010 (from GCP's LU emissions for 1850–2010) but for North America as a whole. GCP's LU emissions for 1850–2005 classify the USA as a moderate sink and Canada as a moderate source (the first slightly greater than the second in absolute terms), while North America as a whole only turns from moderate source to moderate sink around 2006/07, according to GCP's LU emissions for 1850–2010.

   Both the solid green and solid brown dots correct the USA's p/c emissions from land use and land-use change for biomass embodied in trade ($eTrade_{LU}$) in 2000. The corrections refer to the GCP LU emissions for 1850–2005 and to the UNFCCC LULUCF emissions for 1990–2009. With these corrections we switch the perspective from production to consumption indicating that, while the directly human-impacted part of the USA's terrestrial biosphere acts as a net sink, the country is also a net biomass exporter. It would greatly benefit the USA to switch to reporting that accounts for $eTrade_{LU}$ (SI: Fig. S3 – case 4, solid arrow).

   Although only 2000 data are available to study $eTrade_{LU}$, the magnitude of the adjustment involved in switching from a production to consumption perspective is substantial and greater in relative terms than switching perspectives for technospheric emissions. The dotted gray lines acknowledge this finding. They represent the paths to lowering the USA's p/c emissions

from land use and land-use change plus those embodied in eTrade$_{LU}$ to zero, assuming that the terrestrial biosphere as of today (~2000) represents a sustainable state to be reached in 2050.

Figure 2b takes over some, but not all, technospheric emission entries of Fig. 2a. The figure also shows three solid, dark-to-light, green lines. These reflect typical aggressive, long-term emission reduction scenarios (excluding CO_2 emissions from land use and land-use change; in t CO_2-eq/cap) as realized by GTEM, IMAGE, and POLES for the USA and explained in Section 2.8 and SI (Note 4). Even these scenarios fail to meet the condition of equal emissions above and below the gray reference pathway, which reflects the cumulative constraint of 1500 Gt CO_2-eq for 2000–2050 and ensures the 2 °C target will be reached (Table 1a). However, this looks different at the global scale. The additional thin solid light-green line belongs to POLES. It shows how p/c emissions decrease globally. The global emission reduction scenarios behind the other two USA scenarios are not shown. These are very similar to the global POLES scenario shown in the figure. In 2050 the global POLES scenario considerably undershoots the GEE target of 3.0 t CO_2-eq/cap (belonging to the 1500 Gt CO_2-eq constraint; Table 2).

Emission intensity paths (in kg CO_2-eq per 2005 US $) for the USA that correspond to the p/c emission reduction paths (solid, dark-to-light, green lines) are entered with the help of an additional vertical axis (to the right in Fig. 2b). The emission intensity paths correspond in color but are indicated as broken lines. Switching between the two emission reduction scales is straightforward.

3.2 China, a developing country with high total but lower p/c emissions

Figure 2c is similar to Fig. 2a but shows data for China, a country with high total emissions, no KP commitments, and less abundant data on GHG emissions and sinks. We use emission data of the Carbon Dioxide Information Analysis Center (CDIAC) (CO_2) and Environmental Protection Agency (EPA) (non-CO_2) emission data to visualize China's technospheric emissions for 1990–2005 (SI: Tab. S1) because UNFCCC-reported emissions are for one year only (1994). The difference between technospheric emissions in 1994 was about 0.5 CO_2-eq/cap (CDIAC-EPA: 3.9; UNFCCC: 3.4). The UNFCCC emissions value still falls below the highest emission target path which the figure resolves and which reflects the cumulative emissions constraint of 2400 Pg CO_2-eq for 2000–2050 (target path in 1994: 3.5 CO_2-eq/cap). For a better overview we entered only this emission target path. It not only indicates that China's p/c emissions were allowed to increase by 93 % between 1990 and 2050 (Table 2), but shows too that, from about 2000 onward, China's emissions began to exceed this target path and its upper "uncertainty wedge" (determined by the maximal uncertainty in the 2050 GEE value). To recall, the cumulative emissions constraint of 2400 Pg CO_2-eq should preferably be interpreted with reference to 4 °C in 2050 and beyond. However, considering fossil-fuel emissions embodied in trade—China is a net exporter resulting in a reduction of its territorial emissions—brings its emissions back into the wedge-shaped uncertainty range.

GCP's LU emissions for 1850–2005 classify China as a moderate source before 1999/2000 and moderate sink thereafter. However, considering biomass import and export and, thus, embodied LU emissions—China was a net importer of biomass in 2000—appears to nullify this sink and reclassify China as a moderate source.

Figure 2d is similar to Fig. 2b. Regarding the USA, the aggressive, long-term emission reduction scenarios (in t CO_2-eq/cap) of GTEM, IMAGE, and POLES[9] fail to meet the

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[9] Respectively, Global Trade and Environment Model; Integrated Model to Assess the Greenhouse Effect; Prospective Outlook on Long-term Energy Systems (model)

condition of equal emissions above and below the gray reference pathway, which belongs to the cumulative constraint of 1500 Gt CO_2-eq for 2000–2050 and ensures the 2 °C target will be reached (Table 1a). However, in contrast to the USA, two of the reduction scenarios (those of IMAGE and Poles) show that, in the long-term, China's p/c emissions closely follow the global average (by POLES) or even fall below.

Another difference is the remarkable decrease of China's emission intensities realized by all three models. This, together with its low p/c emissions and the projected rapid growth of its economy, explains why China's national response strategy to climate change prioritizes improvement of energy conservation, energy intensity reduction, and improved energy-use efficiency (http://www.beconchina.org/energy_saving.htm).

4 Summary and conclusions

Our study focuses on uncertainty in anthropogenic GHG emissions including emissions from land use and land-use change activities. Our aim was to understand the relevance of diagnostic and prognostic uncertainty in an emissions-temperature setting that seeks to constrain global warming and to link uncertainty consistently across temporal scales.

We discuss diagnostic and prognostic uncertainty in a systems setting that allows any country to understand its national and near-term mitigation and adaptation efforts in a globally consistent and long-term context. In this context cumulative emissions are constrained and globally binding but exhibit quantitative uncertainty, and whether or not compliance with an agreed temperature target will be achieved is also uncertain. To facilitate discussions, we focus on two countries, the USA and China, while limiting global temperature rise to 2, 3, or 4 °C. We show:

– That both diagnostic and prognostic uncertainty need to be considered to facilitate more educated (precautionary) decisions on reducing emissions, given an agreed future temperature target.
– How to combine the two uncertainties which we consider independent. We note that our mode of bridging uncertainty across temporal scales still relies on discrete points in time and is not yet continuous.
– How to perceive diagnostic and prognostic uncertainty–related risk in combination. Here, diagnostic uncertainty refers to the uncertainty contained in inventoried emission estimates and is related to the risk that true GHG emissions are greater than inventoried emission estimates reported in a specified year. In contrast, prognostic uncertainty is derived from a multitude of model-based, forward-looking emission-climate change scenarios; it refers to cumulative emissions between a start year and a future target year, and can be related to the risk that an agreed temperature target is exceeded. We find that, to nullify the diagnostic uncertainty-related risk, the GEE intervals listed in the column (e.g.) "1500 Pg CO_2-eq" of Table 1a would need to be shifted downward by an additional 0.2 or 0.3 t CO_2-eq/cap, while the prognostic uncertainty–related risk of exceeding the 2 °C is unimpaired.
– That, as a direct consequence of the not unequivocal relationship between cumulative emissions and risk, a sharp cumulative emissions value translates into a risk interval for exceeding the agreed temperature target and, vice versa, a sharp risk value translates into a cumulative emissions interval. We interpret these intervals in terms of prognostic uncertainty and make use of the two extreme alternatives – sharp cumulative emissions versus uncertain risk (min/max) and uncertain cumulative emissions versus sharp risk (max/min).

– That scientists face difficulties in adequately embedding cumulative emissions from land use and land-use change in this emission-temperature setting because an achievable future state of sustainability for the terrestrial biosphere in toto has not yet been defined.

– That treating diagnostic uncertainty reaches its limits in the case of sparse data as given, in general, for reporting technospheric GHG emissions by non-Annex I countries and for reporting emissions from land use and land-use change by all countries.

– That prognostic uncertainty becomes too large for cumulative emission constraints for 2000–2050 above ~2100 Gt CO_2-eq. Above 2100 Gt CO_2-eq, GEE values in 2050 can no longer be properly distinguished. Uncertainty overshadows differences in the GEE values which result from differences in both cumulative emissions and start year. Thus our approach cannot be used for temperature targets in 2050 and beyond greater than 4 °C.

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