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Review

Bridging the gap between impact assessment methods and climate science

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ABSTRACT

Life-cycle assessment and carbon footprint studies are widely used by decision makers to identify climate change mitigation options and priorities at corporate and public levels. These applications, including the vast majority of emission accounting schemes and policy frameworks, traditionally quantify climate impacts of human activities by aggregating greenhouse gas emissions into the so-called CO_2-equivalents using the 100-year Global Warming Potential (GWP100) as the default emission metric. The practice was established in the early nineties and has not been coupled with progresses in climate science, other than simply updating numerical values for GWP100. We review the key insights from the literature surrounding climate science that are at odds with existing climate impact methods and we identify possible improvement options. Issues with the existing approach lie in the use of a single metric that cannot represent the climate system complexity for all possible research and policy contexts, and in the default exclusion of near-term climate forcers such as aerosols or ozone precursors and changes in the Earth's energy balance associated with land cover changes. Failure to acknowledge the complexity of climate change drivers and the spatial and temporal heterogeneities of their climate system responses can lead to the deployment of suboptimal, and potentially even counterproductive, mitigation strategies. We argue for an active consideration of these aspects to bridge the gap between climate impact methods used in environmental impact analysis and climate science.

1. Introduction

Human activities perturb the climate system through a variety of forcing agents. Over the industrial era, the total anthropogenic radiative forcing, a measure of the net energy imbalance of the Earth caused by a forcing agent, is 2.29 [1.13–3.33] $W\,m^{-2}$ (Myhre et al., 2013). The major contributors are carbon dioxide (CO_2) and methane

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(CH_4) emissions, which are responsible for about $1.68 \pm 0.17\,W\,m^{-2}$ and $0.97 \pm 0.17\,W\,m^{-2}$, respectively (Myhre et al., 2013). The net contribution from so-called Near-Term Climate Forcers (NTCFs), that is, species with an atmospheric lifetime of less than about one year, is estimated to be a slight negative forcing (cooling) of $-0.06\,W\,m^{-2}$ (Myhre et al., 2013), with large uncertainty bounds largely due to the lack of scientific understanding of aerosol-cloud interactions (Boucher et al., 2013). The contributions from the direct forcing effect of single NTCFs range between $-0.41 \pm 0.20\,W\,m^{-2}$ for sulphur oxides (SO_x) emissions and +0.64 [+0.25 to +1.09] $W\,m^{-2}$ for black carbon (BC) emissions (Myhre et al., 2013). The radiative forcing values from historical land use changes for CO_2 and surface albedo (the ratio between reflected and incident solar radiation at the surface) are of the same order of magnitude but opposite sign, with a warming effect of 0.17–0.51 $W\,m^{-2}$ for CO_2 (1850–2000) and a cooling effect of $-0.15 \pm 0.10\,W\,m^{-2}$ for surface albedo changes (1750–2011) (Myhre et al., 2013). The net effect from changes in emissions of biogenic volatile organic compounds (BVOCs) associated with this land use change is estimated to be an additional cooling contribution of $-0.11 \pm 0.17\,W\,m^{-2}$ (1850–2000) (Unger, 2014a).

Life cycle assessment (LCA) and carbon footprints are largely used to attribute climate change impacts to specific human activities like products, technological systems, or sectors (Hellweg and Milà Canals i, 2014). Decision and policy makers widely rely on the outcomes from comparative climate impact analyses to promote mitigation options, and to design strategies for sustainable production and consumption at a public or corporate level. The most common approach is to aggregate emissions of well-mixed greenhouse gases to so-called "CO_2-equivalents" using the 100-year global warming potential (henceforth GWP100) as the default emission metric. A similar procedure is frequently applied in international agreements, like the Kyoto protocol, the Intended Nationally Determined Contributions (INDCs) for mitigation obligations to 2030 and climate-oriented policy directives, such as those regulating the climate impacts of specific sectors. This practice does not take into account the impacts from emissions of NTCFs or biophysical factors arising from changes in land cover. It also overlooks the temporal and spatial heterogeneities of the climate system response to different forcing agents, and the consideration of emission metrics alternative to GWP100. Studies that have explored the influence of NTCFs (Peters et al., 2011a; Tsao et al., 2012), of changes in surface albedo (Cherubini et al., 2012a; Caiazzo, 2014), of temporal and spatial impact dynamics (Levasseur et al., 2010; Lund et al., 2014; Cherubini et al., 2012b), and of metrics other than GWP100 (Peters et al., 2011b; Reisinger and Ledgard, 2013; Cherubini et al., 2013; Edwards and Trancik, 2014; Ledgard and Reisinger, 2014) on the climate impacts attributed to a specific human activity usually conclude that an international effort on improving existing methods is desirable to prevent the implementation of suboptimal mitigation pathways.

The Life Cycle Initiative under the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) launched the Global Guidance on Environmental Life Cycle Impact Assessment Indicators to revise existing standard methodologies used in environmental impact categories of LCA and footprint studies (Jolliet et al., 2014; Frischknecht et al., 2016), including climate change. Here, as part of the activities from the Global Warming Task Force, we identify key insights from the climate science related literature that are of relevance for advancing climate impact assessment frameworks.

2. Life cycle impact assessment and emission metrics

The life cycle impact assessment phase consists in the conversion of different well-mixed greenhouse gases (WMGHGs) to common units (kg CO_2-eq) after multiplication of each emission flow by the respective emission metric (Hellweg and Milà Canals i, 2014). Emission metrics, which in LCA are usually referred to as characterization factors, are typically simplified measures of the climate system response to forcing agents and are mostly based on outcomes from physical models of varying complexity linking emissions to impacts (Myhre et al., 2013). Metrics can be formulated in absolute terms, for instance based on the temporal evolution of a temperature impact, or in relative terms after normalization to a reference gas, usually CO_2 (Peters et al., 2011a,b; Tanaka et al., 2013). Different emissions have different climate system responses, and a metric that establishes equivalence with regard to one effect does not usually result in equivalence with regard to other effects.

GWP is an integrative measure defined as the integrated radiative forcing of a gas between the time of emission and a chosen time horizon (TH) relative to that of CO_2. The GWP was introduced by the first IPCC assessment report in 1990 with illustrative purposes and, by its own definition, it does not embed any climate system responses or direct link to policy goals (Myhre et al., 2013). Despite the rather cautious introduction by the IPCC, the United Nations Framework Convention on Climate Change, LCA and the majority of national and corporate emission accounting frameworks started to use this metric without any substantial modifications, with the exception of updating the GWP values according to the successive IPCC reports.

GWP is a metric that aligns well with the general principles of LCA. LCA privileges impacts integrated over time and space under the objective of avoiding burden shifting of impacts (Hellweg and Milà Canals i, 2014). LCA also typically follows a "marginal change" approach, in the sense that an additional amount of a certain pollutant is assumed to introduce very small changes on top of a constant background. This approach allows the assessment of environmental impacts associated with the life cycle impacts of a single unit of a product, which gives only a small contribution to the total impact (Huijbregts et al., 2011). Common critiques to GWP concern the fact that, despite its name, it does not equate climate forcing agents on the basis of their effects on surface temperature, nor does it consider them under a specific climate policy target, such as the goal to limit warming to 2 ° above pre-industrial levels (Tanaka et al., 2013; Fuglestvedt et al., 2010; Tanaka et al., 2010; Tol et al., 2012). The use of a TH of 100 years seems to be the result of an "inadvertent consensus" (Shine, 2009) and it is not directly linked to any particular climate policy objective. There are many emission metrics available from the climate science literature that focus on different characteristics of the climate system response to emissions (Reisinger and Ledgard, 2013; Tanaka et al., 2013, 2010; Fuglestvedt et al., 2010; Joos et al., 2013; Peters et al., 2011a; Shine et al., 2005; Azar and Johansson, 2012). By targeting different aspects of the climate impact cause-effect chain, such as radiative forcing (Unger, 2010), temperature (Shine et al., 2005; Azar and Johansson, 2012), sea level rise (Sterner et al., 2016), precipitation changes (Shine et al., 2015), or economic dimensions (Johansson, 2012), these metrics compare emissions on the basis of their instantaneous (Shine et al., 2005) or time integrated impacts (Peters et al., 2011a; Azar and Johansson, 2012). They are computed under a constant (Myhre et al., 2013; Joos et al., 2013) or changing (Tanaka et al., 2013; Reisinger et al., 2011) background climate and can be formulated around a fixed or a target-dependent TH (Edwards and Trancik, 2014; Tanaka et al., 2013; Shine et al., 2007; Jørgensen et al., 2014). A common alternative to GWP is the Global Temperature Change Potential (GTP), which is defined as the impact of a GHG emission pulse on global temperature at the chosen TH, again relative to CO_2 (Shine et al., 2005). With the exception of some gases with very short lifetimes, values of GTP for a TH of about 40 years are usually similar to those of GWP100 (Allen, 2015). Recently, GWP100 is shown to approximately equate