How to compare different short-lived climate forcers – a review of emission metrics

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Summary

In the context of climate change, emissions of different species (e.g. carbon dioxide and methane) are not directly comparable since they have different radiative efficiencies and response times. Since comparisons via detailed climate models are computationally expensive and complex, emission metrics were developed to allow a simple and direct comparison of the climate impacts of the emissions of different species. Because design and application of emission metrics depend on a variety of choices, a variety of different metrics may be used and often with different time-horizons. In this report, we review the current status of emission metrics and provide several illustrative examples using Norwegian emissions. We focus on emission metrics most relevant for comparing the climate effect of different short-lived climate forcers (SLCFs), but also comparing SLCFs with long lived greenhouse gases (LLGHGs). We cover in detail climate metrics based on radiative forcing (RF), integrated radiative forcing (Absolute Global Warming Potential, AGWP), temperature change (Absolute Global Temperature change Potential, AGTP), and integrated temperature change (integrated Absolute Temperature change Potential, iAGTP) in both absolute form and normalized to a reference gas. We briefly discuss several other less common, but relevant, emission metrics. We consider pulse emissions, sustained emissions, and emission scenarios. The species are separated into three groups: species with a simple exponential decay (single time scale), CO_2 which has a complex decay over time (multiple time-scales), and the ozone pre-cursors (NO_x, CO, VOC). When selecting a metric, it is important to have a clear understanding of what policy the metric is meant to serve. Based on this policy goal, different choices must be made. The main choices are 1) use an instantaneous or integrated metric, 2) what impact parameter to use, and 3) for what time horizon.

This report was prepared in response to a request from the Norwegian Climate and Pollution Agency (Klif), which has funded the work. We summarize our findings by discussing appropriate metrics for future work by Klif on SLCFs. Climate policy is not necessarily based on one and only one goal. The UNFCCC expresses, for example, a long-term goal to constrain anthropogenic climate change, while at the same time expressing a short-term goal that focus on rate of climate change. If the long-term goal is to prevent a 2 °C warming, then the AGTP is a suitable metric and this could be supplemented by using a variable time horizon as the target year is approached. For a short-term goal, AGTP with e.g. 10-20 year time horizon may be chosen. Both SLCFs and LLGHGs should be considered for in all goals, as even SLCFs can have long-term effects and LLGHGs can have short term effects. Regardless of metric and time horizon selected, CO_2 is a major component of the total Norwegian climate impact.

1 Introduction

The Norwegian Climate and Pollution Agency (Klif) called in early April 2012 for a project to summarize different methods to estimate the climate effect of various short lived climate forces, and to evaluate which of the methodologies that is best suited to be included in Klif's work on an Action plan for SLCF. This report presents the outcome of the project.

Multicomponent climate policies require a method to compare the climate impact of emissions of different species (Fuglestvedt et al., 2003). While it is most common to compare different long-lived greenhouse gases (LLGHGs), e.g., CO_2 and N_2O, it is also often desired to compare short-lived climate forcers (SLCFs), e.g. black carbon (BC) and organic carbon (OC), and to compare LLGHG and SLCF, e.g., CO_2 and BC . Different species have different radiative efficiencies and remain resident in the atmosphere for different time scales (Forster et al., 2007). Thus, a direct comparison of species by

weight does not indicate the climate impact. A common method of comparing emissions is with Radiative Forcing (RF), though the RF does not capture the temporal trends of the emissions or climate system in either backward- or forward-looking perspectives. The most common emission metric used today is the Global Warming Potential (GWP), which compares the accumulated radiative forcing of a pulse emission of a given species relative to the accumulated forcing of a pulse emission of CO_2. Thus, the GWP captures differences in the RF of different species and additionally includes the variations over time by indirectly incorporating the atmospheric decay of the different species.

The GWP was originally proposed as an "illustrative example" in the IPCC First Assessment Report (IPCC, 1990) and has since been critiqued from many angles, particularly related to its interpretation and application (Victor, 1990; Fuglestvedt et al., 2000; Smith and Wigley, 2000a; Smith and Wigley, 2000b; Manne and Richels, 2001; Fuglestvedt et al., 2003; Shine, 2009; Manning and Reisinger, 2011). In response to the critiques of the GWP, several alternatives have been proposed. The next most common metric in use today is the Global Temperature change Potential (GTP) (Shine et al., 2005; Shine et al., 2007). The GTP compares the temperature change at a point in time due to a pulse emission relative to the temperature change due to a pulse emission of CO_2. The GTP attempts to additionally include the temporal behavior in the climate system, overcoming a key weakness of the GWP.

Various other emission metrics have been proposed, but are in less common usage and have only had limited applications (Tanaka et al., 2010). All of the IPCC Assessment Reports have had a section on emission metrics (IPCC, 1990; IPCC, 1995; IPCC, 2001; IPCC, 2007), and several other IPCC related reports have contributed additional background information (Isaksen et al., 1992; Enting et al., 1994; IPCC, 1994). In this report, we summarize the main emission metrics, and the key assumptions used to estimate the metrics. Several illustrative examples are provided to demonstrate the use of different emission metrics in the case of Norway.

2 Overview of emission metrics

Emission metrics can be used in several ways (Fuglestvedt et al., 2003; Tanaka et al., 2010), but the most common are to 1) compare the climate impacts of different species' emissions, 2) provide an "exchange rate" on how to weight the emissions of different species for mitigation policies, as in the Kyoto Protocol, and 3) perform comparisons of different activities and technologies that emit species at different rates such as in Life Cycle Assessment. Due to the variety of applications, there is no obvious need to have one single metric for all applications, and a range of different metrics may even be used in one application.

It is worthwhile to start with a general formulation of an emission metric (Kandlikar, 1996; IPCC, 2007)

$$AM_i = \int_0^H \left[\left(I\left(\Delta C_{r+i}(t)\right) - I\left(\Delta C_r(t)\right) \right) g(t) \right] dt \qquad (1)$$

where *AM* is an absolute metric, $I(\Delta_i(t))$ is a function describing the "impact" of a change in climate (e.g., concentration, temperature, precipitation), ΔC, at time t, with a discount function, $g(t)$, and compared to a reference system, r, on which the perturbation occurs, i. The discount function can represent a fixed time-horizon using a step-function (such as in most integrated metrics like the GWP) or instantaneous evaluation using a Dirac delta function (such as in most end-point metrics like the

GTP). The use of a step-function for a fixed time-horizon can also be expressed as a standard exponential decay, though different species have different discount rates (Fuglestvedt et al., 2003). The use of a Dirac delta function for end-point metrics has the function of removing the integral and evaluating the integral at the time horizon. The time horizon, H, can take any value between 0 and infinity.

For the different applications of emission metrics, either an absolute metric (AM) or normalized metric (M) is used. To compare two emission perturbations *i* and *j*, the climate impact can be compared as a function of time using AM_i and AM_j. A normalized metric

$$M_i(t) = \frac{AM_i(t)}{AM_j(t)} \quad (2)$$

is made relative to a reference gas (j), usually CO_2, and puts the emissions of two components into the same units, usually called "CO_2-equivalents." The normalized metric value can be considered as a conversion factor from the unit of the emission (e.g., kg CH_4) to the "equivalent" emission of CO_2 that could lead to the equivalent climate impact for the given TH and underlying assumptions; $E_j(CO_2\text{-eq}) = E_j.M_j$. However, for GWP100, the only parameter that is equivalent is the integrated RF over 100 years. Emissions that are equal in terms of CO_2 equivalents are not necessary equal in terms of response at all times. CO_2-equivalents can be derived for all emission metrics. The choice of reference gas is difficult, and the long-time behavior of CO_2 is one of the main reasons for needing a value-based TH in normalized emission metrics (IPCC, 1990; Lashof and Ahuja, 1990).

Several studies have also used a time-varying TH, where the TH changes as it moves towards a target year (TE), TH=TE-t (Shine et al., 2007). The time-varying metric shows the characteristic features of many emission metrics from the economic literature (Manne and Richels, 2001; Johansson, 2012).

We discuss different emission metrics based around the use of Equation (1). While seemingly abstract, the application of Equation (1) can be applied by following some simple steps, and here we give an illustrative example of concentration and radiative forcing. An emission into the atmosphere leads to an increase in the atmospheric concentration of that component. This perturbation (change) in the atmospheric concentration decays back to zero after some time dependent on how quickly the species is removed from the atmosphere, which is described by an impulse response function (IRF). Due to chemical reactions in the atmosphere, some emissions of one type of component can lead to an increase or decrease in the concentration of another type of component (e.g., ozone precursors). While the species is resident in the atmosphere, the increased atmospheric concentration of the species causes an additional radiative forcing, which for emission metrics is usually expressed in a linearized form using the radiative efficiency. A radiative forcing can also be caused by indirect effects (e.g., aerosol effects on clouds). The "impact", *I*, is, thus, governed by the temporal evolution of the radiative forcing, which is dependent on the radiative efficiency and removal rate from the atmosphere leading to $\Delta C(t)$. The "impact" can be directly related to the forcing, or additional models can be used to quantify the climate impact desired. All these terms are explained further below.

All the parameters used in the metrics are defined in Table 1. In the following we present the equations for emission pulses as this is most common for emission metrics, since these can be used as building blocks for other applications. However, we later discuss the equations and results for sustained emissions and emission scenarios. The metrics presented here are not fixed in time, as values are updated due to new scientific knowledge or changes in atmospheric lifetimes and

radiative efficiencies caused by changing atmospheric conditions. As a consequence, the metric values are usually updated in the IPCC reports. Since CO_2 is the reference gas, an update for CO_2 will alter all metrics.

Table 1: Parameters used in the metric equations.

Time horizon (years)	H
Radiative efficiency ($W(m^2kg)^{-1}$); radiative forcing due to a marginal increase in atmospheric concentration	A_x
Parameters for the exponential Impulse Response Function (IRF) for atmospheric decay of each species	
Weight on each exponential (unitless)	a_i, $\Sigma a_i=1$
Decay times of each exponential (years)	τ_i
Number of exponentials (unitless)	I
Parameters of the exponential Impulse Response Function (IRF) of the climate model response to pulse radiative forcing	
Components of the climate sensitivity ($K(Wm^2)^{-1}$)	c_j, $\lambda= \Sigma c_i$
Decay times due to each component of c_i (years)	d_j
Number of decay terms (unitless)	J

2.1 Impulse Response Function (IRF)

Once pollutants are emitted into the atmosphere, the pollutants will initially increase the atmospheric concentration before gradually being removed from the atmosphere leading to a decrease in concentration. In simple representations, the removal from the atmosphere for a pulse emission can be represented by a single or a sum of exponentials. The sum of exponentials is particularly useful as they can be used in convolutions to represent the behavior of arbitrary emissions scenarios (Wigley, 1991; Enting, 2007), be converted into a set of differential equations for efficient solutions (Wigley, 1991), and in some cases the time scales in the IRF have physical interpretations (Li and Jarvis, 2009; Li et al., 2009). Most species can be represented by a single time-scale, though CO_2 is usually represented using multiple time-scales (IPCC, 2007). For some species represented with one time-scale, the underlying physical processes may operate on different time-scales (see later).

2.1.1 Multiple time-scales (CO_2)

For CO_2, the IRF is usually represented with multiple time scales (Archer et al., 2009), and it is assumed a fraction remains in the atmosphere indefinitely (i.e. beyond the timescales of centuries),

$$IRF_{CO_2}(t) = a_0 + \sum_{i=1}^{I} a_i exp\left(-\frac{t}{\tau_i}\right) \quad (3)$$

where $\Sigma a_i=1$, though it is not clear if the time scales can be interpreted as representing physical processes (Li et al., 2009). The decay of CO_2 does not reach zero at infinity with existing IRFs, as opposed to the other species. This is a result of the non-linear kinetics of the CO_2 perturbation, slow ocean circulation, and slow uptake of CO_2 in the land reservoir on geological timescales. The literature suggests that "about 50% of an increase in atmospheric CO_2 will be removed within 30 years, a further 30% will be removed within a few centuries and the remaining 20% may remain in the atmosphere for many thousands of years" (IPCC, 2007; Archer et al., 2009). As the climate changes, the IRF will also change, as higher concentration of carbon in the ocean will reduce the

oceans ability to absorb carbon (Caldeira and Kasting, 1993) and as land and ocean will take up less CO_2 in a warmer climate (Friedlingstein et al., 2006).

The IRF for CO_2 that is most used in emission metrics is calculated based on the Bern Carbon cycle model (Joos et al., 2001) with the IRF experimental setup described by Enting et al. (1994), also see Figure 1 in Joos et al. (2012). In the specific case of the Fourth Assessment Report (IPCC, 2007), the IRF was estimated based on a two-step process, a control and perturbation run. First, for the control, the carbon cycle model is run with historical emissions until 2005, and from 2005 the emissions are calculated to keep a constant CO_2 concentration. Second, in the perturbation run, the emissions from the control are used but a large pulse emission (40GtC) is placed in 2010 and the model is allowed to run until near equilibrium. The IRF is based on the normalized version of the difference between the perturbation and control run, after which a sum of exponentials is fitted. In the decay parameterization, the short and medium time scales (1.2 and 18.5 years) can be loosely interpreted as the uptake in land biosphere and the surface layer of the ocean, the long time scale (172.9 years) loosely interpreted as the surface layer mixing with the deep ocean, and the infinite time scale represents slow geological processes. In connection with AR5, a new study will update the IRF to present conditions, see Joos et al. (2012). This work will produce a new IRF.

Uncertainties in the carbon cycle and in the experimental set up, both have a large affect on the IRF (Enting et al., 1994; IPCC, 1994; Wuebbles et al., 1995; Archer et al., 2009; Eby et al., 2009; Reisinger et al., 2010). Different carbon cycle models lead to large differences in the air-borne fraction after 500 years (up to 0.2) and also the decay parameters in the IRF (Enting et al., 1994, Figure 9.1; IPCC, 1994, Figure 5.4; Archer et al., 2009). Carbon cycle feedbacks can also lead to a large spread in the response of the carbon cycle (Friedlingstein et al., 2006) and consequently metric values (Gillett and Matthews, 2010). Reisinger et al. (2010) estimated the uncertainty associated with CO_2 to be about 25% for AGWP with a 100 year time horizon and about 35% for AGTP with a 20 year time horizon. Otherwise, we are not aware of studies which quantify this uncertainty and variation between models.

Metric values also vary as a function of time as the background atmospheric concentration is constantly changing. With higher background concentration, the IRF has a larger airborne fraction as less carbon can be absorbed by the ocean, but at the same time absorption bands become saturated leading to a decrease in the radiative efficiency. Caldeira and Kasting (1993) argued that these two effects cancel each other out, making the AGWP nearly independent of CO_2 emission scenarios. Reisinger et al. (2011) show that the radiative efficiency of CO_2 will decrease in the future using Representative Concentration Pathways (RCPs), while the reduction in forcing will only be partly offset by increasing carbon cycle feedbacks. Thus, AGWP values will decrease as the background concentration increases.

2.1.2 Single time-scales (everything other than CO_2)

All other species used in simple emission metrics decay with a parameterized based on a simple exponential function:

$$IRF_x(t) = exp\left(-\frac{t}{\tau}\right) \quad (4)$$

Though, in practice, the decay may happen on different time scales for different processes. N_2O removal in the atmosphere is mainly due to photolysis in the stratosphere. Particles, such as black carbon, are removed by wet and dry deposition in the atmosphere, hence the process can be strongly regionally dependent (Berntsen et al., 2006; Shindell and Faluvegi, 2009). CH_4 is removed from the atmosphere from three processes (IPCC, 2001; Boucher et al., 2009): 1) around 88% is removed by reacting with hydroxyl radicals in the troposphere, 2) 7% is destructed in the stratosphere, and 3) 5 % is removed by bacteria in the soil. These three processes act on different time scales, but can be represented by one time scale by connecting a system of first order differential equations leading to the lifetime

$$\frac{1}{\tau} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3} \quad (5)$$

The common ozone precursors (NO_x, CO, VOC) used in emission metrics are based on more detailed calculations and this is discussed in more detail below. Uncertainties in the lifetimes are due to uncertainties in the emission estimates and atmospheric chemistry (Prather et al., 2012).

2.1.3 Temperature

For emission metrics that link from radiative forcing to temperature, an IRF is needed, IRF_T , for the temperature response to an instantaneous unit pulse of radiative forcing. A simple exponential parameterization is usually used,

$$IRF_T(H) = \sum_{j=1}^{J} \frac{c_j}{d_j} exp\left(-\frac{H}{d_j}\right) \quad (6)$$

where *c* are the components of the climate sensitivity and *d* the corresponding time scales time scale. IRF_T can be mapped to a simple box-diffusion energy balance model (Li and Jarvis, 2009; Peters et al., 2011). The exponential term with the shortest time scale maps to the mixed atmosphere-ocean later, the next largest time scale maps to the next deepest ocean layer and so on. The climate sensitivity can be determined by estimating the equilibrium response to a step forcing (sustained forcing),

$$\lambda = \int_0^\infty IRF_T(t)dt = \sum_{j=1}^{J} c_j \quad (7)$$

The parameters for IRF_T are usually calculated as a response in the global temperature to a pulse of radiative forcing, or experiments that allow a pulse to be estimated such as the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (C3MIP) and phase 5 (C5MIP) 1% increasing CO_2 emission scenarios (Olivié et al., 2012). Most temperature based emission metrics used an IRF based on the Hadley model (Boucher and Reddy (2008)) response to a 1% yearly increase in CO_2 emissions until 70 years after which the concentration is held constant for 1000 years. The parameters are derived from a curve fit to the results.

2.2 Radiative efficiencies

Once a species is in the atmosphere and contributes to an increase in the atmospheric concentration of that component, it can cause a new radiative imbalance of energy into the earth system. The radiative forcing is usually calculated by complex radiative transfer models (Forster et al., 2007), but for emission metrics simplifications are usually made based on the current state of the atmosphere. The radiative forcing is defined as the change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while surface and tropospheric

temperatures and state are held fixed at the unperturbed values (IPCC, 2001; Hansen et al., 2005). The radiative efficiency is a linearization of the forcing and is defined as the radiative forcing due to a 1 kg increase in the concentration of a trace gas. The forcing is non-linear for CO_2, CH_4, and N_2O, but linear for many other trace gases.

In many papers, the radiative efficiency is shown in $W/m^2/ppb$, while for calculations it is necessary to use $W/m^2/kg$. The conversion factor from ppb to kg is

$$C_X(kg) = \left(\frac{M_A}{M_X}\right) \times \left(\frac{10^9}{T_M}\right) \times C_X(ppb) \quad (8)$$

where M_A is the mean molecular weight of air (28.96 kg/kmol), M_X molecular weight of molecule X, and T_M total mass of the atmosphere (5.15×10^{18} kg).

2.2.1 Carbon Dioxide (CO_2)

The radiative forcing for CO_2 can be approximated using the expression based on radiative transfer models (Myhre et al., 1998),

$$RF = \alpha \ln\left(\frac{C}{C_0}\right) \quad (9)$$

where C_0 is the current concentration of CO_2 in the atmosphere, $C>C_0$ is the atmospheric concentration at some time in the future, and $\alpha=5.35$ is a constant. This equation is accurate to within 10% (IPCC, 2007). The radiative efficiency is usually estimated using the current atmospheric conditions, C_0, for example, taken for year 2005 in IPCC AR4 (Forster et al., 2007). Since the emission metrics are usually based on a constant background, the radiative efficiency is usually taken as constant. For scenarios, the radiative efficiency will change as a function of time, though the changes are partially offset by changes in the IRF as a function of time (Caldeira and Kasting, 1993; Reisinger et al., 2011).

The radiative efficiency of CO_2 is estimated as the marginal change in RF with concentration, and is thus the derivative of Equation (9),

$$A_{CO_2} = \left.\frac{d(RF)}{dC}\right|_{C=C_0} = \frac{\alpha}{C_0} \quad (10)$$

Since the atmospheric concentration of CO_2 is increasing, the radiative efficiency of CO_2 becomes smaller with time and is, therefore, usually updated in the IPCC reports.

2.2.2 Methane (CH_4), Nitrous Oxide (N_2O), and other gases

The radiative forcing estimates of CH_4 and N_2O are based on radiative transfer models (Myhre et al., 1998; IPCC, 2001) and are parameterized similar to CO_2. The formulas are found in IPCC (2001).

The radiative efficiency for other LLGHGs with low atmospheric concentrations, such as hydrochlorofluorcarbons and hydrofluorocarbons, are calculated from the measured infrared absorption spectra of those species (Pinnock et al., 1995; Hodnebrog et al., Submitted).

2.2.3 Short-Lived Climate Forcers

The radiative efficiency for short-lived components is based on chemical transport models and forcing calculations (IPCC, 2007; Fuglestvedt et al., 2010). The common approach to calculate the

radiative efficiency is to run a model perturbation which removes all emissions of one species at a time and then calculates the difference in radiative forcing between this perturbed case and the reference simulation with all anthropogenic emissions. The radiative efficiency is, then, calculated based on emissions and resulting forcing.

For some species, there are some non-standard issues in calculating the radiative efficiency. These issues can be due to less scientific knowledge leading to larger uncertainties, whether to include indirect effects, or regionality in the emission to response relationship (see Section 2.3). For BC, there is an indirect effect of BC on snow and ice as BC reduces the albedo of such surfaces (Jacobson, 2001; Hansen and Nazarenko, 2004; Rypdal et al., 2009). We have not included the snow albedo effect in the BC metric values presented, which would increase the impact by 10-15% globally (Rypdal et al., 2009; Bond et al., 2011) and even more for Norwegian emissions. Aerosols have indirect effects, which is especially large for sulfate. The literature indicates that the indirect effect of sulfate is likely much larger than the direct effect for shipping and almost as large for land-based emissions (50-100%) (IPCC, 2007). Aviation leads to indirect impacts including formation of contrails and aviation induced cirrus (AIC). These indirect effects have large uncertainties and their impact will vary greatly due to different flight paths; shorter flights spend less time in the critical elevation zone for these processes to occur. The uncertainty on the forcing of contrails in the order of 1.5 to 2 and for AIC about an order of 3 (Fuglestvedt et al., 2010). Further, the uncertainty in the parameterization of the ozone pre-cursors is large, especially for NO_x. For the SLCFs, location of the emissions matter for the forcing (Berntsen et al., 2006) as does the location of the forcing for the climate impact (Shindell, 2012); hence, a global average radiative efficiency number will deviate from actual radiative efficiencies at different locations.

2.3 Regional issues

Two aspects of regionality are important: first, the link from emissions to radiative forcing and second, from radiative forcing to temperature. First, while the location of emissions does not have an impact on the RF for LLGHGs, it does for SLCFs (Fuglestvedt et al., 1999; Naik et al., 2005; Berntsen et al., 2006; Shindell and Faluvegi, 2009), leading to a more distinct region distribution of RF (Berntsen et al., 2006; Bond et al., 2011). Second, for forcings from both SLCFs and even the relatively homogeneous ones caused by LLGHGs, there is a distinct pattern in the temperature response controlled largely by the response pattern of the climate feedbacks (Boer and Yu, 2003; Shindell and Faluvegi, 2009; Shindell, 2012). Thus, the temperature response is not necessary strongest in the region where the emissions are largest, and an emission in one region may cause a temperature response in other regions.

Regionality can be investigated by looking at latitudinal bands. A schematic presentation of this regionality issue is given in Figure 1. While the regional emission-forcing relationship is rather well known, there are large uncertainties in the regional forcing-temperature relationship. More research is needed to get robust numbers for the regional forcing-temperature relationship. Those SLCFs that have an atmospheric residence time of a couple of weeks or less will not have time to be evenly distributed in the global atmosphere and, hence, result in the largest atmospheric perturbations near the point of emission and its latitude band. In general, strong climate feedbacks due to snow and ice cover at higher latitudes increase the temperature perturbations from forcings, with about 45 % enhancement for extratropical relative to tropical CO_2 forcing (Shindell and Faluvegi, 2009).

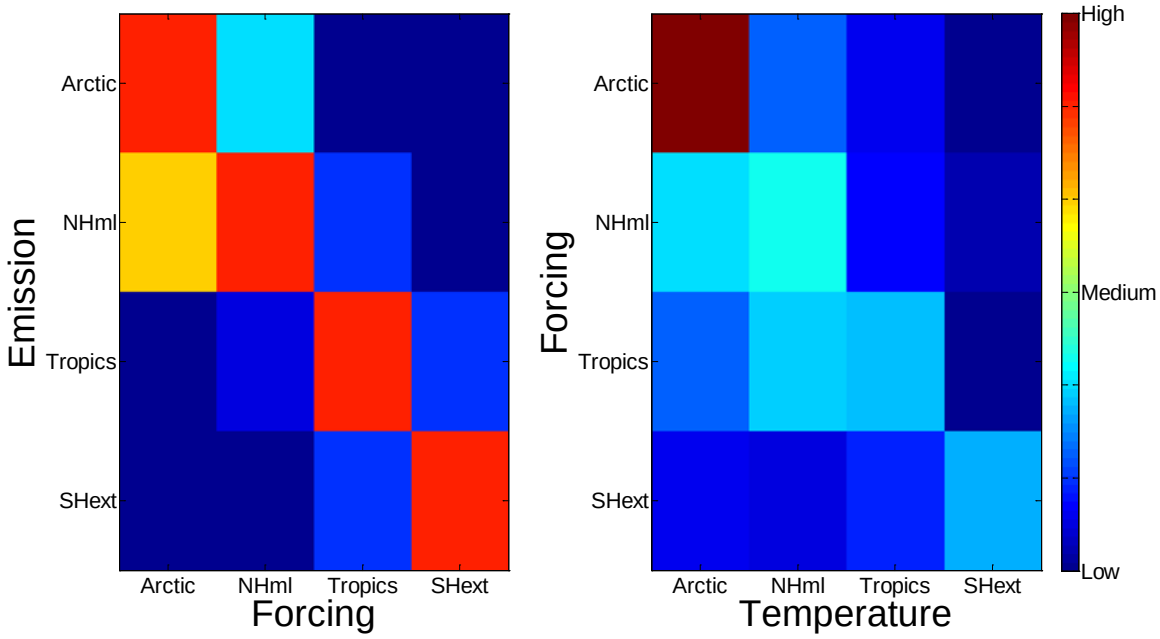

Figure 1: A schematic regional relationship between emission, forcing, and temperature perturbation for SLCFS for the regions: The Southern Hemisphere extratropics (90-28° S, SHext), the tropics (28° S-28° N), the Northern Hemisphere mid-latitudes (28-60° N, NHml), and the Arctic (60-90° N). Values for the emission-forcing relationship is inspired by Naik et al. (2005) and the forcing-temperature relationship is based on Shindell (2012). The uncertainties are largest for the latter relationship. The forcing-temperature relationship will differ for different pollutants due to different processes in the climate system. These figures should be read by starting on the left side and, then, choose what regions to see the response for, which is labelled on the bottom. If we look at Norwegian emissions, we should start with Arctic emissions (60-90°C). If we are only interested in the forcing in the Arctic, we have to look at the square that combines Arctic emissions with Arctic forcing. That is the top left square of the figure. If we are interested in the global forcing from Norwegian emissions, we have to sum the forcing from all regions. In this specific case, that would be the top row (horizontal). Most of the forcing would occur in the Arctic, some in the middle latitudes of the Northern Hemisphere, while very little in the Tropics and Southern Hemisphere. The forcing-temperature figure has to be used the same way. If the global temperature reponse of Norwegian emissions is of interest, all squares in the right hand side figure have to be summed since the emissions will potentially give forcing in all four latitude bands. As these numbers become more robust, these relationships will be an improvement compared to a metric that is global, and, thus, does not consider the location of the emissions.

Some studies also focus on regional metrics (Lund et al., 2011). Shindell and Faluvegi (2009) separate the world into four latitude bands. While there is a strong understanding of the climate system on a global scale, the uncertainties are much larger for regional responses. Hence, large regions for metric calculations give more confidence than small regions. Thus, metrics for latitude bands or continents are currently more appropriate than metrics for individual countries. In addition, the regional emissions have to be large enough to get a signal in climate models for metric values to be estimated. The metrics presented here can be expanded to regional metrics by using regional values for the metric parameters, but the level of detail will depend on the current state of knowledge. For Norwegian emissions, it might be reasonable to use a 60-90 °N emission band in future metric calculations. A good set of values for such calculations does not exist today, but can be made in future work. A further division of Norway into smaller regions with different response sensitivities will be difficult due to the issues discussed above.

2.4 Absolute metrics

We here present the absolute terms of different metrics. For each metric, we show the mathematical formulation for simple exponential decay species as examples. The parameterizations for CO_2 and ozone pre-cursors are similar, and the mathematical formulation for those species can be found in Aamaas et al. (2012). The impact of ozone is not given an own metric since the ozone effect is caused by emissions of other species (CH_4, NOx, CO, and VOC). Hence, the impact of ozone is included in metrics for those ozone pre-cursors.

2.4.1 Radiative forcing (RF) as function of t

For emission metrics, the radiative forcing (RF) for all components is calculated as

$$RF = radiative\ efficiency\ \times IRF. \tag{11}$$

In the context of Equation (1), the impact is RF, and the discount is a Dirac delta function at time *t* implying an end-point metric. The RF for pollutants with a simple exponential decay is

$$RF_x(t) = A_x exp\left[-\frac{t}{\tau}\right] \tag{12}$$

where *Ax* is the radiative efficiency, which is assumed constant, and τ is the atmospheric lifetime of the pollutant. For CO_2, a sum of exponentials is used (Joos et al., 2012). The radiative forcing can also depend on the forcing agent, leading to the efficacy, which is defined "as the ratio of the climate sensitivity parameter for a given forcing agent (λ_i) to the climate sensitivity parameter for CO_2 changes, that is, $\varepsilon_i = \lambda i / \lambda_{CO2}$ (IPCC, 2007). Efficacies can vary by around 25%, and can be used to modify the *RF* so that it more closely resembles the temperature response to a given forcing. Fuglestvedt et al. (2003) proposed, and Berntsen et al. (2005) applied, the efficacy concept to the simple emission metrics to be discussed below.

2.4.2 Absolute Global Warming Potential (AGWP)

The absolute global warming potential (AGWP) for species *i* is the integrated radiative forcing,

$$AGWP_i(H) = \int_0^H RF_i(t)dt \tag{13}$$

In the context of Equation (1), the impact is RF, with the discounting as a step function (no discounting for t<H and full discounting for t>H; hence, a weight function of 1 for t<H and 0 for t>H. Fuglestvedt et al. (2003) estimated an equivalent exponential discount function that gave the same AGWP and found that different species implicitly had different discount rates. The IPCC did not give a direct physical interpretation of the AGWP, but gave some tentative interpretations for three time horizons (20, 100, 500 years) (IPCC, 1990). They describe that for some environmental impacts it is important to evaluate the cumulative warming over an extended period after the emissions. For instance, the evaluation of sea level rise needs a time horizon of 100 years or longer. For short term effects, a time horizon of a few decades could be used, such as the response to radiative forcing over continental areas.

The absolute Global Warming Potential (AGWP) for pollutants with a simple exponential decay

$$AGWP_x(H) = A_x\tau\left(1 - exp\left(-\frac{H}{\tau}\right)\right) \tag{14}$$

2.4.3 Absolute Global Temperature change Potential (AGTP)

The absolute global temperature change potential (AGTP) for species *i* is global temperature change (ΔT) at time *t* (Shine et al., 2005) is,

$$AGTP_i(H) = \int_0^t RF_i(t) IRF_T(H-t)dt, \quad (15)$$

In terms of Equation (1), the AGTP is generally interpreted as temperature (the whole integral), as an end-point indicator (discounted using a Dirac delta function) with an evaluation time of *t*. It is also possible to interpret the AGTP with IRF_T as the discount function. A non-zero IRF represents the "discounting" or decay in the surface temperature response caused by the deep ocean (energy is partitioned between the surface ocean, deep ocean, and the share radiated back to space). If IRF_T=1, no discounting, which is the case for AGWP. According to the AGWP, a species with a short (hours, weeks, years) but strong forcing will have an impact indefinitely as the integration does not forget this forcing; in contrast, the AGTP will "forget" the forcing with while it is in the deep ocean or (eventually) radiated back to space (see Peters et al. (2011)).

The absolute Global Temperature Change Potential (AGTP) for pollutants with a simple exponential decay

$$AGTP_x(H) = \sum_{j=1}^{J} \frac{A_x \tau c_j}{(\tau - d_j)} \left[exp\left(-\frac{H}{\tau}\right) - exp\left(-\frac{H}{d_j}\right) \right] \quad (16)$$

It is possible to extend the AGTP into a regional form (c.f., Collins et al., 2012; Shindell, 2012),

$$ARTP_i^r(H) = \int_0^t \sum_s (K_i^{rs} RF_i^s)\, IRF_T(H-t)dt, \quad (17)$$

where *r* represents the region with the response, *s* the region of the forcing, and K^{rs} a matrix of scalars relating the RF in *s* to the response in *r*, see Figure 1. A similar expression is possible to link regional emissions with radiative forcing, and hence from regional emissions to regional response.

2.4.4 Integrated Absolute Global Temperature change Potential (iAGTP)

The integrated temperature change potential (iAGTP) for species *i* is the integral of the $AGTP_i$ (Peters et al., 2011),

$$iAGTP_i(H) = \int_0^t AGTP_i(t)dt, \quad (18)$$

In terms of Equation (1), the impact is temperature, and the discount function is no discounting for t<H and full discounting for t>H. The iAGTP has been discussed indirectly by some authors (O'Neill, 2000), but in more detail in Peters et al. (2011). Preliminary work on the GWP was based on integrated temperature change (Wuebbles, 1989; Derwent et al., 1990). The link to temperature, however, did not make it into the First Assessment Report (IPCC, 1990). Peters et al. (2011) investigated whether the GWP was similar to the iGTP and found close agreement for a wide range of time horizons, but not for very SLCFs like black carbon. The similarity is since AGWP represents the total energy added to the system (into the ocean) and iAGTP/λ the energy lost from the system (out to space). Since the energy currently in the atmosphere is much smaller than the energy added to the ocean (AGWP), it follows that AGWP is approximately iAGTP/λ. The reason is that the heat capacity of the ocean is much larger than of the atmosphere. Given these quantitative relationships, it is arguably better to interpret the AGWP as iAGTP.

The integrated absolute Global Temperature Change Potential (iAGTP) for species with a single decay time is

$$iAGTP_x(H) = \sum_{j=1}^{J} \frac{A_x \tau c_j}{(\tau - d_j)} \left[\tau \left(1 - exp\left(-\frac{H}{\tau} \right) \right) - d_j \left(1 - exp\left(-\frac{H}{d_j} \right) \right) \right] \quad (19)$$

2.5 Normalized metrics

The absolute metrics for a species are often normalized to an index of the climate response from a reference gas, normally CO_2,

$$M_x(t) = \frac{AM_x(t)}{AM_{CO_2}(t)} \quad (20)$$

where AM stands for AGWP, AGTP, or iAGTP and M is GWP, GTP, or iGTP, respectively. Hence, GWP for species *i* is defined as

$$GWP_i(H) = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt} \quad (21)$$

GWP is, thus, defined as the ratio of the time-integrated RF from a pulse emission of 1 kg of some compound *i* relative that of 1 kg of the reference gas CO_2. Similarly, GTP for species *i* is

$$GTP_i(H) = \frac{\Delta T(H)_i}{\Delta T(H)_{CO_2}} = \frac{\int_0^H RF_i(t) IRF_T(H-t)dt}{\int_0^H RF_{CO_2}(t) IRF_T(H-t)dt} \quad (22)$$

GTP is defined as the ratio of the global surface temperature change at time *H* after an emission of some compound *i* relative to the same amount of emissions of the reference gas CO_2. Emissions E_x can be converted into equivalent emissions of CO_2 by multiplying with this normalized metric,

$$CO_2eq(t) = M_x(t) \times E_x \quad (23)$$

that results in the same climate response for the given metric (O'Neill, 2000; Fuglestvedt et al., 2003). The GWP is the most common emission metric in use, probably since it is used to weight the LLGHG in the Kyoto Protocol. The AGWP is occasionally used, but often due to its connection with sustained emissions (see below). The AGTP and GTP are the next most common metrics, with both the absolute and normalized forms receiving attention.

In terms of weighting GHGs, a time-dependent version of the GTP has been developed, GTP(TE-t), where TE represents the year a temperature target is specified (e.g., 2 degree limit in 2100). The time-dependency puts more weight in SLCFs as the target is approached, a characteristic seen in many economic approaches (Manne and Richels, 2001; Johansson, 2012). This property may be a characteristic of moving towards a target, and not necessarily a characteristic of the economic model. The iAGTP and iGTP is a relatively new metric (Peters et al., 2011), with applications mainly in the interpretation of the AGWP and GWP.

The normalized metric is dependent on the absolute metric of CO_2, since the absolute metric of CO_2 is the denominator. For time horizons (H) less or around a species' lifetime (τ), GWP is affected by AGWP for both the species and CO_2, as both AGWPs are sensitive of time horizon. However, as time horizon increases, the changes in the GWP depend only on the changes in AGWP for CO_2.

2.5.1 Other metrics

While the presented metrics are the most used, there is a range of other metrics suitable for different areas of usage. Other metrics are used, but they are generally specific to a particular paper or application. In the following we summarize some of the main metrics, but do not go into extensive detail since they are not widely applied.

There are two metrics recently developed which are the same as the iAGTP. For a linear IRF, the 'surface temperature response per unit continuous emissions' (STRE) (Jacobson, 2010) is mathematically equivalent to the iAGTP. STRE is based on sustained emissions and cannot, therefore, be easily used for other emission scenarios, such as a pulse. The Mean Global Temperature change Potential (MGTP) (Gillett and Matthews, 2010) is the iAGTP divided by the T, and thus in a normalized gas is identical to the iGTP. There are two important differences between STRE and GTP: STRE gives effect relative to C not CO2, and STRE uses one single lifetime and not an IRF. Archer et al. (2009) argue against this approach, and the use of a single lifetime for CO_2 is not in line with our understanding of the slow removal of the excess CO_2 due to anthropogenic emissions.

Bond et al. (2011) proposed the Specific Forcing Pulse (SFP) that measure the immediate energy perturbation for BC and OC. This metric considers regionality in the impact, because SFP is the amount of energy added to or removed from a receptor region by a chemical species, per mass of emission in a source region. The global sum of SFP equals to AGWP; hence, SFP is a reformulation of AGWP. While this metric has only been used for BC and OC, the usage could also extend to other SLCFs with a lifetime less than a year.

Other metrics have been based on economic models. Manne and Richels (2001) investigated how constraints will affect the usage of GWP and impact the pricing of different LLGHGs. Recently, the Global Cost Potential (GCP) and Cost-Effective Temperature Potential (CETP) were developed (Johansson, 2012), which show similar characteristics to the Manne and Richels (2001) study. For a cost-benefit framework, the Global Damage Potential (GDP) is suitable, which looks at the marginal damages of emissions (Kandlikar, 1995; Boucher, 2012). A dynamical approach that makes changes in emissions over time consist with a specific pathway of future climate scenario can be done with the Forcing Equivalence Index (FEI) (Wigley, 1998; Manning and Reisinger, 2011). Hence, there is not one fixed metric number that can be used for all times. This metric is only suitable in the context of a calculated future climate pathway or stabilization.

An overview of all the metrics is given in Table 2. This table gives a qualitative idea of the accumulated knowledge on the different metrics and which species and applications have been considered. The SFP has only been used in one application specific to BC. Economic approaches have only been used on LLGHGs. iAGTP/MGTP/STRE have only been used in a few studies. Thus, most accumulated knowledge is on AGWP and AGTP. Tanaka et al. (2010) provide a more comprehensive overview of other simple emission metrics. In Table 3, a listing of key issues for the different metrics is given. These issues are discussed in this section, where these metrics are presented, but also in Sections 4 and 6. Different starting points of using emission metrics will give different usage of emission metrics and time horizons since the strong and weak points for the metric vary.

Table 2: An overview of the applications of different metrics to different species. For example, there are more research articles on economic approaches for LLGHGs compared to SLCFs.

Species	AGWP/AGTP	iAGTP/MGTP/STRE	SFP	Economic/GCP/CETP/GDP/

				FEI
LLGHGs	Many studies	Several studies		Several studies
Ozone pre-cursors	Many studies	Several studies		
BC	Many studies	Several studies	One study	
Other SLCFs	Many studies	Several studies		

Table 3: The main characteristics and key issues of different emission metrics. The key issues relate to value based choices that depends on the policy goals.

Metric	**Characteristics**	**Key issues**
GWP/AGWP	"CO_2 equivalent" in terms of integrated forcing	• GWP for H=100 years is the most common metric, as used by the Kyoto Protocol • "Remembers" everything that occurs before the time-horizon, even though the perturbation might be short-lived • Does not map directly to a climate response (e.g., temperature)
GTP/AGTP	"CO_2 equivalent" in terms of temperature at chosen point of time	• Maps directly to a well-known property of the climate system (temperature) • The second most used metric • Only an instantaneous view of temperature, but this does include the time history of emissions and forcing • Can be used with a variable time horizon giving metric values that change with time • Greater relative uncertainty than the GWP
iGTP/iAGTP/MGTP	"CO_2 equivalent" in terms of integrated temperature	• Numerically similar to GWP, but gives a better physical interpretation than GWP • Related to a linear damage function • Good if temperature over a period is of interest
RF	Radiative forcing	• Robust comparison of emissions between two points in time, even for SLCFs with lifetimes considerable less than 1 year • Only an instantaneous view, which includes the time history of emission • Does not include the response of the climate system
STRE	See iAGTP	• See iAGTP • Only developed for sustained emissions
SFP	Energy added/removed in the first year, similar to AGWP	• Good for SLCFs with lifetimes considerable less than 1 year • Aims to capture regional effects • Only applicable to SLCFs • See GWP
GCP/CETP/GDP	Metrics based on economic models, either a cost-effective or cost-benefit framework	• Has a response much closer to the socio-economic system • Increased uncertainty and less transparency as a reduced form climate model needs to be coupled to an economic model
FEI	Metric based on a	• Dynamic, as the metric values can change

	climate pathway or stabilization	with time • Only suitable for a locked climate pathway

3 Scenarios and sustained emissions

A pulse emission can be seen as the building block of an emission scenario via convolutions (Wigley, 1991; Enting, 2007). Pulse emissions are used due to their simplicity and generality and are, thus, preferred for scientific analysis. On the other hand, policy makers may have greater interest in the comparison of emission scenarios. A particularly type of scenario often used is a sustained emission which assumes emissions continue indefinitely at a pre-defined level. While SLCFs are quickly forgotten in the response of a pulse emission, both the impacts of SLCFs and the LLGHGs are present in a sustained emission scenario. It is also possible to have more general emissions scenarios (Moss et al., 2010), though these are not often used as for emission metrics, but are used to compare the response over time (such as the temperature response to a given scenario). We will first present the simplest emission scenario, sustained emissions, followed by the more general case. We also expand on the relationship between pulse and sustained emission metrics.

3.1 Sustained emissions

A simple emission scenario is to have a continuation of the pulse emissions, which are sustained emissions. The absolute metric of a sustained emission can be calculated as the cumulative sum of the absolute metric of a pulse emission. Sustained emissions are a specific type of scenario that neglects changes due to economic growth, technology improvements, mitigation policies or the lifecycle of infrastructure. From a policy perspective, sustained emission may be more relevant, since in reality, emissions are unlikely to stop instantaneously as in a pulse emission. However, from a scientific perspective, processes easily observable in a pulse scenario can be masked by cancellations in a sustained scenario. The choice between a pulse and sustained emission scenario is an important value judgment as they place very different weights on SLCFs and LLGHGs.

In the following, we show the equations for the different metrics with sustained emissions. The instantaneous radiative forcing (RF) for species with a simple exponential decay and sustained emission is

$$RF_{x,s}(H) = A_x\tau\left(1 - exp\left(-\frac{H}{\tau}\right)\right) \quad (24)$$

This equation is identical to the AGWP for a pulse emission, and this point is returned to in the following section. The AGWP for a sustained emission is

$$AGWP_{x,s}(H) = A_x\tau\left[H - \tau\left(1 - exp\left(-\frac{H}{\tau}\right)\right)\right] \quad (25)$$

The AGTP for a sustained emission is

$$AGTP_{x,s}(H) = \sum_{j=1}^{J} A_x\tau\lambda\left(1 - exp\left(-\frac{H}{d_j}\right)\right) + AGTP_x(H) \quad (26)$$

And finally, the iAGTP for a sustained emission is

$$iAGTP_{x,s}(H) = \sum_{j=1}^{J} A_x \tau \lambda \left(H - d_j \left(1 - exp\left(-\frac{H}{d_j} \right) \right) \right) + iAGTP_x(H) \quad (27)$$

Similar equations can be derived for CO_2 and ozone precursors, but are not shown here in the interests of space.

3.2 Connecting pulse and sustained emission metrics

A property of convolutions with a linear response and the Heaviside step function (equivalent to a sustained emission), leads to the instantaneous forcing of a sustained emission (RF_s, left hand side) is equal to the integrated forcing of a pulse emission (AGWP, right hand side),

$$RF_{x,s}(t) = \int_0^t H(s) R_x(t-s) ds = \int_0^t R_x(s) ds = \int_0^t RF_{x,p}(s) ds = AGWP_x(t) \quad (28)$$

Further, the same is true for the temperature response,

$$\Delta T_{x,s}(t) = \int_0^t RF_{x,s}(s) R_T(t-s) ds = \int_0^t AGWP_x(s) R_T(t-s) ds = iAGTP_x(t) \quad (29)$$

so that the instantaneous temperature perturbation to a sustained emission is equal to the integrated temperature perturbation to a pulse emission. Thus, there is a close connection between pulse and sustained emission metrics; the instantaneous impact of a sustained emission is the same as the integrated impact of a pulse emission. In early work, Shine et al. (2005) noted that the GWP was similar to the instantaneous temperature response to a sustained emission. This is equivalent to the integrated temperature response of a pulse emissions, and this has been shown to be similar to the GWP (Peters et al., 2011), thus, confirming the intuition of Shine et al. (2005).

3.3 Emission scenarios

For emission scenarios, the RF, AGWP, AGTP, and iAGTP values can be calculated with a convolution,

$$(f \times g)(t) = \int_{-\infty}^{\infty} f(s) g(t-s) ds \quad (30)$$

where *f* and *g* are functions and *g* represents the emission metric for a pulse emission. For instance, the AGWP for a scenario is the convolution of the emission scenario and AGWP for a pulse emission:

$$AGWP_i^{Scenario}(t) = \int_0^t E_i(\tau) AGWP_i^{Pulse}(t-\tau) d\tau \quad (31)$$

The convolution can be estimated by numerical integration, such as with a simple summation, using the Trapezoidal rule, Simpson's rule, numerical quadrature and so on. Most numerical integrations have problems with species with a short lifetime (e.g. BC), typically when the time step is larger than the residence time ($\Delta t > \tau$). This problem can be solved by reducing the time step; however, this greatly slows down the calculation time. In some cases, it is possible to evaluate the convolution using a system of linear equations (Aamaas et al., 2012), and this greatly speeds computation times.

4 Sample applications

In this section, we present some applications of these metrics for Norwegian emissions. As input data, we used the 2008 emissions from the Emissions Database for Global Atmospheric Research (EDGAR) (EC, 2011), with the exception of BC and OC from 2005 (Zbigniew Klimont, personal communication).

Climate impacts can be calculated by connecting these emissions with the components' radiative efficiency and lifetime presented by Fuglestvedt et al. (2010). These parameterizations for the long-lived greenhouse gases are from IPCC (2007), for BC, OC, direct SO_2, contrail, and aircraft induced cirrus from Fuglestvedt et al. (2010), for aircraft NO_x from Stevenson et al. (2004), for surface NO_x the global run from Wild et al. (2001), for CO the mean of UiO and LMDz runs from Berntsen et al. (2005), and for VOC from Collins et al. (2002). NH_3 is based on Shindell et al. (2009). The BC parameterization here does not consider the impact of BC in snow, but can be scaled to account for this effect. The indirect effect of SO_2 from shipping is based on the average of Lauer et al. (2007). Since Fuglestvedt et al. (2010) estimate the indirect effect of other SO_2 emissions crudely to be 50-100% of the direct effect, we multiply the direct effect by 1.75 to include both the direct and indirect effect. The parameterization of the temperature response is based on the Hadley model (Boucher and Reddy, 2008).

The EDGAR data differs from the official emission databases for Norway. However, we have used the EDGAR data since a range of pollutants are included. The point of the following example calculations is not the emissions used as input, but rather an overview on how different emission metrics and time horizons give different results. The EDGAR data is not based on official statistics and in some cases uses different definitions. For example, there is a significant allocation of fugitive emissions (methane) to the offshore sector, which we have removed to make more comparable to official Norwegian estimates. Norwegian electricity is dominated by hydropower, but the power sector in EDGAR includes public heat plants, petroleum refining, and the manufacture of solid fuels (coal). This explains the non-zero impact from the power sector. Emissions from international navigation are not included in the emission estimates.

4.1 Metric values as a function of time-horizon

The GWP, GTP, and iGTP values for a range of pollutants are shown in Figure 2 (see attached Excel file for numbers for AGWP, GWP, AGTP, and GTP). Because the metric values are normalized relative to the metric value of CO_2, the metric values of CO_2 are always a value of 1. While most species have metric values that are much higher than 1, the emissions of CO_2 in kg are much larger than for other species. Thus, when the emissions are combined with the metric values, the "CO_2-equivalent" emissions are still dominated by CO_2. For instance, the GWP value with a 100 year time horizon is 453 for BC, however, CO_2 dominates over BC in terms of the total climate impact of Norwegian emissions for that metric since the emissions of CO_2 are much larger than BC.

Metric values change over time due to both the temporal behavior of the species in the numerator and CO_2 in the denominator. Generally, metric values will increase as the time horizon increases until a point near the adjustment time of the species and decrease thereafter due to the effects of CO_2 in the denominator. The decrease in the GTP is quicker than for GWP and iGTP, since both GWP and iGTP integrate the effects over time and, thus, "remember" what occurred previously, even though for a pulse emissions the RF eventually decays to zero as energy is radiated back to space. GTP is an end-point metric that only looks at the climate system at a specific time. As shown in earlier work, there is a similarity between the GWP and iGTP, but neither is similar to the GTP (Peters et al., 2011). The GTP values are generally lower. Organic carbon (OC) and SO_2 have negative RF and, hence, negative metric values for all times. Some of the ozone precursors (NO_x, CO, VOC) are initially negative (positive) and, then, change sign as different responses take effect. For N_2O, it takes about 50 years before its GTP value begins to decrease. When looking at a unit of emissions (as in 1 kg CO_2

relative to 1 kg BC), we observe that the climate impact is mainly driven by either species with strong, but short-lived impact (e.g. BC) or weak, but long-lived impacts (e.g. CO_2).

It is also possible to have metrics with a variable time horizon. Figure 3 shows the GTP for CH_4, N_2O, and BC as the time horizon moves towards 2100 (T=2100-t), the mirror image of Figure 2. As the target year is approached, the importance of the CH_4 and BC increases. Hence, mitigation of SLCFs is not given much weight early in the period, but is given strong weight as the given target year is approached. For the LLGHGs, such as N_2O, mitigation throughout the period is beneficial. If the metric GWP100 is used instead, the metric values are constant through time, and BC has always the largest metric number.

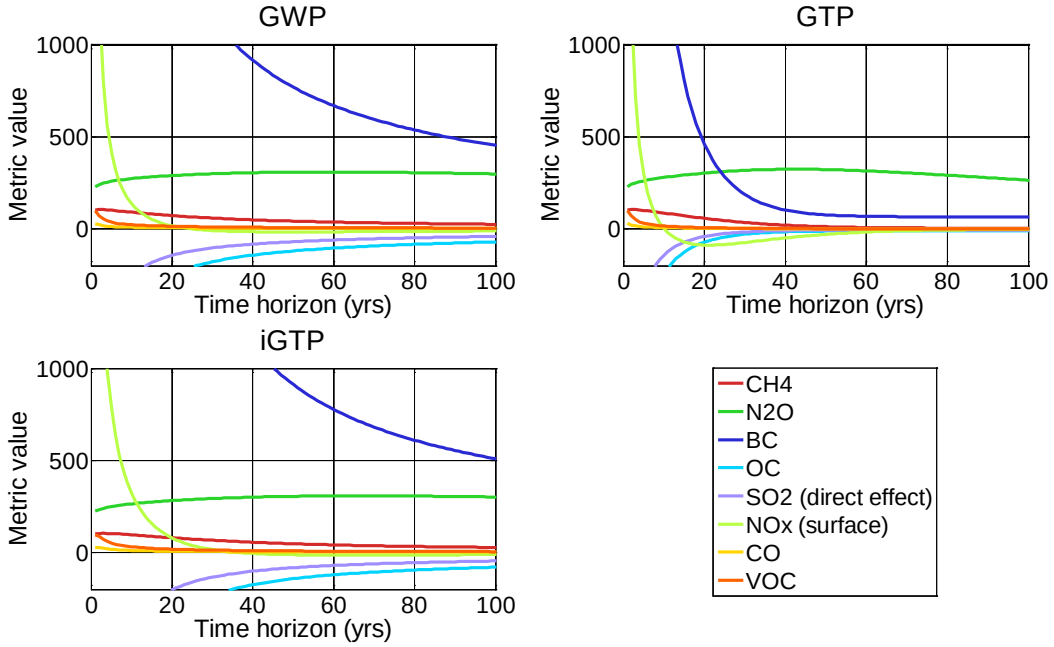

Figure 2: GWP, GTP, and iGTP values for time horizons between 1 and 100 years for a range of pollutants. (The very high and low values are cut out in order to present the values around 0 better.)

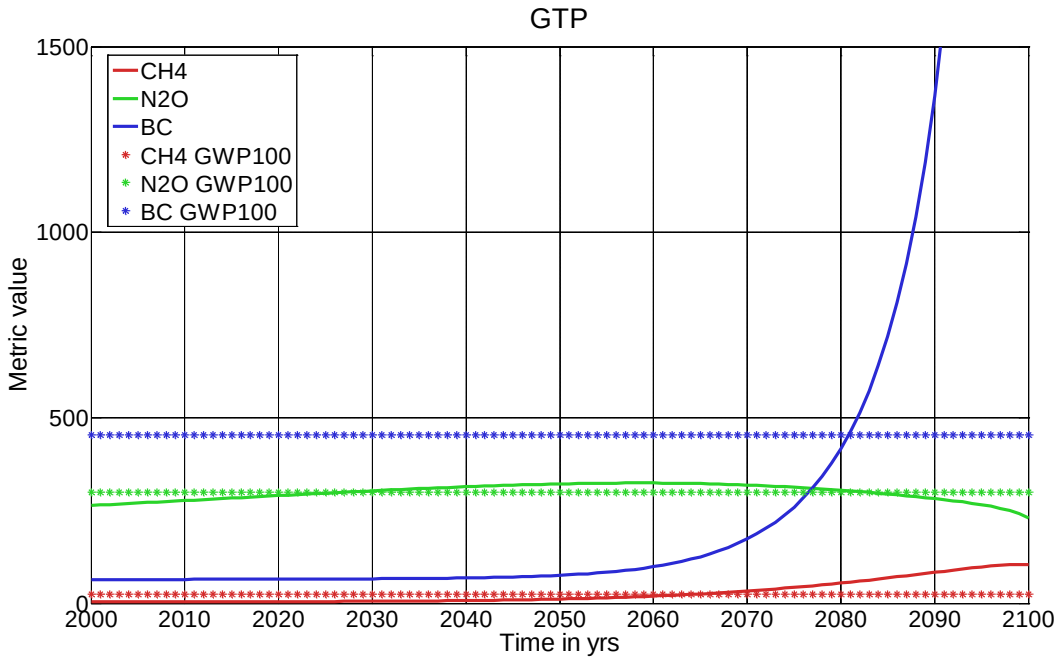

Figure 3: GTP values relative to a variable time horizon moving towards 2100. Thus, in 2000 the time horizon is 100 years, in 2050 the time horizon applied is 50 years, and in 2100 the time horizon is 0 years. This is the mirror image of Figure 2 along the time axis. The dotted lines show GWP100 for the same pollutants.

4.2 Metrics/ΔT by source, sector, and component

Figure 4 shows the CO_2-equivalent emissions for Norwegian emissions, including both SLCFs and LLGHGs and using different emission metrics. The importance of the SLCFs decreases with increasing time horizon and has relatively little weight according to the GTP with a 100 year time horizon. CO_2 dominates the metric weighted emissions in all cases, even when GTP10 is used. To allow an alternative comparison, Figure 5 shows the comparison in Figure 4 compared to the common GWP100. The species that are most affected by such a change are SO_2, CH_4, BC, and OC. For shorter (longer) time horizons the SLCFs get more (less) important.

We have used the difference in Norwegian emissions between 1990 and 2008 and presented that difference for different metrics in Figure 6. In that period, the CO_2 emissions have had a small increase, while the CH_4 emissions have been reduced significantly. With GWP100, the CH_4 reduction is almost as large as the increase for CO_2. The pollutants that have the largest impacts when using GWP100 are CO_2, CH_4 and SO_2. For some of the other metrics, reductions in CH_4 outweigh increases in CO_2.

Figure 7 shows the temperature perturbation separated by species for pulse and sustained emissions for Norwegian emissions in 2008. The climate impact is determined by a species' radiative efficiency and atmospheric lifetime, as well as the magnitude of emissions. While the SLCFs are important for the temperature perturbation in the first years after a pulse emission, CO_2 dominates in the long run, which is due to longer response time for CO_2 than most other species. In the sustained emission case, the emissions continue into the atmosphere indefinitely; hence, the temperature perturbation from SLCFs is not reduced as time increases, but instead reaches approximately steady-state. However, the concentration of CO_2 increases with time as it does not decay to zero and, thus, accumulates in the atmosphere, leading to a near linear increase in the temperature perturbation from CO_2

emissions. The figure shows clearly an initial warming from NOx, followed by a long-term cooling. In the sustained case, these conflicting impacts nearly cancel each other out.

The same temperature perturbation is divided according to sectors in Figure 8. Pulse emissions from all sectors give rise to warming, with the exception of cooling from some sectors, especially from the industry sector in the first 10 years and a small cooling from off-road land lasting about 30 years. The cooling is due to emissions of SO_2. In the long run, the power and industry sectors have the largest perturbation for both pulse and sustained emissions, as CO_2 dominates over the cooling components. Emissions of synthetic gases come mainly from the industry sector.

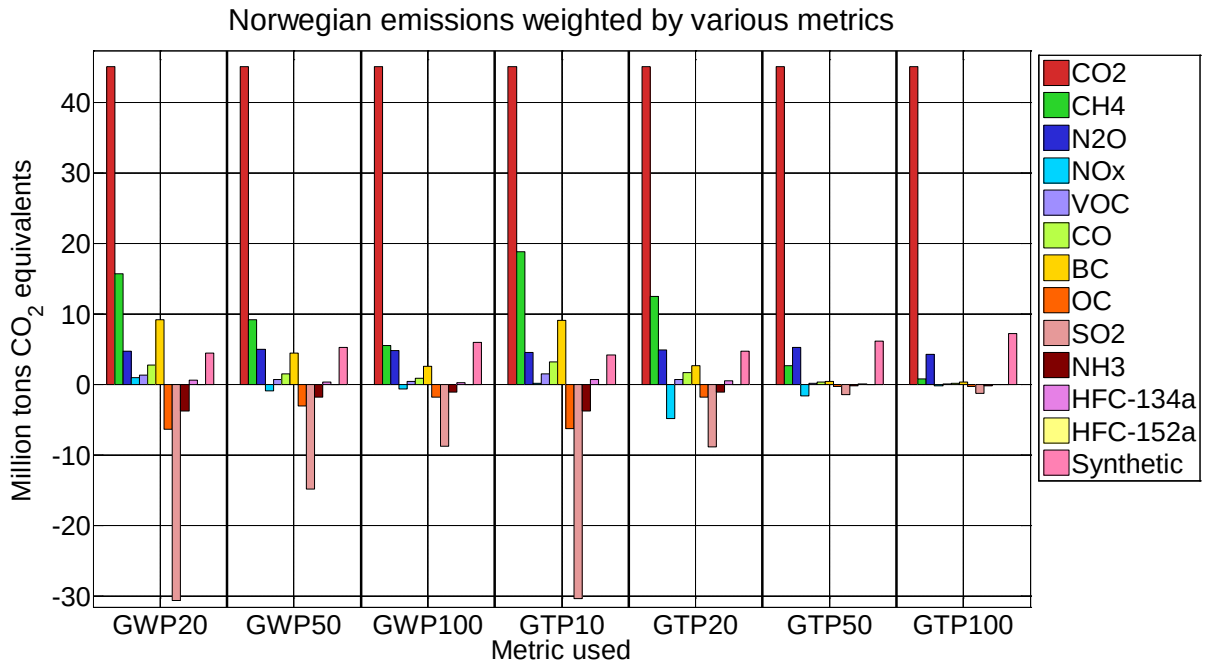

Figure 4: The weighting of different Norwegian emissions using various emission metrics. For all metrics, even for GTP10, CO_2 is the most important species. "Synthetic" represents all remaining mainly halogenated hydrocarbons in the Kyoto and Montreal Protocols, as well as SF_6. The indirect effect of SO_2 is included, as in all figures presented in this report. All land-based or near land-based emissions of NOx are parameterized as surface NOx,

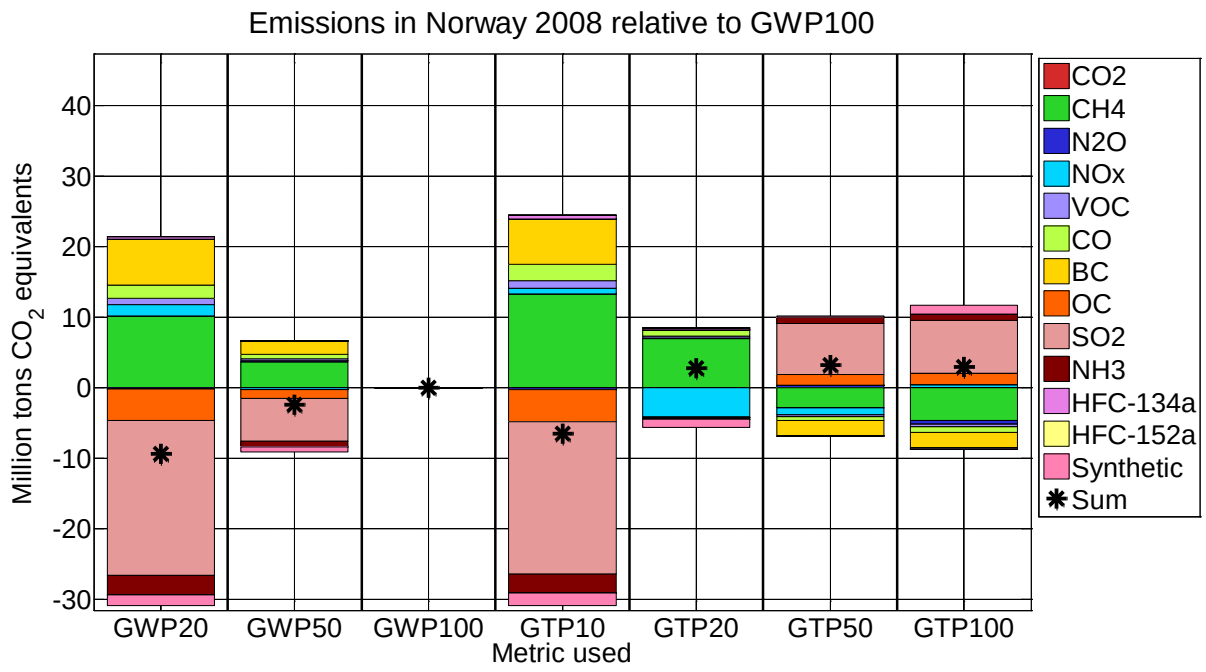

Figure 5: The emissions from Figure 4, but expressed relative to the GWP100 values, calculated as GXPXX-GWP100. The SLCFs are relatively more important for shorter time horizons. If we go from GWP100 to GTP100, this change will lead to a smaller impact from CH_4. However, as we shorten the time horizon, the change is less negative and turns positive for GTP20. The pollutants that are most affected by changing metric and time horizon are SO_2, CH_4, BC, and OC.

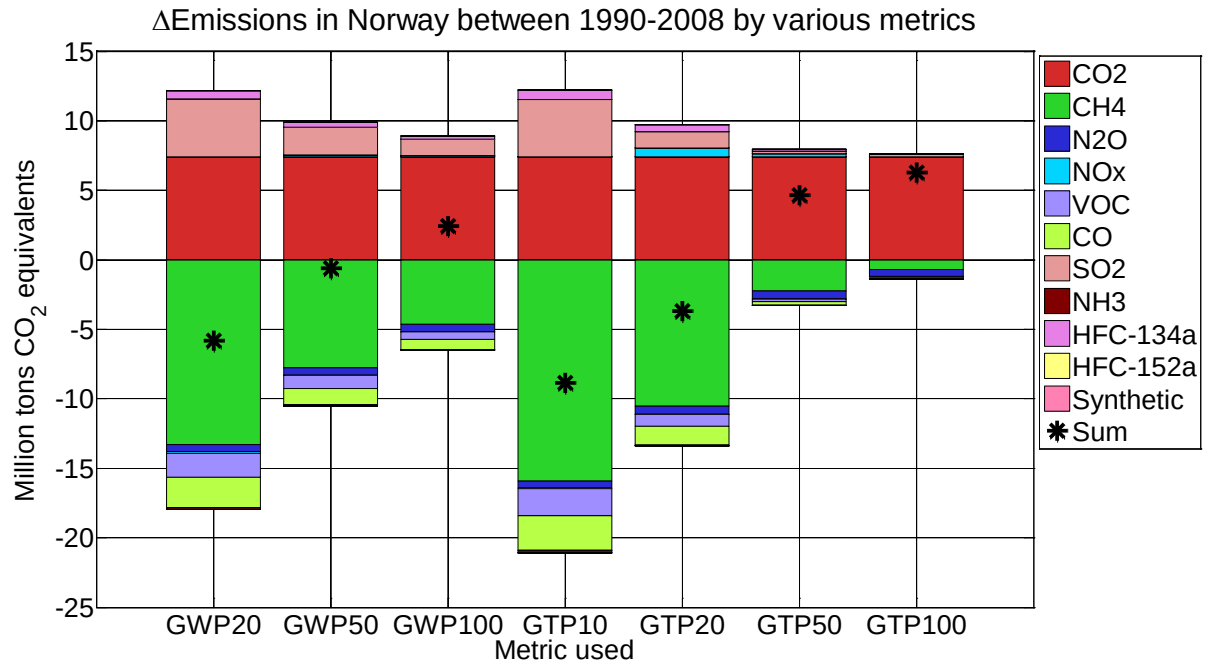

Figure 6: The change in Norwegian emissions between 1990 and 2008 using alternative metrics. There has been a relatively small increase in CO_2 emissions, but a large reduction in CH_4. For more than half of the examples presented here, the cooling from reducing CH_4 emissions outweighs the warming from increasing CO_2 emissions. In terms of GWP100, changes in this time period have had greatest impact from CO_2, CH_4, and SO_2.

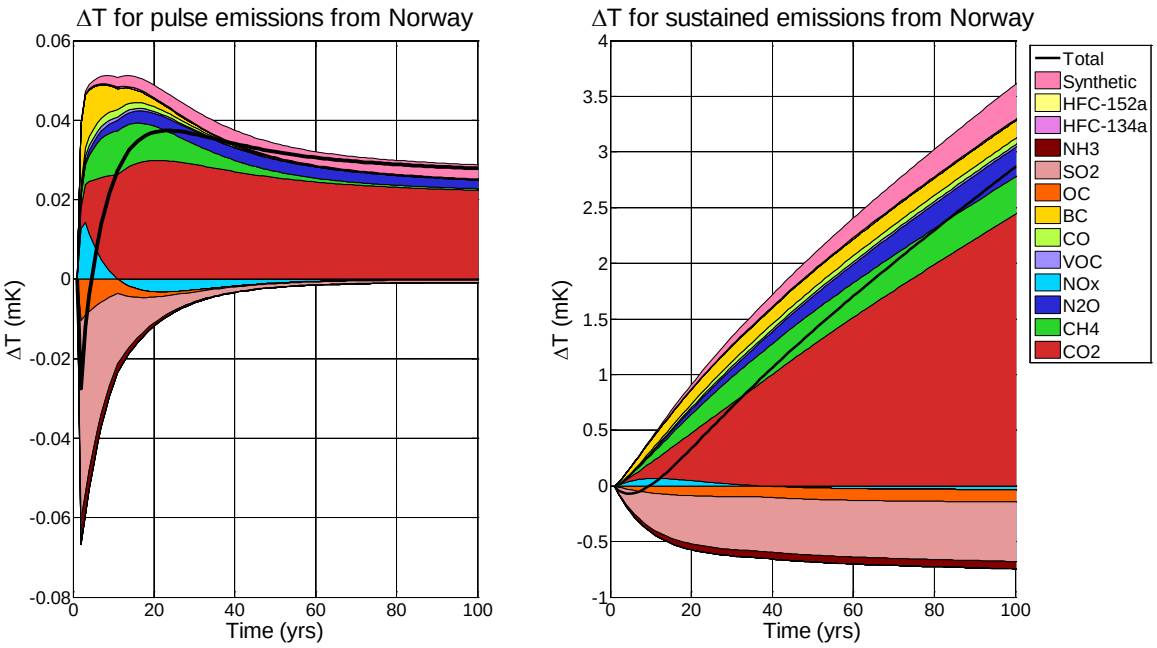

Figure 7: The temperature perturbation by different species due to Norwegian emissions in 2008 for a pulse and sustained case. "Synthetic" represents all remaining mainly halogenated hydrocarbons in the Kyoto and Montreal Protocols, as well as SF_6. The indirect effect of SO_2 is included, as in all figures presented in this report. All land-based or near land-based emissions of NOx are parameterized as surface NOx,

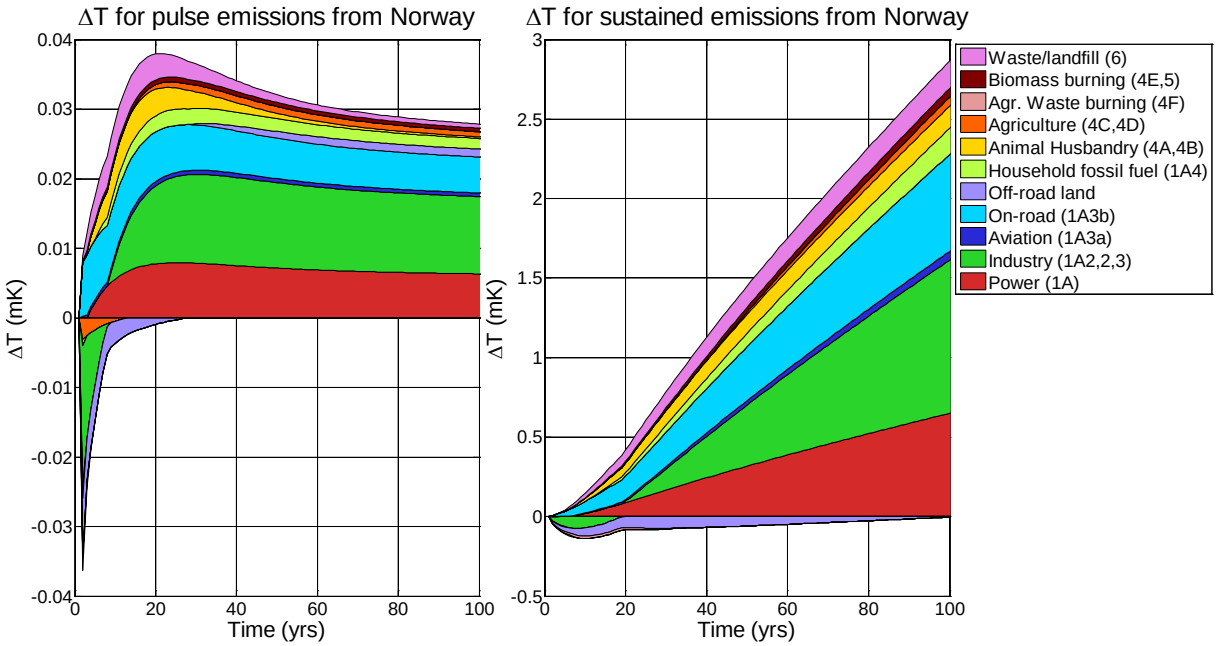

Figure 8: The temperature perturbation for different sectors due to Norwegian emissions in 2008 in a pulse and sustained case.

5 Research areas

In this section, we briefly discuss key uncertainties that need to be reduced through continued research. Since metrics are based on simple parameterizations of more complex models, the uncertainties in climate models (such as climate sensitivity) also affect emission metrics. There are large uncertainties and model variations in the CO_2 and temperature impulse response functions (Joos et al., 2012; Olivié and Peters, 2012). Also for most other species, a better quantification of lifetimes and RE would be of interest. Direct effects are generally better understood than indirect and secondary effects. Uncertainties are generally largest for the chemical reactive SLCFs. Thus, more robust metrics require improved knowledge on those processes.

Most knowledge on metrics is at the global scale and for LLGHGs. Uncertainty increases, and gaps in the science are largest for regional aspects of metrics, such as the response pattern of forcing and temperature to global and regional emissions. While these issues also affect LLGHGs, they are more prominent for SLCFs. While it is well understood that SLCFs and regional issues are important, the parameterizations required for regional metrics needs more research.

6 Discussion and conclusion

When selecting an emission metric, first one needs a clear understanding of what policy the metric should serve. Then there are three main choices that need to be considered, 1) instantaneous versus integrated metrics, 2) what impact parameter to use (RF, ΔT,…), and 3) for what time horizon. Since the purposes behind using metrics differ, different metrics may be preferable for different applications. The choices depend on the particular policy question. Science cannot provide information on which value choices to make, thus it is important that policymakers have a critical view on emission metrics and understand the implications of different value choices. In the case of emission metrics, an interaction between science and politics is needed.

There is no particular reason why there should be *one and only one goal* for our climate policy (Fuglestvedt et al., 2000; Rypdal et al., 2005; Jackson, 2009; Daniel et al., 2012; Sarofim, 2012). In particular there may be harmful impacts of exceeding a long-term temperature constraint (e.g. 2°C), while at the same time there is more immediate concern about the rate of change over the next decade or so. The rationale behind a policy focusing on SLCFs must be that there are potential harmful effects of climate change over the next few decades. If we were *only* concerned about long-term consequences (that is, on the timescale of reaching the 2°C limit), a GTP-type metric with a relatively long time-horizon could be the natural choice. In this case, the CO_2-equivalent emissions of current emissions of SLCFs would be quite small (Berntsen et al., 2010). SLCFs should also be considered under a long-term goal, but their CO_2-equivalent emissions would be smaller and mitigation measures would be less cost-effective. However, if we *also* have a goal to limit the current rate of change (that is, over the next one or two decades), then emissions should be compared using a different metric, with a shorter time-horizon, which would put more emphasis on the SLCFs (see Figure 4). LLGHGs should also be included in evaluation of possible mitigation measures under a short-term goal. However, due to the shorter time-horizon used, their CO_2-equivalent emissions would be smaller, but still important, and mitigation measures would be less cost-effective. Having two independent climate goals, such as a short- and a long-term goal, is not different from policies where emissions of many SLCFs are regulated both for air quality and climate impacts.

Currently, the most used metric is GWP100, which is adopted by the Kyoto Protocol and, hence, official emission statistics. The GWP100 represents a response of radiative forcing, integrated over time for 100 years. The GWP100 was originally (and is mostly) used for LLGHGs, such as comparing CO_2 with CH_4 and N_2O, though numerous applications exist for SLCFs.

It has been agreed at UNFCCC meeting in Cancun, and reaffirmed in Durban, to avoid the global mean surface temperature from increasing by more than 2 °C relative to pre-industrial level, and potentially 1.5 °C. If this temperature limit is the main goal for mitigation, a metric specifically focused on temperature may be more relevant; hence, AGTP could be a useful metric. Current research indicates that the 2 °C temperature threshold is likely to be reached within about 50 years (Joshi et al., 2011). In that perspective, a 50 year time horizon from today could potentially be justified partially on scientific grounds. Alternatively, a variable time horizon towards 2060 (2010+50) with increasing metric values as 2060 is approached (see Figure 3). How the metric values and, thus, e.g. taxes will change over time, needs then to be communicated to stakeholders so that they take this into account when they make their decisions. If the focus is on the rate of change in the next decades, which would put more emphasis on emissions of SLCFs, a shorter time-horizon may be justified. Note however that even with GTP10, CO_2 is still the dominant species for Norwegian emissions (see Figure 4).

While emissions of LLGHGs will be most important for the peak temperature, emission reductions of SLCFs can reduce temperature increase rates towards the peak and can "trim the peak" (Solomon et al., 2011). In that perspective, the long-term goal to limit the temperature peak, which is dominated by LLGHGs, can be compared by GWP100, GTP50, or some other metric that looks at accumulation of emitted LLGHGs. If the short-term goal of limiting rate of change, which is influenced by the SLCFs considered, as well as CO_2, then these emissions could be compared using a GTP-type metric with a shorter time horizon, for instance a time horizon of 10 or 20 years.

If a comparison between SLCFs is required, and not a comparison of SLCFs and LLGHGs together, then this may better specify which metrics to use. A relatively short time horizon may be relevant if the focus is on reducing temperature change in the next decades. Since SLCFs are not compared to LLGHGs, then absolute metrics may be more relevant as opposed to normalized metrics. For example, the AGTP with a short time horizon could be a sufficient method to compare SLCFs over short time horizons. However, comparing SLCFs alone ignores the dominant effect of CO_2 (Figure 4).

Metrics have been developed for (one-year) pulse emissions and for sustained emissions. Although mitigation measures hopefully will have an effect and be sustained over many years, pulse-based metrics are still the best tool for policy analysis. This is because they provide a more versatile tool for comparing the impact of any future emission scenario (including the sustained case). The following example shows how this works. The mitigation leads to future emissions of BC given by $E_{BC}(t)$, where t is time and a pulse-based metric M_{BC} with variable time horizon (as described above). The CO_2-equivalent emissions ($E_{BC}(CO_2\text{-eq})$) over the period between t=0 and t=I for this scenario is then

$$E_{BC}(CO2 - eq) = \sum_{t=0}^{I} E_{BC}(t) \cdot M_{BC}(I - t) \quad (32)$$

where I is the number of years with emissions considered. CO_2-equivalent emissions of other components due to alternative mitigation strategies can, then, be calculated using the same method

and the impacts can be compared. With a metric based on sustained emission changes only, the special case of constant future emission change can be evaluated.

Based on the literature we have presented the analytical expressions of radiative forcing, integrated radiative forcing, temperature, and integrated temperature in both absolute and normalized forms. We have discussed interpretations of these metrics, and key assumptions behind them. The discussion has been illustrated with examples using Norwegian emissions. SLCFs have been compared with LLGHGs using these metrics. There is no clear need to use the one metric in all applications, and different applications may use different metrics. Hence, a comparison of LLGHGs may need another type of metric than a comparison of SLCFs. For a focus on the climate impacts of SLCFs, a temperature based metric with a short time horizon can be justified depending on the goal. If the long-term goal is to prevent a 2 °C warming, AGTP with a variable time horizon towards the year this limit is likely reached would be suitable. Though, it is important to note, that CO_2 is still the most dominant component even if a metric and time-horizon are chosen that puts more weight on SLCFs.

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Appendix

See attached Excel file for an overview of metric values for AGWP, GWP, AGTP, and GTP after a pulse emission. We present values for different SLCFs, but also for a few LLGHGs to put the SLCFs in context. The GWP and GTP of CO_2 will always have value of 1 since it is the reference gas.

Glossary

- AGTP: Absolute Global Temperature change Potential, the change in global surface temperature at a given time after emissions
- AGWP: Absolute Global Warming Potential, integration/summation of RF at a given time, unit: W/m^2*yr
- iAGTP: integrated Absolute Global Temperature change Potential, the integration/summation of AGTP at a given time.
- Impulse Response Function (IRF): The temporal response to a unit pulse emission (or forcing) into the atmosphere and describes how much of the emission remains in the atmosphere after a given amount of time. For most species the IRF is a simple exponential decay, while CO_2 (and temperature) are usually based on a sum of exponentials with different time-scales.
- Perturbation: Introduce a small change in the system, for instance, some quantified emissions of CO_2.
- Pulse emission: An instantaneous emission to the atmosphere which is theoretically interpreted as occurring instantaneously, though practically is sometimes considered to be an emission for one single year followed by zero emissions.
- Radiative efficiency: How much the radiative forcing will change if the atmospheric concentration is increased by one unit of a pollutant. Unit: $W/m^2/kg$

- Radiative forcing: When a perturbation (for example change in CO_2 concentration) change the net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. Simple version: The rate of energy change per unit area of the globe as measured at the top of the atmosphere.
- Sustained emission: Constant emissions every year for eternity.

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