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Modeling the linkage between climate change and violent conflict

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Abstract

In this paper we present a basic mathematical model of a causal relationship between climate change and climate change-induced violent conflict. This model is based on the IPCC variables related to the subject and addresses the question what implications a framing of the climate conflict-nexus in these logically connected variables can potentially have on the result of studies on causal relationships between climate change and violent conflict. We derive two fundamental scenarios: If the technological progress factor exceeds the climate change impacts in the long run, a society will remain able to protect itself against climate change but this case also provides the ability for violent conflict. In contrast, if climate change impacts exceed technological progress, a society eventually loses its ability for violent conflict and cooperates for mere survival. The model can be used to understand the dynamics and interdependencies between the variables considered.

1. Introduction

In recent years, considerable research has been conducted to improve the understanding of the relationship between climate change and violent conflict. Entire volumes have been dedicated to this issue (Gleditsch 2012; Scheffran et al. 2012b). Despite the progress that has been made in this field, it is still debated whether or not there is a causal relationship between climate change and violent conflict. While some researchers see a clear relationship between these variables (Burke et al. 2009; Hsiang et al. 2011; Hsiang et al. 2013), others are more cautious with regard to a possible link between these quantities (Buhaug 2010; Scheffran et al. 2012c), mainly because of the complexity of the subject matter.

Yet, the question can be posed: If violent conflict was to increase with progressing climate change, how would this relationship evolve? Models of the climate-conflict linkage, which are based on interdisciplinarily used variables like vulnerability, adaptive capacity, climate sensitivity, and exposure as defined by the Intergovernmental Panel on Climate Change (IPCC 2007a), could help concretize what influence these different variables actually have on the potential societal effects of climate change. Such information on e.g. the likelihood of onset of violent conflicts could prove to be valuable for the adjustment of intervention or mitigation strategies.

Altered environmental conditions as a consequence of climate change can affect societies directly in numerous ways (Scheffran et al. 2012c): e.g. through severe weather events (Adger et al. 2005; Kates et al. 2006), sea-level rise (Klein et al. 2001), or irregularly changing precipitation patterns (Schilling et al. 2012). These changes can manifest themselves in altered availability of fresh water resources, food, and energy, or in adversely affected human health (WBGU 2008). Furthermore, unequally distributed impacts can cause indirect effects via reinforced or changing inequality patterns (Kates et al. 2006; Marino and Ribot 2012). Resulting social effects can include political events such as demonstrations, reinforced or changing hierarchies and politics (Kominek and Scheffran 2012). And unequal changes in livelihood can cause social changes such as migration (Lindstrom 1996) or cooperation (BenDor et al. 2009) on the one hand and conflict or violence on the other hand (Barnett and Adger 2007).

While there are numerous studies about the climate conflict nexus that use empirical quantitative or qualitative approaches (see table in Scheffran et al. 2012d), models of climate-conflict linkages are rare (example in Devitt and Tol 2012; see review in Scheffran et al. 2012a). Applying various concepts of climate change and conflict, most empirical studies in this field consider a selected set of climatic or weather-related variables (e.g. temperature, precipitation, extreme weather events) that are then correlated with particular aspects of violent conflict such as the number, intensity, or onset of armed conflicts (Scheffran et al. 2012d). Nonetheless, while these studies can describe a specific issue of the climate change-conflict relationship, it is not easily possible to generalize their findings to make them usable for modeling purposes.

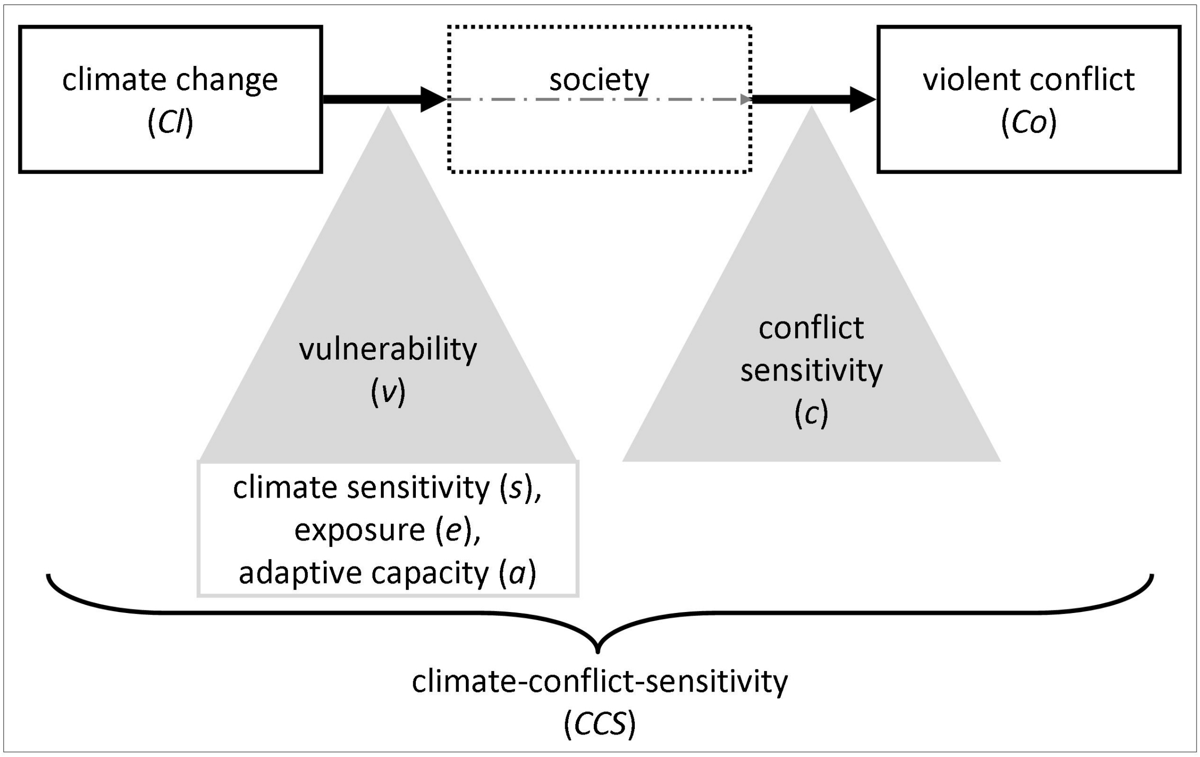
Recently, there have been new approaches and concepts to explain the relationship between climate change and the resulting impacts on societal stability and conflict (e.g. Adger 2010; Mearns and Norton 2009; O'Brien and Wolf 2010). These have framed the human-environment interaction in different ways. However, in the end these different approaches have boiled down to looking at the same variables that are used by the IPCC such as vulnerability, adaptive capacity, and sensitivity. This joint basis may be problematic as the strong overlap prevents any newly developed framework from being considerably different from the IPCC's approach. Thus, it is important to assess what the relationships between these fundamental variables in the climate conflict nexus actually imply (if anything). Such an assessment needs to consider these fundamental variables at an abstract level in order to analyze what the nature and extent of their basic relationships actually is.

To do so, this paper addresses the challenge of actually modeling the climate change-conflict relationship by developing a model of the climate-conflict-sensitivity (CCS), which is the ratio of a conflict function and a climate change function. In this approach, we assume that in general an increase in climate change affects society in such a way that the result is an increase in the occurrence of violent conflict. The model setup and the fundamental equations are based on this assumption and are presented in the subsequent section 2. The derivatives of the CCS can be used to answer questions such as whether the amplitude of a violent societal response increases or decreases, and whether the acceleration of the effect on violence increases or decreases with progressing climate change. This assessment is conducted in section 3. The results are discussed in section 4, section 5 concludes.

2. Setup of the model

To describe the direct and indirect effects of climate change on violent conflict, quantitative variables need to be defined. While the most important indicators of climate change (temperature, precipitation, number of extreme weather events) are relatively easy to measure directly, the societal influences on the causal chain between climate change and conflict are complex (Scheffran et al. 2012c). Therefore, the latter are harder to quantify, which necessitates the use of characteristic indicators to depict the climate change impacts on society (Figure 1).

Figure 1: Schematic overview of the model variables and their interdependencies.



In this model, the impact of climate change on a society depends on its vulnerability. Furthermore, the reaction of a society to turn to violence also depends on the conflict sensitivity of the society. If a society was not vulnerable at all, climate change would have no detrimental effect. And if a society was not sensitive to conflict at all, it would always react peacefully even if climate change was to strongly impact the society. Therefore, the causal relationship between climate change and violent conflict depends on two key intermediates: the societal vulnerability v and the society's conflict sensitivity c. Societal vulnerability is a composite variable that is assumed to consist of three components: the exposure e of the society to climate change, the climate sensitivity s, and the adaptive capacity a of the society (IPCC 2007a). Table 1 summarizes our definitions of the model variables and their defining equations, which are explained in the subsequent sections.

Tab. 1: Equations and variables used in the model

Exposure to climate change:

$$e_R\left(Cl_R(t),t\right) := k_{e_R}(t)\,Cl_R^2(t) \tag{1}$$

Adaptive capacity of a society:

$$a_R\left(Cl_R(t),t\right) := k_{a_R}(t)\cdot\left(\left|e^t - Cl_R^2(t)\right| + \varepsilon\right) \tag{2}$$

Vulnerability to climate change:

$$\begin{aligned} v_R\left(Cl_R(t),t\right) &:= \frac{e_R\left(Cl_R(t),t\right)s(t)}{a_R\left(Cl_R(t),t\right)} \\ &= \frac{k_{e_R}(t)\,Cl_R^2(t)\,s(t)}{k_{a_R}(t)\cdot\left(\left|e^t - Cl_R^2(t)\right| + \varepsilon\right)} \end{aligned} \tag{3}$$

Conflict as a function of vulnerability and climate change:

$$\begin{aligned} Co_R\left(Cl_R(t),t\right) &:= v_R\left(Cl_R(t),t\right)c_R(t)\,Cl_R(t) \\ &= \frac{e_R\left(Cl_R(t),t\right)s(t)}{a_R\left(Cl_R(t),t\right)}c_R(t)\,Cl_R(t) \\ &= \frac{k_{e_R}(t)\,s(t)\,c_R(t)}{k_{a_R}(t)}\cdot\frac{Cl_R^3(t)}{\left|e^t - Cl_R^2(t)\right| + \varepsilon} \end{aligned} \tag{4}$$

a	adaptive capacity	k	constant for calibration, k > 0
Cl	climate change	R	index denoting the geographic region
Co	climate change-induced violent conflict	s	climate sensitivity
c	conflict sensitivity	t	time
e	exposure	v	vulnerability
ε	constant, ε > 0		

2.1. Climate change

$$Cl_R(t) > 0 \tag{5}$$

The climate change function Cl is assumed to be positive over time (Eq. 5). In this model, it is an abstract variable. Thus, the climate change function does not refer to a specific indicator of climate change such as temperature or precipitation changes. For statistical purposes and to be applicable in empirical research the climate change function would need to be defined more precisely in terms of measurable quantities and calibrated to fit with the other model functions.

2.2. Climate sensitivity

The climate sensitivity s is a global physical constant. It is defined as the equilibrium annual global mean increase in temperature for a doubling of atmospheric CO_2 equivalents compared to pre-industrial levels (IPCC 2007b). Therefore, it can be considered to be an indicator for the extent of the climate system's reaction to a particular amount of greenhouse gas forcing. However, it has to be noted that the current estimates of climate sensitivity vary considerably depending on the particular climate model used to determine this quantity.

2.3. Exposure

Because exposure is expected to increase with progressing climate change (IPCC 2007a), the exposure function depends on the climate change function and a calibration function $k_{e_R}(t)$, which is assumed to be positive (Eq. 1). While a linear function would be the simplest representation of this correlation, we have chosen to use a quadratic functional relationship to be able to cancel the climate change dimension in the vulnerability function.

2.4. Adaptive capacity

Some projections of previous technological developments into the future have led to the assumption that in the long run the exponentially increasing technological development can help to mitigate or cope with the impacts of climate change (Nagy et al. 2012). But in the short run climate change may have regionally such large effects that present local technologies may be insufficient to adequately cope with them. Yet, a well informed society with knowledge on the potential regional climate change effects and best practice coping strategies may directly mitigate potential climate change effects. Thus, the adaptive capacity function consists of a technology-dependent part that increases exponentially over time. But this technology-based adaptive capacity is reduced by regional climate change effects, which are divided by a regional knowledge function (Eq. 2).

It is assumed in the adaptive capacity function that if the regional climate change effects increase less than exponentially over time, the exponentially growing technology-based part of the adaptive capacity will exceed them in the long run (for large t). In that case, the difference in the brackets is positive and the absolute value operator has no effect. But in the short run, a negative difference is possible if new technologies are not available quickly enough to offset regional increases in climate change effects. In this case, the absolute value operator assures that the adaptive capacity function always remains non-negative and the ε causes the adaptive capacity to stay above zero even if the difference decreases further over time.

2.5. Vulnerability

The definition of the vulnerability function is based on a three-fold understanding of vulnerability (IPCC 2007a). It is defined to consist of the three multiplicative components – exposure, climate sensitivity, and adaptive capacity – and a calibration function that is assumed to be independent from climate change. In contrast to exposure and climate sensitivity, an increase in adaptive capacity, e.g. through technological innovation or a better informed society, reduces the vulnerability in the considered region and mitigates climate change effects. Thus, in the definition of the vulnerability function the product of the exposure function and the climate sensitivity is divided by the adaptive capacity function (Eq. 3).

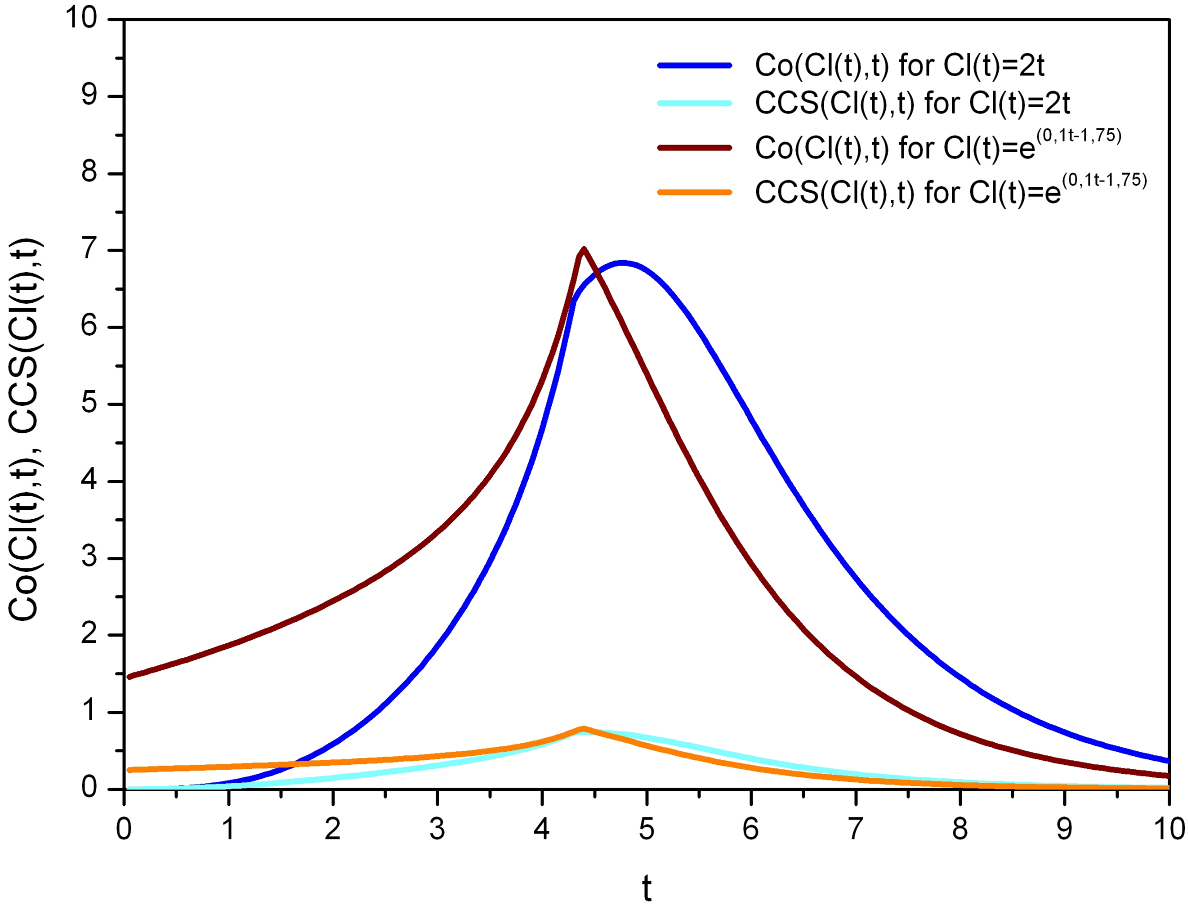
2.6. Conflict sensitivity

The conflict sensitivity function is assumed to be positive. For a conflict sensitivity of zero, there is no climate change-related conflict because the society would react to any changes in climate in a peaceful manner. Then the climate-conflict-sensitivity would be zero as well. Such a case is trivial. In the subsequent analyses only non-trivial scenarios will be addressed using a positive conflict sensitivity.

2.7. Conflict

The violent conflict function is defined as climate change-related violent conflict only (Eq. 4) and does not refer to a measurable quantity such as the number of armed conflicts or battle deaths per year (e.g. Gleditsch et al. 2002; PRIO 2011; Raleigh et al. 2010). To allow statistical inferences, the underlying functions – vulnerability, conflict sensitivity, climate change, exposure, and adaptive capacity – and their constants would need to be calibrated. In this theoretical assessment (Figure 2), we merely assume that the variables are related in the way that is described in the set definitions above (Table 1).

Figure 2: Two examples of the conflict function and its corresponding climate-conflict-sensitivity. All constants are set to 1, ε = 100.



3. To which extent do conflicts increase with increasing climate change?

In this assessment we assume that climate change-induced violent conflict exists. This generally implies that a worsening of climate change reinforces violent conflict. The question is whether the intensity of the influence of climate change on conflict changes with progressing climate change: Do the impacts increase or slow down with further progress of climate change? And does the rate of the change in impacts vary with further progress? In other words, does climate change lead to violent conflict more directly and at an increasing rate or does its additional influence diminish with progressing climate change?

To address these questions, we define the climate-conflict-sensitivity (CCS) as an indicator of the relationship between the conflict function and the climate change function[1] (Eq. 6). If the regional climate-conflict-sensitivity (CCS_R) was known, scientists could generate conflict scenarios on the basis of climate change scenarios.

$$CCS_R\left(Cl_R\left(t\right),t\right) := \frac{Co_R\left(Cl_R\left(t\right),t\right)}{Cl_R\left(t\right)} \Leftrightarrow Co_R\left(Cl_R\left(t\right),t\right) = CCS_R\left(Cl_R\left(t\right),t\right)\cdot Cl_R\left(t\right) \quad (6)$$

To understand the CCS_R more closely even without exact knowledge of future climate change, the following questions can be posed and answered in the subsequent sections:

How does the CCS_R change with increasing climate change (Eq. 7)?

$$\frac{\partial CCS_R\left(Cl_R\left(t\right),t\right)}{\partial Cl_R\left(t\right)} \geq 0 \ \vee \ \frac{\partial CCS_R\left(Cl_R\left(t\right),t\right)}{\partial Cl_R\left(t\right)} \leq 0 \ ? \quad (7)$$

Does the change of the CCS increase or decrease with increasing climate change (Eq. 8)?

$$\frac{\partial^2 CCS_R\left(Cl_R\left(t\right),t\right)}{\partial^2 Cl_R\left(t\right)} \geq 0 \ \vee \ \frac{\partial^2 CCS_R\left(Cl_R\left(t\right),t\right)}{\partial^2 Cl_R\left(t\right)} \leq 0 \ ? \quad (8)$$

The answers to these questions require the first and second partial derivatives of the CCS_R with respect to its climate change component. Therefore, the individual variables are inserted into the defining equation, the constants are combined in one term, and functions are substituted to simplify the equation for use in subsequent calculations (Eq. 9):

$$\begin{aligned} CCS_R\left(Cl_R\left(t\right),t\right) &= \frac{Co_R\left(Cl_R\left(t\right),t\right)}{Cl_R\left(t\right)} = \frac{v_R\left(Cl_R\left(t\right),t\right)\cdot c_R\left(t\right)\cdot Cl_R\left(t\right)}{Cl_R\left(t\right)} \\ &= k_{v_R}\left(t\right)\cdot \frac{e_R\left(Cl_R\left(t\right),t\right)\cdot s\left(t\right)}{a_R\left(Cl_R,t\right)}\cdot c_R\left(t\right) \\ &= k_{v_R}\left(t\right)\cdot \frac{k_{e_R}\left(t\right)\cdot Cl_R^2\left(t\right)\cdot s\left(t\right)}{k_{a_R}\left(t\right)\cdot\left(\left|e^t - Cl_R^2\left(t\right)\right| + \varepsilon\right)}\cdot c_R\left(t\right) \\ &= \frac{k_{v_R}\left(t\right)\cdot k_{e_R}\left(t\right)\cdot s\left(t\right)\cdot c_R\left(t\right)}{k_{a_R}\left(t\right)}\cdot \frac{Cl_R^2\left(t\right)}{\left|e^t - Cl_R^2\left(t\right)\right| + \varepsilon} \end{aligned} \quad (9)$$

Now the constants, which are independent of climate change, can be combined in the following way (Eq. 10):

$$m := \frac{k_{v_R}\left(t\right)\cdot k_{e_R}\left(t\right)\cdot s\left(t\right)\cdot c_R\left(t\right)}{k_{a_R}\left(t\right)} \quad (10)$$

Substitution of the variables (Eq. 11) results in

[1] Hsiang and others (2013) attempt to determine something like a CCS. However, in their assessment they do not just focus on climate change-induced conflict but rather apply statistical methods to assess the relationship between all forms of conflict and climate change.

$$CCS_R\left(Cl_R\left(t\right),t\right)=m\cdot\frac{Cl_R^2\left(t\right)}{\left|e^t-Cl_R^2\left(t\right)\right|+\varepsilon} \tag{11}$$

with m > 0.

3.1. Differentiability of the CCS_R

Before turning to the questions concerning the change of the CCS_R and the rate of its change, the CCS_R function's differentiability needs to be checked to ensure that it is differentiable throughout the domain over which it is defined. In the definition of the CCS_R function all defining functions except for the adaptive capacity function are themselves differentiable over their entire domains. The adaptive capacity function has a singularity, at which the technology term equals out the climate change term and thus the absolute value vanishes. Therefore, it is useful to split the CCS_R function in two differentiable functions without any singularities (Eqs. 12 and 13).

$$CCS_R^+\left(Cl_R\left(t\right),t\right):=m\cdot\frac{Cl_R^2\left(t\right)}{e^t-Cl_R^2\left(t\right)+\varepsilon}\quad for\quad e^t-Cl_R^2\left(t\right)>0 \tag{12}$$

and

$$CCS_R^-\left(Cl_R\left(t\right),t\right):=m\cdot\frac{Cl_R^2\left(t\right)}{-e^t+Cl_R^2\left(t\right)+\varepsilon}\quad for\quad e^t-Cl_R^2\left(t\right)<0 \tag{13}$$

3.2. How does the CCS_R change with increasing climate change?

We now analyze whether the CCS_R and thus the likelihood of conflict increases or decreases with progressing climate change (Eq. 7). Partial differentiation of the CCS_R (Eqs. 14 and 15) yields:

$$\begin{aligned}\frac{\partial CCS_R^+\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial Cl_R\left(\Delta t\right)}&=m\cdot\frac{2Cl_R\left(\Delta t\right)\left(e^{\Delta t}-Cl_R^2\left(\Delta t\right)+\varepsilon\right)-Cl_R^2\left(\Delta t\right)\cdot\left(-2Cl_R\left(\Delta t\right)\right)}{\left(e^{\Delta t}-Cl_R^2\left(\Delta t\right)+\varepsilon\right)^2}\\&=m\cdot\frac{2Cl_R\left(\Delta t\right)e^{\Delta t}+2Cl_R\left(\Delta t\right)\cdot\varepsilon}{\left(e^{\Delta t}-Cl_R^2\left(\Delta t\right)+\varepsilon\right)^2}\\&=m\cdot\frac{2Cl_R\left(\Delta t\right)\left(e^{\Delta t}+\varepsilon\right)}{\left(e^{\Delta t}-Cl_R^2\left(\Delta t\right)+\varepsilon\right)^2}>0\quad\forall\, m>0\end{aligned} \tag{14}$$

and

$$\begin{aligned}\frac{\partial CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial Cl_R\left(\Delta t\right)}&=m\cdot\frac{2Cl_R\left(\Delta t\right)\left(-e^{\Delta t}+Cl_R^2\left(\Delta t\right)+\varepsilon\right)-Cl_R^2\left(\Delta t\right)\cdot\left(2Cl_R\left(\Delta t\right)\right)}{\left(-e^{\Delta t}+Cl_R^2\left(\Delta t\right)+\varepsilon\right)^2}\\&=m\cdot\frac{2Cl_R\left(\Delta t\right)\left(\varepsilon-e^{\Delta t}\right)}{\left(-e^t+Cl_R^2\left(\Delta t\right)+\varepsilon\right)^2}\begin{cases}>0 & for\quad e^{\Delta t}<\varepsilon\\<0 & for\quad e^{\Delta t}>\varepsilon\end{cases};\forall\, m>0\end{aligned} \tag{15}$$

Therefore, based on the model assumptions the regional CCS_R^+ increases with increasing regional climate change. The same holds for the regional CCS_R^- for a very low technological term ($e^{\Delta t} < \varepsilon$). For a larger technological term ($e^{\Delta t} > \varepsilon$) the CCS_R^- decreases with increasing climate change.

A growing climate-conflict-sensitivity means that if an increment of one unit on the climate change effects scale initially causes an increase of one unit on the conflict scale, it will later have an amplified effect. Consequently, a decreasing climate-conflict-sensitivity means that the considered unit would later have a reduced effect on the conflict scale. These findings are discussed in detail in section 4.

3.3. Does the change of the CCS increase or decrease with increasing climate change?

Further differentiation (Eqs. 16 and 17) yields:

$$
\begin{aligned}
&\frac{\partial^2 CCS_R^+\left(Cl_R(\Delta t),\Delta t\right)}{\partial^2 Cl_R(\Delta t)} \\
&= m\cdot\frac{2\left(e^{\Delta t}+\varepsilon\right)\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)^2-2Cl_R(\Delta t)\cdot\left(e^{\Delta t}+\varepsilon\right)\cdot 2\cdot\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)\left(-2Cl_R(\Delta t)\right)}{\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)^4} \\
&= m\cdot\frac{2\left(e^{\Delta t}+\varepsilon\right)\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)+2\left(e^{\Delta t}+\varepsilon\right)\cdot 4Cl_R^2(\Delta t)}{\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)^3} \\
&= m\cdot\frac{2\left(e^{\Delta t}+\varepsilon\right)\left(e^{\Delta t}+3Cl_R^2(\Delta t)+\varepsilon\right)}{\left(e^{\Delta t}-Cl_R^2(\Delta t)+\varepsilon\right)^3} > 0 \quad \forall\, m>0 \quad \text{because of } e^{\Delta t}-Cl_R^2(\Delta t)>0.
\end{aligned} \tag{16}
$$

and

$$
\begin{aligned}
&\frac{\partial^2 CCS_R^-\left(Cl_R(\Delta t),\Delta t\right)}{\partial^2 Cl_R(\Delta t)} \\
&= m\cdot\frac{2\left(\varepsilon-e^{\Delta t}\right)\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)^2-2Cl_R(\Delta t)\cdot\left(\varepsilon-e^{\Delta t}\right)\cdot 2\cdot\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)\left(2Cl_R(\Delta t)\right)}{\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)^4} \\
&= m\cdot\frac{2\left(\varepsilon-e^{\Delta t}\right)\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)-2\left(\varepsilon-e^{\Delta t}\right)\cdot 4Cl_R^2(\Delta t)}{\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)^3} \\
&= m\cdot\frac{2\left(\varepsilon-e^{\Delta t}\right)\left(-e^{\Delta t}-3Cl_R^2(\Delta t)+\varepsilon\right)}{\left(-e^{\Delta t}+Cl_R^2(\Delta t)+\varepsilon\right)^3}\begin{cases} <0 & \text{for } e^{\Delta t}<\varepsilon \\ >0 & \text{for } e^{\Delta t}>\varepsilon \end{cases} ;\ \forall\, m>0\,,\ \text{because of}:
\end{aligned} \tag{17}
$$

Now, the following cases can be distinguished depending on which term is dominant (Eq. 18):

$$m \cdot \frac{2\left(\varepsilon - e^{\Delta t}\right)\left(-e^{\Delta t} - 3Cl_R^2\left(\Delta t\right) + \varepsilon\right)}{\left(-e^{\Delta t} + Cl_R^2\left(\Delta t\right) + \varepsilon\right)^3} \begin{matrix} > \\ = \\ < \end{matrix} 0$$

$$\Leftrightarrow \quad \left(\varepsilon - e^{\Delta t}\right)\left(-e^{\Delta t} - 3Cl_R^2\left(\Delta t\right) + \varepsilon\right) \begin{matrix} > \\ = \\ < \end{matrix} 0\,;\forall\, m > 0\,,\, because\ of\ -e^{\Delta t} + Cl_R^2\left(\Delta t\right) > 0$$

$$\begin{aligned} &For\ e^{\Delta t} - Cl_R^2\left(\Delta t\right) < 0\ and\ e^{\Delta t} < \varepsilon\ : \\ &-e^{\Delta t} - 3Cl_R^2\left(\Delta t\right) + \varepsilon < -4e^{\Delta t} + \varepsilon < -4e^{\Delta t} + e^{\Delta t} = -3e^{\Delta t} < 0. \end{aligned} \tag{18}$$

$$\begin{aligned} &For\ e^{\Delta t} - Cl_R^2\left(\Delta t\right) < 0\ and\ e^{\Delta t} > \varepsilon\ : \\ &e^{\Delta t} + 3Cl_R^2\left(\Delta t\right) - \varepsilon > 4e^{\Delta t} - \varepsilon > 3e^{\Delta t} + \varepsilon - \varepsilon = 3e^{\Delta t} > 0. \end{aligned}$$

Thus, in all but one case the tendency effect of the climate-conflict-sensitivity increases with increasing climate change. Only when the effect of climate change exceeds the technological term ($e^{\Delta t} - Cl_R^2\left(\Delta t\right) < 0$) and there is hardly any technological term at all ($e^{\Delta t} < \varepsilon$), the increasing effect of the $CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)$ decreases with further climate change.

3.4. The three resulting scenarios

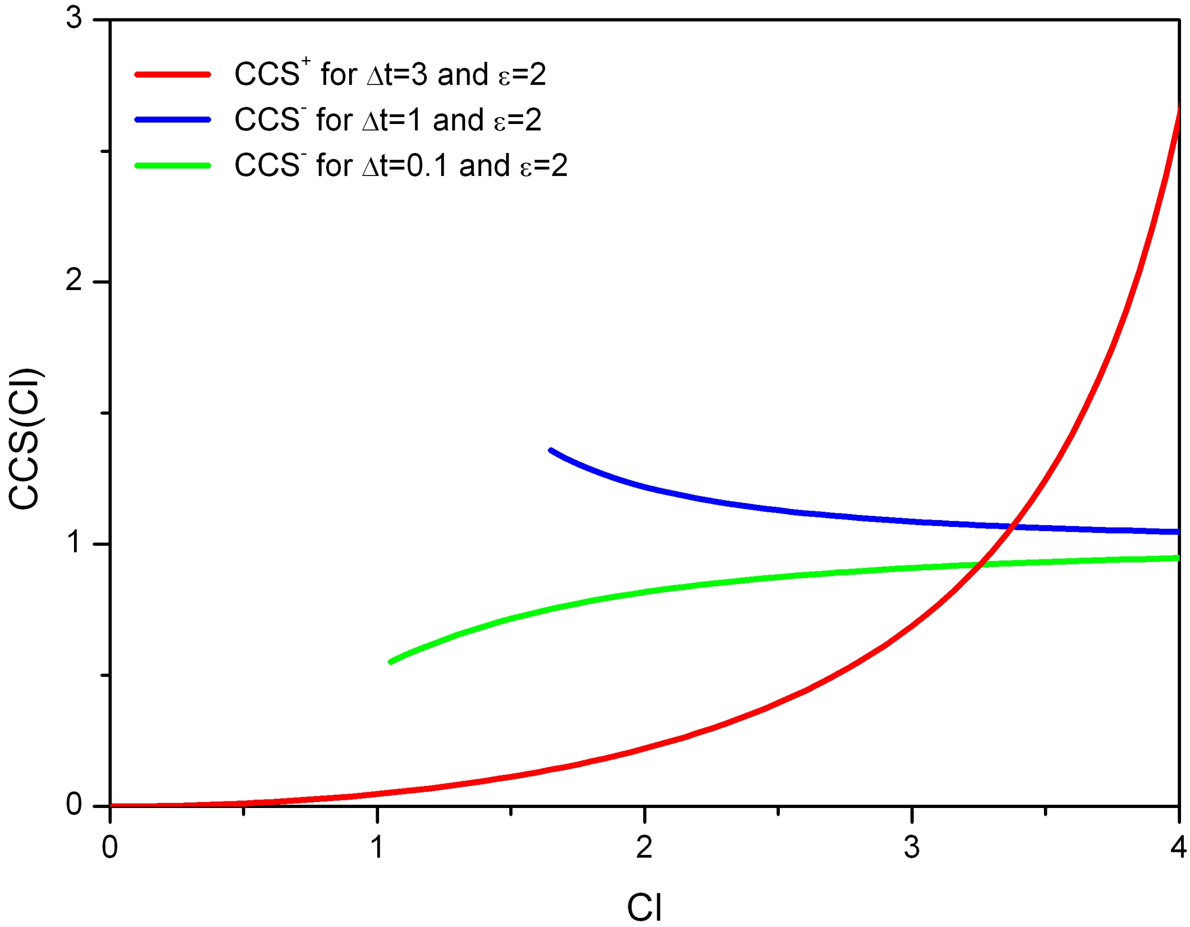
The model can be used to describe three fundamental scenarios (Table 2): In one scenario the technological innovation, which increases exponentially over time, can be used to compensate for the occurring climate change effects. In this scenario the positive branch of the climate-conflict-sensitivity needs to be considered, i.e. $CCS_R^+\left(Cl_R\left(t\right),t\right)$. The first and second partial derivatives with respect to climate change are positive, which entails that with increasing climate change conflicts increase more than linearly (Figure 3).

Table 2: Inequalities that describe three scenarios: positive branch (scenario 1, left) and negative branch (scenario 2, center; and scenario 3, right) of the climate-conflict-sensitivity function. The negative branch is distinguished further depending on the role of technology.

$e^{\Delta t} - Cl_R^2\left(\Delta t\right) > 0$	$e^{\Delta t} - Cl_R^2\left(\Delta t\right) < 0$	$e^{\Delta t} - Cl_R^2\left(\Delta t\right) < 0$
$CCS_R^+\left(Cl_R\left(\Delta t\right),\Delta t\right) > 0$	$CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right) > 0$	$CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right) > 0$
	$e^{\Delta t} < \varepsilon$	$e^{\Delta t} > \varepsilon$
$\frac{\partial CCS_R^+\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial Cl_R\left(\Delta t\right)} > 0$	$\frac{\partial CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial Cl_R\left(\Delta t\right)} > 0$	$\frac{\partial CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial Cl_R\left(\Delta t\right)} < 0$
$\frac{\partial^2 CCS_R^+\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial^2 Cl_R\left(\Delta t\right)} > 0$	$\frac{\partial^2 CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial^2 Cl_R\left(\Delta t\right)} < 0$	$\frac{\partial^2 CCS_R^-\left(Cl_R\left(\Delta t\right),\Delta t\right)}{\partial^2 Cl_R\left(\Delta t\right)} > 0$

In the other two scenarios climate change impacts exceed technological innovation capabilities. Consequently, the negative branch of the climate-conflict-sensitivity needs to be considered ($CCS_R^-\left(Cl_R\left(t\right),t\right)$). In this case the derivatives change signs. For hardly any technological innovation (scenario 2) the first partial derivative of the climate-conflict-sensitivity with respect to climate change is positive while the second partial derivative is negative. In case the technological innovation is larger (scenario 3), the signs of the derivatives are opposite to those of scenario 2.

Figure 3: Examples of a climate change dependent climate-conflict-sensitivity function that represent the three scenarios of a positive or negative branch of the climate-conflict-sensitivity function for a given point in time.



4. Discussion

Based on the assumption that an increase in climate change generally leads to an increase in climate change-induced violent conflict and on further model assumptions relating to definitions from the IPCC (2007a), the two branches of the climate-conflict-sensitivity function need to be analyzed separately. In this discussion an interpretation of the two branches with their relating functions, the resulting scenarios, and potential developing dynamics is provided.

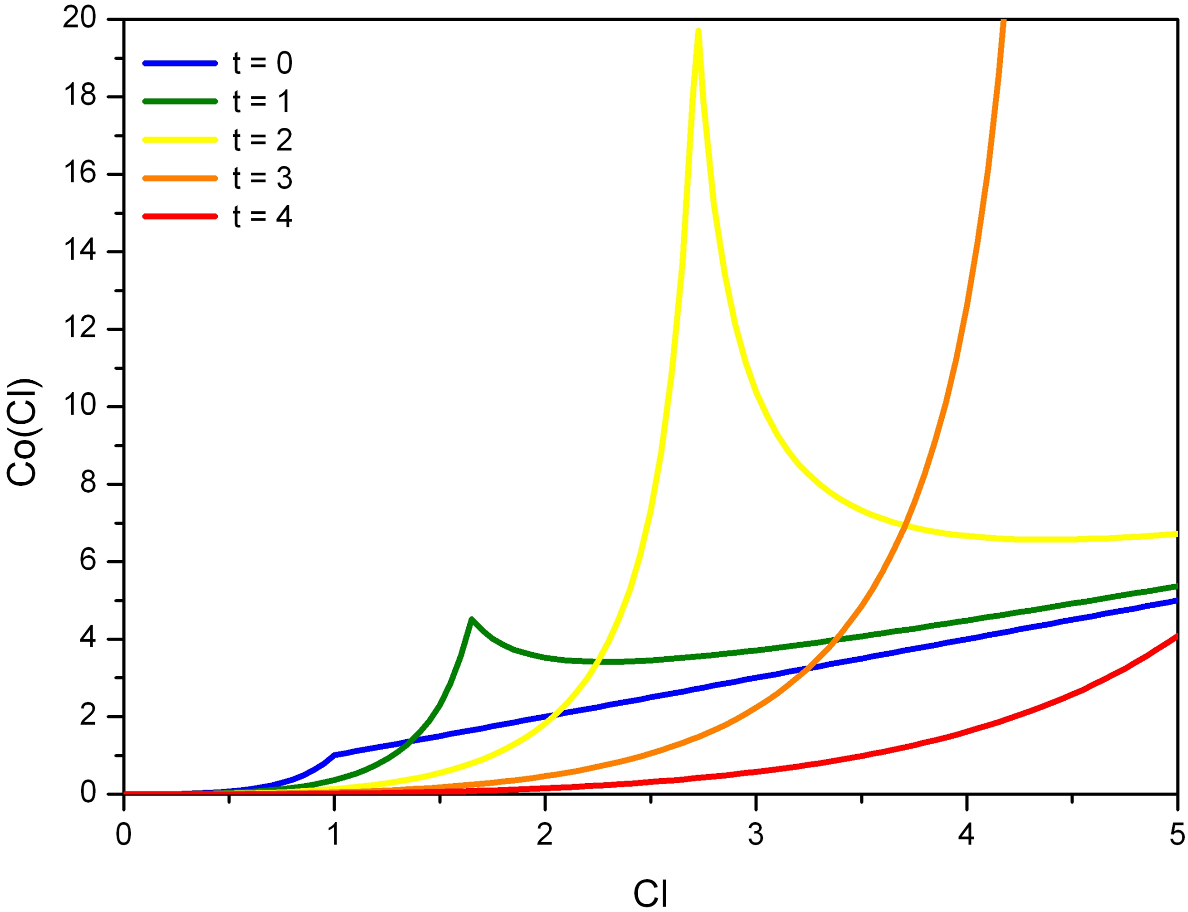
4.1. Negative branch - climate change exceeds technological innovation

In the defining equation of the adaptive capacity function in this model (Eq. 2), the adaptive capacity can be negatively affected if the quadratic term of environmental impacts approaches the value of the exponential term that represents technological progress. This corresponds to the situation that the climate change effects start to exceed technological innovation (Table 3, scenarios 2 and 3). However, because technological innovation is assumed to increase exponentially over time, climate change can only exceed it for a short period of time (scenario 2), which coincides with sudden strong impacts of climate change such as severe events. Although in this situation the climate-conflict-sensitivity still increases with increasing climate change, it does so at a decreasing rate, which implies a slight tendency towards cooperation. If climate change impacts exceed technological innovation for a longer time period (scenario 3) climate change also grows at least exponentially over time and such a development would have strong negative effects (Lenton et al. 2008; Notz 2009; UNFCCC 2007; WBGU 2008). In this situation the climate-conflict-sensitivity decreases and consequently conflicts do so as well. It even decreases with an increasing rate, which implies that cooperation emerges instead of conflict rather quickly.

4.2. What happens if the climate change term equals the technological innovation term?

In the model, the adaptive capacity function is assumed to be non-zero because for a zero adaptive capacity the conflict function and the climate-conflict-sensitivity would not be defined. But if the adaptive capacity function approaches $k_{a_R} \cdot \varepsilon$, the quadratic term, which mainly consists of the climate change function, becomes almost equal to the exponential term of the technological innovation. In line with the argumentation of section 4.1, the shift towards the technological innovation function implies that the climate change function increases more than exponentially over time. Additionally, the conflict function then also increases more than exponentially because of the way it is defined.

Figure 4: Conflict function over climate change for different time steps and all constants set to 1. ε = 0.99, therefore the rising part of the function corresponds to scenario 1 whereas the decreasing part corresponds to scenario 3.



If the adaptive capacity function approaches $k_{a_R} \cdot \varepsilon$ with technological progress still exceeding climate change impacts, the conflict function increases until it reaches a maximum (Figure 4). In contrast, if it approaches $k_{a_R} \cdot \varepsilon$ with climate change impacts exceeding technological progress, conflicts diminish again, which implies rising cooperation. Therefore, an adaptive capacity of $k_{a_R} \cdot \varepsilon$ is essentially a tipping point moving the system from conflict to cooperation or vice versa.

4.3. What do possible model dynamics actually mean for society?

Consider a society with a good technological innovation and relatively low climate change effects (positive branch, scenario 1), so that the society is potentially able to cope with negative implications of climate change. Then this society also has a certain potential for climate change-induced conflict. With increasing climate change, the climate change-induced conflicts are likely to increase and even at an increasing rate (scenario 1).

If climate change increases more than exponentially for a short period, which can happen if the society is affected by a severe event (negative branch, scenario 2a), conflicts are initially still likely to occur. However, there is a diminishing likelihood for the onset of new conflicts because the rate of increase in the climate-conflict-sensitivity decreases.

But if climate change increases more than exponentially for a longer time period (negative branch, scenario 2b) and therefore the severe impacts persist and increase such as in tipping point scenarios (Lenton et al. 2008; Stafford et al. 2010), cooperation is likely to emerge, perhaps against the "joint external enemy climate" because the climate-conflict-sensitivity decreases at an increasing rate.

If the climate change impacts diminish again so that technological innovation becomes once more sufficient for mitigation and adaptation, the potential for conflict re-grows at an increasing rate (positive branch, scenario 1).

4.4. Contradictions, limits, and applications

In the model, the situation of climate change impacts exceeding technological progress in the adaptive capacity function correlates with cooperation and a reduction of the *CCS* function, while in the opposite case the adaptive capacity function correlates with conflict and an increase in the rate of change of the increasing *CCS* function. This seems like a contradiction: adaptive capacity, which describes the ability to shade society from climate change impacts, correlates in one case with conflict while its mathematical counterpart correlates with cooperation. This can be explained as follows: A negative difference between the two key terms of the adaptive capacity function corresponds to a climate change function that increases very strongly over a short period of time. Therefore, an affected society is likely to suffer from strong impacts like flooding, storms, droughts, or severe health risks (IPCC 2007a; UNFCCC 2007; WBGU 2008). Consequently, the situation it faces would be shaped by severe effects on infrastructure, population, and public health. Thus, the cooperative behavior results from the joint necessity to merely survive.

The model neither allows inferences about the results of a negative climate change function nor of a general underlying correlation that an increase in climate change would reduce conflicts. In the model, the climate change function is defined as positive over time and is generally positively correlated with the violent conflict function. But if there was no climate change, there could be no climate change related conflict. Additionally, various cases are considered in the discussion such as more slowly or quickly increasing climate change because for the adaptive capacity and the other functions not only the absolute values of the climate change function matter but particularly the function's rates of change.

The functions in the model are mathematically defined for the purpose of analyzing the causal relationships among them. To apply the model to empirical data necessitates a scaling index that defines how the quantities considered need to be statistically combined. Important issues in this context are, e.g., whether the climate change function is measured in global surface temperature or precipitation, how exposure is computed, and how technological innovation is measured in order to deduce the adaptive capacity function as described in the model. Other details such as the influence of a democratic or autocratic governmental system or regional education are not included in the adaptive capacity function yet, even though scientists discuss indicators for the effects of the governmental system on the adaptive capacity of society (Brooks et al. 2005; Hinkel 2011). In order to resolve regional differences, the calibration coefficients could be used either theoretically or in combination with empirical data.

All in all, this model can be used to understand the dynamics and causal relationships of the correlated variables it consists of, especially the adaptive capacity of a society and the societal sensitivity of turning to climate change-induced violent conflict or cooperation when being affected by progressing climate change.

5. Conclusion

In this paper we present a model of the causal relationship between climate change and climate change-induced violent conflict. While in general an increase in the climate change function correlates with an increase in the conflict function and a reinforcing increase in the climate-conflict-sensitivity, the model allows for over-exponential increases in climate change, which corresponds to cooperative behavior and a decreasing climate-conflict-sensitivity. The first scenario represents an adaptive capacity, which enables the affected society to shade itself against climate change but also provides the ability for violent conflict. The second scenario describes an adaptive capacity, with which the affected society rather cooperates to merely survive.

Based on empirical research (IPCC 2007a; UNFCCC 2007; WBGU 2008), the second scenario appears to be rather likely as a regionally confined short-term scenario, while the first scenario relates to the long-term projections if there is a generally positive overall causal relationship between climate change and violent conflict, as assumed.

The analyses show that at an abstract level different scenarios can be considered that can be applied to describe the interdependencies of vulnerability, adaptive capacity, exposure, and the climate-conflict-sensitivity of a society, which are characteristic indicators to depict the climate change impacts on society. Further sociological research is required to explain and understand the social mechanisms and behavior underneath these summarizing indicators, which are triggered by progressing climate change and may result in climate change-induced violent conflict.

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