1 Combining temperature rate and level perspectives in emission
2 metrics

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7 **Abstract.** The ultimate goal of the United Framework Convention on Climate Change, which is reconfirmed by the
8 Paris Agreement, is to stabilize the climate change at level that prevents dangerous anthropogenic interference, and it
9 should be achieved within a time frame that allow the natural systems to adapt. Numerous emission metrics have been
10 developed and applied in relation to the first target, while very few metrics have focused on the second target regarding
11 rate of change. We present here a simple and analytical physical emission metric based on the rate of global
12 temperature change and link that to a metric based on a target for the temperature level. The rate of change perspective
13 either can supplement the level target or can be considered together in one commitment that needs one combined
14 metric. Both emission metrics depend on assumptions on a temperature baseline scenario. We give some illustrations
15 on how this framework can be used, such as different temperature rate and level constraints based on the
16 Representative Concentration Pathways. The selection of the time horizon, for what time period and length the rate
17 constraint is binding, and how to weight the rate and level metrics are discussed. For a combined metric, the values
18 for short-lived climate forcers are larger in periods where the critical rate is binding, with larger temporal increases
19 during the rate constraint period as the atmospheric perturbation timescale of the species becomes shorter. Global CO_2
20 emissions remain the most important, or among the most important, drivers of temperature rates even during periods
21 of binding rate constraints.

22 1 Introduction

23 Human activity causes emissions of a range of gases and particles that alter the climate (Myhre et al., 2013), which
24 has wide reaching consequences (IPCC, 2014). Article 2 in the United Framework Convention on Climate Change
25 (UNFCCC) states that the ultimate objective is "stabilization of greenhouse gas concentrations in the atmosphere at a
26 level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be
27 achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food
28 production is not threatened and to enable economic development to proceed in a sustainable manner" (UNFCCC,
29 1992). This statement has two specific goals. The first is a long-term stabilization of the climate, e.g. below 1.5 or 2
30 ^{0}C as in the Paris Agreement (UNFCCC, 2015). Less attention has been given to the second target, which concerns
31 the rate of climate change that allows ecosystems to adapt.

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32   According to Diffenbaugh and Field (2013); LoPresti et al. (2015); Settele et al. (2014) , many plants and animals will

33   not be able to keep track with climate change in the 21st century in the mid- and high-range climate change scenarios,

34   the Representative Concentration Pathways RCP4.5, RCP6.0, and RCP8.5. The quicker the temperature increase, the

35   larger is the velocity of climate change, which is a measure of how fast temperature isotherms are moving towards the

36   poles (Loarie et al., 2009). A temperature increase of 0.2 ^{0}C/decade over the 21st century will result in a larger climate

37   velocity than the dispersal capacity for a number of plant and animal species, and even 0.1 ^{0}C/decade is critical for

38   some. The global temperature has historically varied by as much as 0.2 ^{0}C/decade for single decades (Hansen et al.,

39   2010; Morice et al., 2012; Smith et al., 2008), while the literature suggest that such trends are critical for plants and

40   animals when lasting several decades. The required movement of plants and animals will be the fastest in extensive

41   flat landscapes. These studies show there might be some maximum temperature rate that is acceptable, just as an

42   absolute global temperature level of increase of e.g. 1.5 or 2 ^{0}C is seen as tolerable.

43   If only considering CO_2, the timing and magnitude of the largest temperature rate increase is determined by the CO_2

44   emissions peak and level (Bowerman et al., 2011). This perspective was widened by Matthews et al. (2012), that found

45   that the rate of warming depends linearly with the rate of increase of CO_2 cumulative emissions, while the eventual

46   warming level depends on the total cumulative CO_2 emissions. For a cumulative total of CO_2 emissions, the

47   temperature rate is highly dependent on the pathway of emissions (LoPresti et al., 2015). O'Neill et al. (2006) propose

48   interim targets, as opposed to near- or long-term targets, such as a 2050 target of about 430 ppm CO_2- equivalents that

49   ensure rate warming of no more than 0.1 ^{0}C/decade, or 550 ppm CO_2- equivalents for 0.2 ^{0}C/decade. Kallbekken et

50   al. (2009) argue for limiting the cumulative CO_2 emission budget in the next few decades to limit the rate of warming,

51   while such a rate approach enables short-lived climate forcers (SLCFs) also to be included in climate policy.

52   UNFCCC (1992) states in Article 3 that that climate policies should be "cost-effective so as to ensure global benefits

53   at the lowest possible cost" as well as "be comprehensive", and "cover all relevant sources, sinks and reservoirs of

54   greenhouse gases." In order to operationalize Article 3, emissions of various species must be made comparable, which

55   can be done by applying emission metrics. The most widely used metric is based on the cumulative global mean

56   warming effect over a time horizon (i.e., the Global Warming Potential (GWP), (IPCC, 1990)) or the global

57   temperature increase at some point in the future (e.g. the Global Temperature change Potential (GTP) (Shine et al.,

58   2007; Shine et al., 2005)) as a measure of dangerous anthropogenic interference. The GWP is not directly linked to

59   the rate or level targets, while the GTP with a time horizon is compatible with the level target, such as limiting global

60   temperature increase to less than 2 ^{0}C.

61   Here, we take Article 2 of the UNFCCC as our starting point, assuming that climate policies will be targeted to keep

62   both the rate of change as well as the long-term stabilization below certain thresholds. To make the GTP-metric

63   suitable for the long-term stabilization target, as discussed above, a key point is how to set the time horizon. Following

64   Tol et al. (2012), the time horizon should be set to when the temperature stabilization target is expected to be reached

65   (binding). This requires an a priori assumption about the future climate development and we will denote this the

66   *baseline scenario*.

67 Based on Article 2 of the UNFCCC, there is a need for a transparent metric compatible with the rate target. Such a
68 metric concept could be explored due to its potential usefulness, as well as providing insight, even though the political
69 feasibility might be low. As the temporal development in temperature is also linked to the rate target, GTP in some
70 form is also relevant for the rate metric. Following the same argument as for the GTP/stabilization target above, we
71 assume that with the climate scenario used there is some period where the rate of change will be above an acceptable
72 threshold. If not, then the rate of change is considered not to be a problem and policies should only focus on the long-
73 term stabilization target. With this framework, we suggest a modified GTP metric to address the rate target by
74 quantifying how pulse emissions at a given time contribute to warming within the period where the rate constraint is
75 binding.

76 Most of the developed metrics related to the rate goal are not purely physical, but also include economics. Manne and
77 Richels (2001) presented an emission metric that in principle is the Global Cost Potential (GCP) based on an economic
78 model that considered both the absolute temperature change and rate of temperature change, which was revisited by
79 Ekholm et al. (2013). Wallis and Lucas (1994) reformulated global warming potentials to include rate of change, and
80 Peck and Teisberg (1994) discussed optimal carbon emission trajectories given costs of different warming rates and
81 levels. These metrics are based on economic modeling, which is not necessary transparent to the metric user.
82 Kirschbaum (2014) developed the physical metric climate-change impact potential (CCIP) by giving identical weight
83 to three parameters, the temperature increase, rate of warming, and accumulated warming. He focused on emission
84 cases over a time period of 100 years until 2100 and did not develop a general rate metric which for instance separate
85 between periods that are rate constraint binding and not binding.

86 The rate of change perspective can be adopted to supplement a long-term stabilization target in two different ways.
87 One may regard the rate of warming and the long-term stabilization as two independent environmental issues (although
88 affected by the same emissions, much like air quality and climate change) or it may be regarded as one single problem.
89 In the former case, separate commitments in terms of weighted emissions (i.e. two sets of CO_2-equivalents and
90 emission metrics) for each of the problems could be negotiated, while with the latter approach a single commitment
91 is given using one common emission metric that includes a weighting to account for both the rate of change and the
92 long-term warming. The different configurations should all be based on the same basket of gases and particles, as all
93 the species affect both the level and rate of change.

94 In Sect. 2, we show alternative potential rate metrics. We present our suggested analytical and simple emission metric
95 that is relevant for the objectives addressing both the long-term stabilization and the rate of change in Sect. 3. In Sect.
96 4, we give some applications of these metrics for the 21st century. We discuss the implementation in a mitigation
97 policy framework, applications of the developed metrics and the linkage to cost-effectiveness in Sect. 5. Section 6
98 concludes.

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2 Alternative rate metrics

Given that the rate of change causes damage (according to Article 2), one would intuitively attempt to derive a metric

based on the rate of change (i.e. based on $R(t) = \frac{d(\Delta T(t))}{dt}$). To illustrate why we would argue that the framework

described above (using a modified GTP) is a better approach, a schematic temperature response after a pulse emission

is shown in Fig. 1. The temperature rate of change is always largest at the time of emissions ($t_e = t_{Rmax}$) and gradually

reduced until t_{R0}, where the temperature rate turns negative. On the other hand, the absolute temperature change is

positive throughout the period, with the largest increase at t_{R0}.

Possible metrics based on R(t)

1. $AM(t_e, t) = R_{max}(t_e, t)$

    Choosing the time horizon so that the rate of change is at its maximum, is equal to setting the time horizon
    effectively to zero. Due to the atmospheric decay given by an impulse response function, the rate of
    temperature increase is always largest as $t_e \rightarrow 0$, as seen in Fig. 1 in the Supporting Information. Then the
    relative metric would be equal to the ratio of radiative effects, that is a similar framework as applied in the
    Radiative Forcing Index (RFI) (IPCC, 1999) , which has been criticized (e.g., Fuglestvedt et al., 2010).

2. $AM(t_e, t) = \int_{t_e}^{t_{R0}} R(t_e, t')dt'$

    With this approach, we integrate the rate only when the rate of change is positive. However, this integral is
    equal to the AGTP(t_e, t_{R0}). Thus, a relative metric would use a (potentially very) different time horizon for
    different species (see also Sect. 2 in the Supporting Information). For very SLCFs like BC, t_{Ro} would be less
    than a year after emissions.

3. $AM(t_e, t) = \int_{t_e}^{t_L} R(t_e, t')dt'$

    where t_L is the time horizon for the long-term stabilization target. This definition is exactly equal to the
    proposed AGTP for use in relation to the long-term stabilization target.

3 Definition of rate and level metrics used in this paper

Based on the general approach described in the introduction, we develop the formal definition of our rate and level

metrics. The metrics are defined for pulse emissions (see Fig. 1), noting that metrics for a sustained emission change

or any future emission path can easily be derived from the pulse metrics (Fuglestvedt et al., 2010). For both metrics,

we assume that a general binding target constraint occurs over some time period. As the calculation of these metrics

depends on the baseline scenario for the temperature development, the dependence on scenarios are first shown.

2.1 Dependence on scenario

Both the rate and level metrics depend on the choice of the baseline scenario. There is a critical temperature rate and temperature level, which gives binding constraints for the metrics. The baseline scenario determines the time horizon or range of time horizons depending on when the targets are binding. This is illustrated in Fig. 2, where the level constraint is binding between t_{L1} and t_{L2}, while the rate constraint is binding between t_{R1} and t_{R2}. The time horizons for the two targets will of course be different, with the time horizon for the rate metric always shorter than for the level metric. The choice of a proper baseline scenario is not straightforward and beyond the scope of this paper. In Sect. 8 in the Supporting Information, we combine different Representative Concentration Pathways (RCPs) with different rate and level constraints, and show how this determines possible time horizons.

2.2 Level metric

The time-dependent GTP is a temperature emission metric that is well-known to be used relative to the level target, for instance the 2 ^{0}C target (Shine et al., 2007). The time horizon can potentially be set to when 2 ^{0}C global warming is reached (Joshi et al., 2011), while our framework focuses on the timing of the temperature stabilization. We define here the level metric AM_L for emissions at time t_e for species i given by the level term calculated from the Absolute Global Temperature change Potential (AGTP):

$$AM_L(t_e) = \int_{t'=t_{L_1}}^{t_{L_2}} \Delta T_i(t_e, t') dt' = \int_{t'=t_{L_1}}^{t_{L_2}} AGTP_i(t' - t_e) dt' \tag{1}$$

The level target period is binding for some limited period between t_{L1} and t_{L2} when the temperature increase is above the target level $\Delta T = T$, for instance T=2 ^{0}C, as illustrated in Fig. 2(A). In the case for emission occurring after t_{L1} ($t_e > t_{L1}$), we set t'= t_e. The target period could be shortened to one specific year, e.g. year 2100, which would give a metric identical to a time-dependent AGTP for a pulse emission. However, we integrate over a period as the temperature stabilization may in reality occur over a longer period or may not be able to be specified to a single year due to uncertainty in emissions and climate response (Shine et al., 2007). Additional warming above the level is given equal weight throughout the period of binding level constraint. As emissions at time t_e approaches the level target period starting at time t_{L1}, the time horizon for the AGTP calculations is gradually reduced.

2.3 Rate metric

We propose a physical and analytical rate metric that depends on when the rate constraint is binding. A specific total allowable rate of change for the global temperature over time must be selected that reflects a level of ecological risks that can be tolerated. Natural variability will come on top of the rate of change imposed by anthropogenic forcing. The maximum anthropogenic rate, which then determines the constraint for the metric, is then the difference between the total allowable rate and possible contribution by natural variability. We acknowledge that determining the specific maximum anthropogenic rate is not straightforward; however, the scope of this paper is to lay out the framework for how rate considerations could be implemented in a comprehensive approach following Article 2 of the UNFCCC.

Given the baseline scenario selected, a period when the rate constraint is binding is determined. This is illustrated in Fig. 2(B), where the rate is estimated to be above the threshold, and thus binding, between t_{R1} and t_{R2}. The absolute metric value (AM_R) for a unit pulse emission at time t_e is defined to be the integral of the temperature change within

166   this period cf. Eq. (2). A temperature increase is given the same weight whenever in that period this warming occurs,

167   as any additional warming is equally critical throughout the period of the binding rate constraint.

168    $$AM_R(t_e) = \int_{t'=t_{R_1}}^{t_{R_2}} \Delta T_i(t_e, t')dt' = \int_{t'=t_{R_1}}^{t_{R_2}} AGTP_i(t' - t_e)dt' \qquad (2)$$

169   In the case for emission occurring after t_{R1} ($t_{R1} < t_e < t_{R2}$), then (AM_R) is given by

170    $$AM_R(t_e) = \int_{t'=t_e}^{t_{R_2}} \Delta T_i(t_e, t')dt' = \int_{t'=t_e}^{t_{R_2}} AGTP_i(t' - t_e)dt'. \qquad (3)$$

171   The potential pathways to temperature T_L are many and the dotted line in Fig. 2(B) shows an alternative pathway with

172   a temperature rate increase at $t_{R1} < t' < t_{R2}$ just below the rate threshold and, thus, gives no binding rate constraint, which

173   gives $AM_R(t)=0$ for all time horizons. Hence, we consider the damage during the period with a rate constraint

174   ($t_{R1} < t' < t_{R2}$), but not after ($t' > t_{R2}$).

175   The proposed rate metric can be seen as a special case of the integrated AGTP and identical to the integrated AGTP

176   within the time window $t_{R1} < t' < t_{R2}$ (Azar and Johansson, 2012; Peters et al., 2011); however, the metrics are different

177   due to different choices of integration periods. If the constraint period converges to 0, then the metric is identical to

178   the time-dependent AGTP.

179   Both the level and rate metric can be normalized to a reference gas e.g. CO_2 to form unitless relative metrics M_L and

180   M_R, respectively.

181   **2.4 Combining level and rate metric**
182   The rate of change can supplement the long-term target by regarding them as separate environmental issues both

183   related to climate change, with two separate mitigation commitments and corresponding metrics for the level and rate

184   perspectives. For the rate issue, the CO_2-eq. emissions will be calculated using the rate metric described above, while

185   for the long-term e.g. the GTP(t) will be used. In this framework, the parties to an agreement would negotiate separate

186   quantitative emission reductions for a rate agreement and a level agreement, thus effectively weight the importance of

187   the rate versus the level constraint. It is important to note that emission reductions of any warming species should be

188   accounted for both commitments. E.g. is a stakeholder reduces their methane emissions, they will get credit for that

189   under both the rate and level commitments, albeit with different metric and CO_2-eq. values.

190   If the targets rate of change and the long-term warming are regarded as one single coupled problem, then a common

191   metric needs to be established. However, successfully achieving the combined emission reduction target based on one

192   combined metric does not automatically assure that both individual targets are reached.

193   If the two targets are combined into one, the importance of the individual targets must somehow be weighted relative

194   to each other. This weighting is not a scientific question, but rather involves value judgments and possibly economics,

195   and as such would be determined through a negotiation process. Here, we illustrate a simple linear weighting by giving

196   the rate metric a weight α, and the level metric $1-\alpha$, where $0 \leq \alpha \leq 1$. The combined metric for species i normalized to

197   CO_2 ($M_{R\&L}$) is then

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198   $$M_{R\&L,i}(t_e) = \alpha \frac{AM_{R,i}(t_e)}{AM_{R,CO_2}(t_e)} + (1-\alpha) \frac{AM_{L,i}(t_e)}{AM_{L,CO_2}(t_e)}.$$ (4)

199   This metric is a pure level metric when $\alpha=0$ and pure rate metric when $\alpha=1$. For emissions taking place after the rate

200   constraint is binding, i.e. for $t_e > t_{R2}$, we set $\alpha=0$. Then, only the level target is relevant and level metric values are

201   applied without any weighting. Thus, if the rate target is met, a combined metric focuses purely on the level target.

202   Both metrics are integrated over some constraint period, but can also be used for individual constraint years. Since all

203   the metrics discussed here are defined relative to a baseline scenario, the specific metric values are all known as a

204   function of (future) time of emissions (t_e). This time dependence must be communicated to the stakeholders so they

205   would know how to make investments that effect emissions over some future time period.

206   In this framework, the relative weight of the rate constraint versus the long-term level is determined through the policy

207   choice of α, and a single CO_2-eq. mitigation commitment is negotiated. As emitters are free to choose which species

208   to abate, the outcome of the mitigation efforts are more uncertain when applying a common metric (Daniel et al., 2012;

209   Fuglestvedt et al., 2000).

210   **3   Results**

211   We calculate the level metric, rate metric (i.e., setting $\alpha=0$ and $\alpha=1$, respectively), and combined metric values ($M_{R\&L}$)

212   for the SLCFs CH_4 and BC and the long lived greenhouse gas (LLGHG) N_2O based on radiative efficiencies and

213   perturbation lifetimes from IPCC AR5 (Myhre et al., 2013). Further, the Impulse Response Function (IRF) for CO_2

214   applied is based on the Bern Carbon Cycle Model (Joos et al., 2013), while the IRF for temperature comes from the

215   Hadley CM3 climate model (Boucher and Reddy, 2008). The schematic temperature response due to pulse emissions

216   of these species that is compatible with Fig. 2 is given in Fig. S1(B) in the Supporting Information.

217   Due to the quick response of SLCFs, mitigation of the warming SLCFs has the potential to regulate the temperature

218   development and, thus, the temperature rate, for short time horizons (see Sect. 2 in the Supporting Information).

219   Emission reduction of CO_2 will also reduce the short-term temperature rate, in addition to reduced long-term warming.

220   To demonstrate how the metrics presented in Sect. 3 are applied, we have to choose time horizons for binding rate and

221   level targets. Our default baseline scenario is an illustration of the framework that is not deduced from a specific

222   scenario. The default case is based on binding rate constraint for the 2031-2050 period and a level target reached in

223   the 2081-2100 period. All figures in the paper use these constraints unless otherwise explained. We will in Sect. 5.44.4

224   relate this hypothetical baseline scenario with potential temperature developments. The later part of Sect. 4 focuses

225   on CH_4 and presents different dimensions or choices for these metrics.

226   **3.1   Different weighting factors**

227   In Fig. 3, we show metric values for CH_4, BC, and N_2O based solely on the rate or level targets, as well as for an equal

228   weighting ($\alpha=0.5$). Figs. 3(A), 3(C), and 3(E) are the default cases with a 20 years binding period for both rate (2031-

229   2050) and level (2081-2100), while Figs. 3(B), 3(D), and 3(F) shows how this changes as the binding period is reduced

230   towards a minimum of 1 year, that is a rate target in 2050 and level target in 2100. The years on the x-axis correspond

231   to the time of emissions, t_e in Eqs. (2) and (3). As the rate target is no longer binding after 2050, values for a pure rate

232 metric ($\alpha=1$) are only given before that. Metric values for other weightings (α) are shown in Sect. 5 in the Supporting

233 Information.

234 For SLCFs, the metric values increase for emissions occurring towards the start of the rate-binding and level-binding

235 periods, with a second increase towards the end of the rate-binding and level-binding periods for the species with the

236 shortest perturbation timescales, such as BC. This fluctuating behavior in metric values for CH_4 is similar to the

237 findings of Manne and Richels (2001) with similar rate-binding and level-binding constraints. The metric values for

238 SLCFs are, for a period, larger when the binding periods start earlier, since a binding constraint in a given year results

239 in larger metric values than no binding for the SLCFs. One example is the elevated metric values from 2081 and

240 onwards for BC in Fig. 3(C) compared with Fig. 3(D). However, the differences between a long binding period (Figs.

241 3(A), 3(C), and 3(E)) and a short one (Figs. 3(B), 3(D), and 3(F)) is generally small. The longer the long binding

242 period is, the larger the difference. The opposite occurs for LLGHGs as those species have a relatively decreasing

243 impact on the temperature as the time horizon decreases, thus, they have a relatively smaller role for the short-term

244 rate change. The higher the α value is set, the larger influence has the rate metric, and the larger variability with time

245 is in the combined metric value. The deviation of this combined metric value compared to GWP(100) is largest for

246 BC due to its short perturbation timescale, and the difference is largest for emissions during the rate-binding and level-

247 binding periods.

3.2 Different rate constraints

249 Depending on the choice of baseline scenario and the rate and level constraints, the timing and length of the periods

250 when the constraints will be binding will vary. Next, we consider how the combined metric for CH_4 varies depending

251 on how long the rate constraint period lasts (Fig. 4(A)) and when the rate constraint becomes binding (Fig. 4(B)). The

252 earlier the rate constraint becomes binding, the larger is the metric value in early 21st century (see Fig. 4(A)). However,

253 as the rate metric is an integral over the binding rate constraint period (with equal weighting over time), the metric

254 values during the first part of these periods are in general lower for longer binding periods. On the other side, the peak

255 at the end is relatively higher for longer binding periods, as the level metric contributes more if we assume no change

256 of the level target. If both the rate and level targets are moved correspondingly in time, the metric value curves are

257 identical, just moved. The reduced metric values at the beginning for longer binding periods occur since the

258 temperature response of CH_4 decays at the end of the period, while CO_2 give a much longer lasting response. Moving

259 the rate constraint period without changing the length of the period just moves the metric curve (see Fig. 4(B)).

3.3 Different time horizons for the level target

261 If we only consider the level target, the level metric value at a fixed year is larger the earlier this level target is reached.

262 Shine et al. (2007) have previously shown this relationship with a pure GTP metric. Fig. 4(C) shows the combined

263 metric as we move the level target period gradually from 2081-2100 to 2041-2060. As the rate constraint is kept

264 constant in this illustration, a drop in the combined metric value is observed for all cases at the end of the rate constraint

265 period (2050). The size of this drop decreases with decreasing distance between the rate-binding and level-binding

266 constraints. Instead of a reduction of 66% from 71 to 25 in 2050 with a level target period of 2081-2100, the drop is

267 only 4.0% when the level target period is moved earlier by 40 years. However, a temporal distance of about 10 years

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268   between the binding rate and level constraints is unlikely since the rate temperature increase will likely be gradually

269   reduced approaching the timing of the global temperature stabilization. In summary, the rate constraint becomes more

270   important for the combined metric as the temporal distance increases between the binding period of the rate constraint

271   and the level constraint.

272   **4   Discussion**

273   **4.1   Implementation**

274   A policy covering a range of species with a rate perspective can be implemented in various ways. Two/multi-basked

275   approaches have previous been discussed by Daniel et al. (2012); Fuglestvedt et al. (2000); Jackson (2009); Rypdal et

276   al. (2005). We present two approaches to combine the level and rate targets. The first method applies the level metric

277   and rate metrics individually, which we call the separate commitment approach. The second approach uses the

278   combined metric, thus, a common commitment.

279   **4.1.1 Separate commitments - two metrics**

280   Each party to an agreement now has two mitigation commitments, both quantified in terms of total CO_2-eq. emission

281   reductions, but using either the pure rate metric or the pure level metric to calculate the CO_2-eq. emissions. A dual

282   target is less flexible than a single target, which is likely more costly. Note that these commitments should be defined

283   (but could change) for all years following the time of the agreement. Figs. 3 and 4 show that the metric values varies

284   significantly with time of the emissions reductions, in contrast to the more traditional use of the (fixed) GWP_{100}.

285   **4.1.2 A common commitment - one metric**

286   In this case, each party has only one commitment in terms of CO_2-eq. emissions, using the combined rate and level

287   metric, with a chosen α ($0<\alpha<1$). As for the dual target case, the metric values varies with time, in particular for SLCFs,

288   with a sharp reduction for emissions after the end of the rate-binding period. The same argument holds also for this

289   case, i.e. that the parties need to know how the metric values change over time in order to implement cost-effective

290   policies. This case is probably simpler to implement for the parties as they have only one commitment to consider.

291   To implement cost-effective policies, the parties to the agreement need to know how the metric values change over

292   time when they plan investments that will reduce emissions for a longer period. The pulse metrics presented in this

293   paper, with their discontinuities, is only a building block. The abrupt change in emission metric value at the end of a

294   constraint period can make this emission metric confusing for decision makers. We discuss two options that will

295   remove this discontinuity. The first is to sum the absolute values of the rate metric and level metric, and then normalize

296   to CO_2:

297     $$M_{R\&L,i}(t_e) = \frac{AM_{R,i}(t_e)+AM_{L,i}(t_e)}{AM_{R,CO_2}(t_e)+AM_{L,CO_2}(t_e)}$$ (5)

298   This change of formula will smooth out the curve for the combined metric and give lower metric values during the

299   rate constraint period. Fig. S5 in Supporting Information is a remake of Figs. 3(A), 3(C), and 3(E) based on this

300   alternative formula. As we find our original formula simpler and easier to adjust the relative weighting, we prefer Eq.

301   (3).

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302   The second alternative is to look at emissions over a longer period, which is often the case for decision makers leading

303   to emission changes lasting over a period. We give an illustrative example where decision makers can choose between

304   20 years of constant emissions of CH_4 versus CO_2. The emission metric value is then the average emission metric

305   value over a time period of 20 years following the implementation. The combined emission metric for CH_4 peaks in

306   2049 when considering individual years (see Fig. 3(A)), but an investment in 2049 has a metric value near the

307   minimum (see Fig. 5) due to the low metric values in the following years. The peak occurring around 2030 does not

308   have a discontinuity. The shape of the curve is similar for BC emissions, but with a relatively faster increase towards

309   2030 and larger decrease towards the end of the binding rate constraint period. Thus, a strategy for polluters and

310   policymakers cannot be based on the emission metric value for a single year, but a broader period relevant for

311   investments and policies.

312   **4.2 Cost-effective metrics**
313   The level and rate metrics presented here are purely physical based in that only physical quantities (like time, radiative

314   efficiency, etc.) are used to calculate their numerical values. However, from an economics point of view they represent

315   a cost-effective framework. On a fundamental level, emission metrics can either adopt a cost-effective or cost-benefit

316   approach which results in the metrics GCP (Manne and Richels, 2001) and Global Damage Potential (GDP) (Kandlikar,

317   1995), respectively (Tol et al., 2012). The GWP, which is also calculated from physical quantities only, can be derived

318   based on a cost-benefit approach where the benefit is optimized by weighting damages and costs. Alternatively, in the

319   cost-effective approach binding constraints are determined exogenously (e.g. the 1.5 and 2 ^0C targets are based on

320   political negotiations), and policies are developed to reach the policy target in a cost-effective way. Under given

321   assumptions, it can be shown that the GTP metric is suited for cost-effective approach to a level target (Tol et al.,

322   2012). The time horizon applied to calculate the metric values depends on the time interval when the constraints are

323   likely to be binding in an assumed baseline scenario.

324   **4.3 Weighting global emissions**
325   The impact in terms of CO_2-eq. emissions of different species depends on what perspective to take, whether level or

326   rate metric, what time horizon, or focusing on some other parameter. In Fig. 6(A), we show how different perspectives

327   compare based on the default level and rate metric cases, including GWP(100) and the Global Precipitation-change

328   Potential for pulse for a 20 year time horizon ($GPP_P(20)$) (Shine et al., 2015). For emissions in 2008 (EC, 2011;

329   Shindell et al., 2012), CO_2 is the most important contributor for all metrics, even the pure rate metric. If we keep the

330   emissions constant at the 2008 level and focus on the combined metric, the global BC and CH_4 emissions are given

331   little when they occur about 40-50 years before a binding constraint period (see Fig. 6(B)). The SLCFs increase their

332   influence closer to and during the rate-binding and level-binding constraint periods. The increase is most notable for

333   CH_4 in the first years, while the quick temperature response of BC leads to the largest increase for BC towards the end

334   of the rate constraint periods. However, global CO_2 emission is the most important or among the most important

335   drivers of temperature rates even during those binding periods. The most notable exception is the outsized influence

336   of BC in the final years of the rate and level binding constraint periods. These conclusions also hold for the rate metric

337   and level metric, as well as when applying emission scenarios such as the RCP6.0 (see Fig. S6 in the Supporting

338   Information).

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4.4 Temperature development and RCPs

The time horizons of the level and rate targets are dependent on assumptions of the baseline scenario. In this study, we have presented applications of the level, rate, and combined metric with illustrative examples. However, the RCPs could be suitable for determining the timing of rate and level criteria. The global temperature increase and the decadal rate change according to RCP2.6, RCP4.5, RCP6.0, and RCP8.5, as well as historic data, is provided in Sect. 3 in the Supporting Information. According to RCP2.6, the global temperature stabilizes around 2060, while all other RCPs give an increase in temperature throughout the 21st century. Due to natural variability, the decadal temperature change can vary, historically cooling of almost -0.2 ^{0}C/decade to warming up to 0.25 ^{0}C/decade (Hansen et al., 2010; Morice et al., 2012; Smith et al., 2008). Similar fluctuations can be expected in the future. Current average decadal increase is approaching 0.2 ^{0}C/decade. All RCPs indicate an anthropogenically driven rate of increase of about 0.2 ^{0}C/decade in the next decades potentially giving the order of 0.4 ^{0}C/decade when natural variability is added, which will likely be harmful for some of the plants and animals (Settele et al., 2014). A gradual reduction in the rate increase for the second half of the 21st century is seen for RCP2.6 and RCP4.5.

Our default case ends the binding rate constraint by 2050, which is partly consistent with a binding rate constraint of 0.2 ^{0}C/decade in RCP4.5, or alternatively 0.1 ^{0}C/decade in RCP2.6. The 1.5 or 2 ^{0}C target from the Paris Agreement (UNFCCC, 2015) is for 2100. Collins et al. (2013) used the period 2081-2100 as a time proxy of climate change at the end of the 21st century, which is identical to our default level target period. Additional metric examples based on RCP4.5 and RCP8.5 with a range of different rate constraints are given in Sect. 8 in the Supporting Information.

For RCP8.5, the combined metric value increases throughout the century since the rate constraint is binding for the entire period or becomes binding (for >0.3 ^{0}C/decade). On the other side, RCP4.5 gives a secondary maximum towards the end of the binding rate constraint period similar to Fig. 3 as the rate constraint is only binding in the first part of the century. In RCP2.6, one can argue that the level target is reached by 2060 as the global temperature increase since the pre-industrial time is set to fluctuate around 1.5 ^{0}C from 2060 and for the rest of the century. A similar case is presented in Fig. 4(C).

Our default combined metric case, which is partly inspired by RCP4.5, has similar metric fluctuations as Manne and Richels (2001), with increasing (decreasing) metric values in the period of binding rate constraint for CH$_4$ (N$_2$O), and similar changes as the time of the level target is approached. Updated calculations by Ekholm et al. (2013) of the GCP for CH$_4$ for the 2 ^{0}C level target and a combination of the 2 ^{0}C level target combined with a rate constraint gave similar findings. However, the absolute values between our and their estimate differ, since they apply the GCP in some form based on economic assumptions and we apply analytical emission metrics.

The temperature development may be different from the baseline scenario, which could warrant the need for a regular updates of metric values. For instance, the temperature pathways are influenced by climate policy. If a stringent climate policy based on the metrics discussed here are applied, this will change this pathway as emissions are mitigated. This pathway change will further change the period when the rate constraint is binding, which changes the assumptions of the metric calculations i.e., a 'policy feedback.' If sustained and effective climate policy is practiced, the global

374   temperature trajectory will be lower than the baseline scenario. Not only is the temperature rate impacted, but also the

375   magnitude and the time horizon of the temperature stabilization or peaking. Another issue is what emission metric and

376   time horizon should be applied for emissions after both targets are reached, as continued climate policy is likely needed

377   to avoid further global warming, which potentially indicates that the emission metric values can be kept constant.

378   The rate metric presented here has a rate constraint that is either binding or not binding. Alternatively, a metric could

379   potentially be produced that assess different levels of temperature rates, for instance have a rate constraint starting at

380   the maximum allowable rate of change (e.g., 0.2 ^{0}C/decade) that increases linearly in weight above that. This would

381   give additional weight to the periods with the largest temperature rates.

382   The anthropogenic contributed temperature rates may hypothetically fluctuate, hence, the rate constraint binding may

383   occur for several different periods separated by periods that are not binding. We have not given examples of this in

384   our analysis of a rate metric since such behavior is unlikely, but this behavior can easily be included. In Eq. (2), an

385   additional constraint period term between t_{R3} and t_{R4} can be added.

386   Some of the individual pathways of the RCPs indicate overshooting (Clarke et al., 2014), i.e. the level target is meet

387   in the long run but with a overshooting in the short-term. The AR5 WG3 Scenario database (Krey et al., 2014) shows

388   that overshooting pathways tend to have larger temperature rate increases, as well as for longer periods, than pathways

389   that approach level targets without overshoot (see Sect. 4 in the Supporting Information for details on scenarios

390   pathways that leads to CO_2 concentrations of 430-480 ppm and 530-580 ppm). Similar findings are previously

391   quantified by O'Neill and Oppenheimer (2004). Overshooting may lead to more ecological risks, as well as climate

392   feedback risks, than those pathways without overshoot (O'Neill and Oppenheimer, 2004). The overshot pathways

393   result in larger combined metric values for SLCFs than the other pathways with identical long-term level targets due

394   to longer rate constraint periods closer in time to the level constraint.

395   **5   Conclusion**

396   We have presented a physical and analytical rate metric concept that is compatible with the rate target described in

397   Article 2 in the UNFCCC. In addition, we have developed a combined metric that considers both the rate and level

398   target. We discussed and argued against alternative rate metrics derived from the rate of change. Several issues have

399   been discussed, such as determining when the rate and level constraints are binding and how to weight the rate and

400   level metrics. Further, we considered applying the rate of change perspective with two different approaches. One is to

401   argue for the long-term temperature stabilization target and the target of reducing the rate of climate change as two

402   different issues that need separate metrics. The other is to consider the two issues in one common framework that

403   warrant one combined metric with a selected weighting of the two targets. We presented some illustrative examples

404   of how these metrics can be used, as well as linking them to the RCPs. The suggested rate metric may be applied, as

405   the global temperature increase in the next decades can be harmful for some ecosystems. The total metric values for

406   SLCFs increase distinctly in periods when the rate constraint is binding, and the shorter the atmospheric perturbation

407   timescale is for a species. However, global emissions of CO_2 are the most important contributor when using the rate

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408   metric, except for BC and partially CH$_4$ at the end of the binding period of rate constraint. The metrics presented here

409   for pulse emissions must be seen as building blocks for the users. The discontinuity in metric value at the end of a

410   constraint period can be difficult to communicate to users, while looking at emissions over a longer period resolves

411   this issue. We illustratively showed that an investment that leads to 20 years of sustained emissions gives a smoother

412   temporal metric profile for CH$_4$ than one based on pulses for each year. The utilization of these metrics are likely most

413   effective when the decision makers know how the metric values vary over time.

414   **Acknowledgements**

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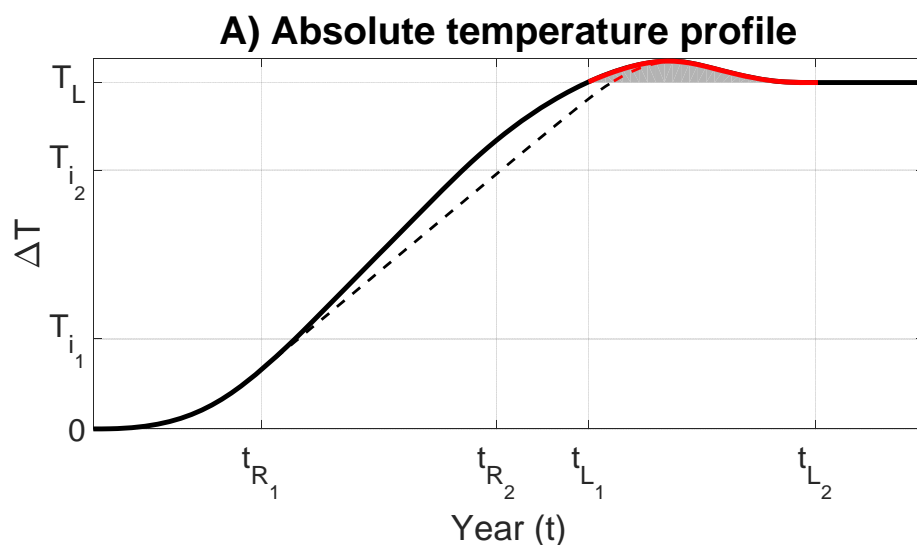
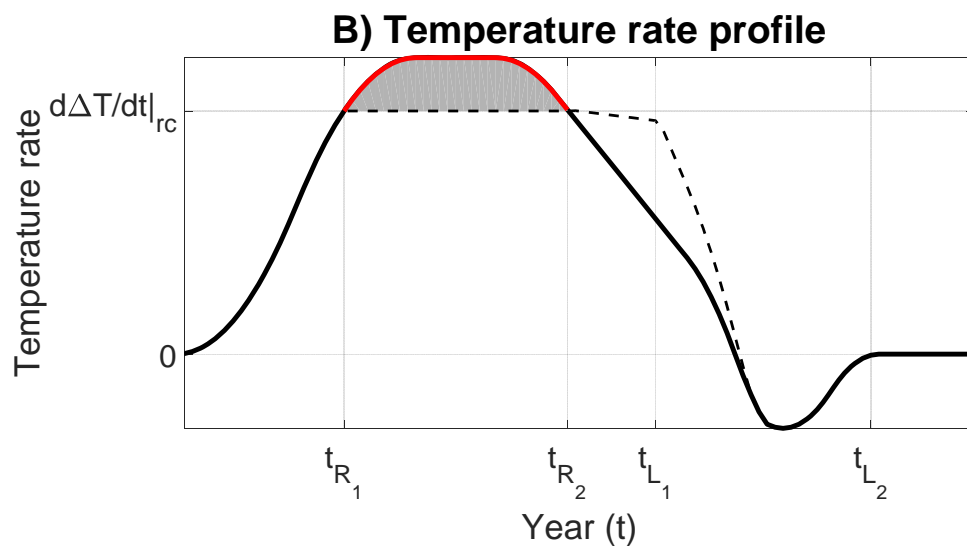517   18(1): 57-62.

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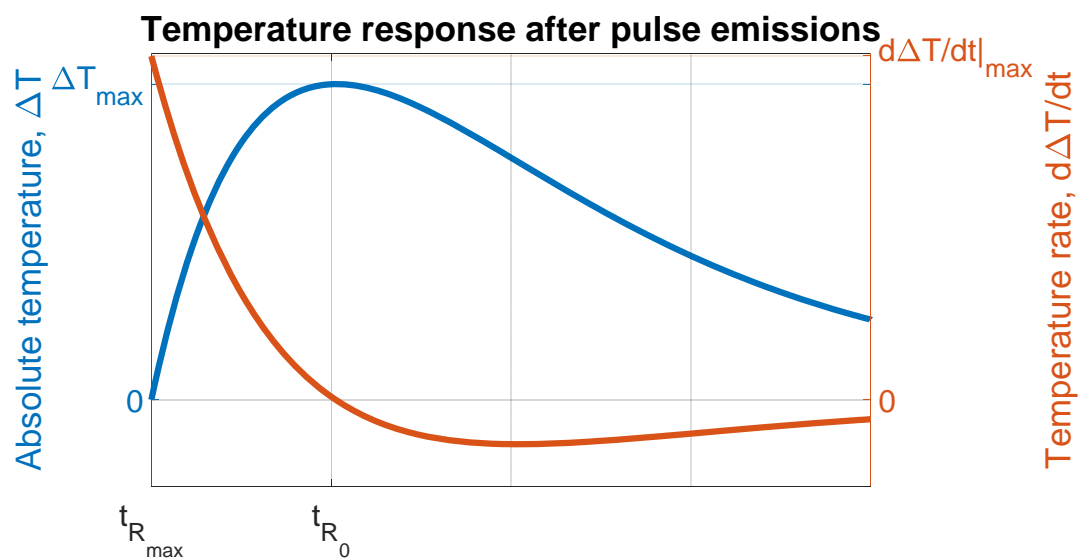
521   Figure 1: A schematic of how the absolute temperature and temperature rate evolve after a pulse emission of a warming

522   species. The max rate of change occurs at $t_{Rmax} = 0$. This figure is based on CH_4, but the principal is the same for all other

523   warming species.

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Figure 2: A schematic of a baseline scenario where the global temperature initially have an increasing rate of change and eventually levels off. The total temperature change is given in A and the temperature rate in B. The level constraint above the level temperature T_L occurs in the time period between t_{L1} and t_{L2} (shown in red). The rate of temperature increase is above some set critical level between t_{R1} and t_{R2} (shown in red) and makes the rate constraint binding for that period. The dotted line indicates an alternative baseline scenario that do not cross the rate constraint threshold, but leads eventually to the same total temperature increase.

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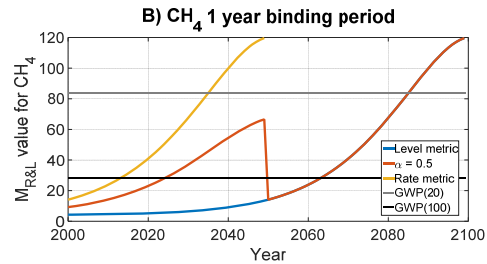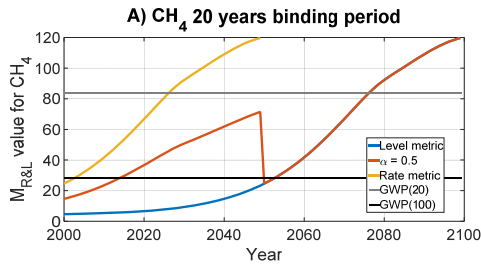
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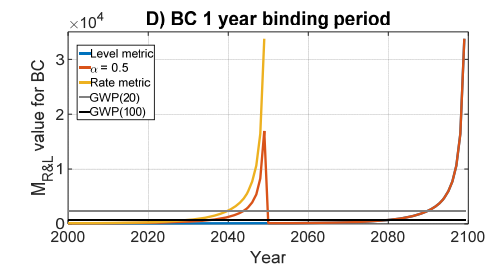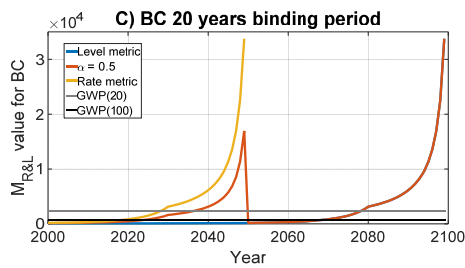
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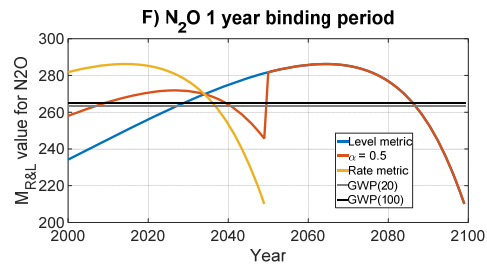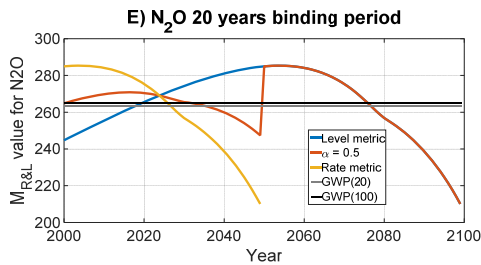
537 **Figure 3: Illustrative values for the level and rate metrics, as well as a combined metric based on equal weighting, for CH₄,**

538 **BC, and N₂O. Metric values for other weightings (α) are shown in Sect. 5 in the Supporting Information. The rate constraint**

539 **is binding for the period 2031-2050, and the level reached in 2081-2100 in A, C, and E. For B, D, and F, the rate is binding**

540 **in 2050 and level binding in 2100. α is the weight given to the rate metric in the period that is binding. GWP(20) and**

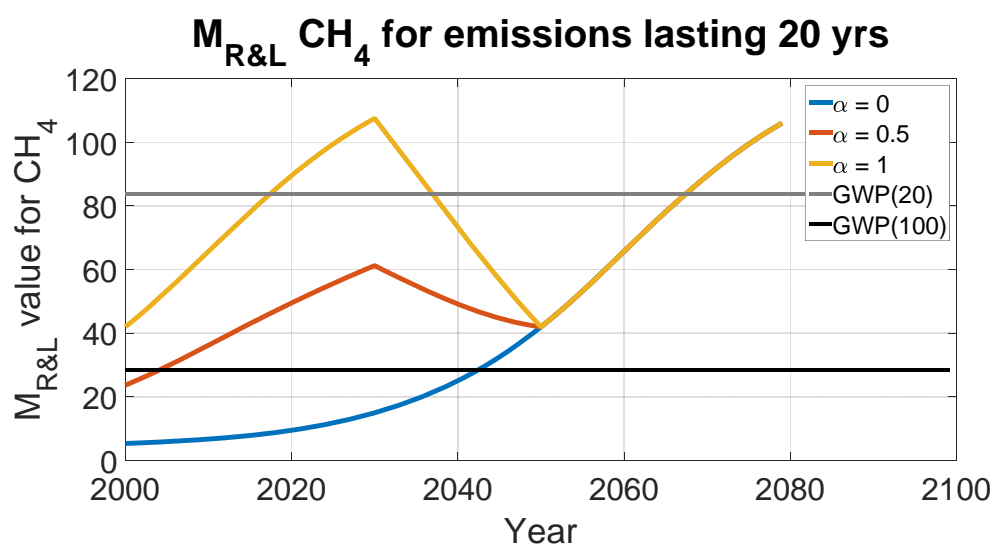541 **GWP(100) values are given as reference.**

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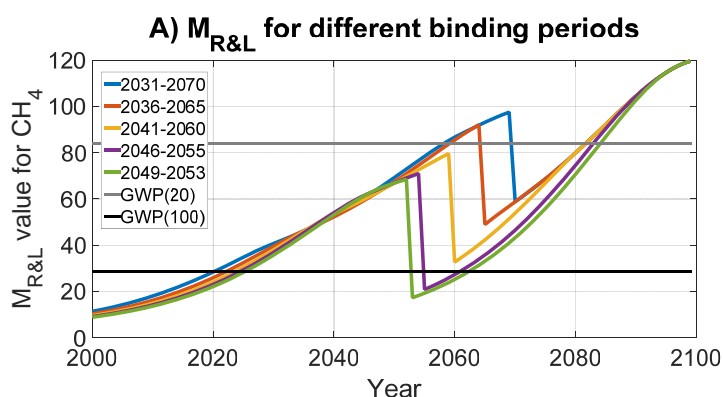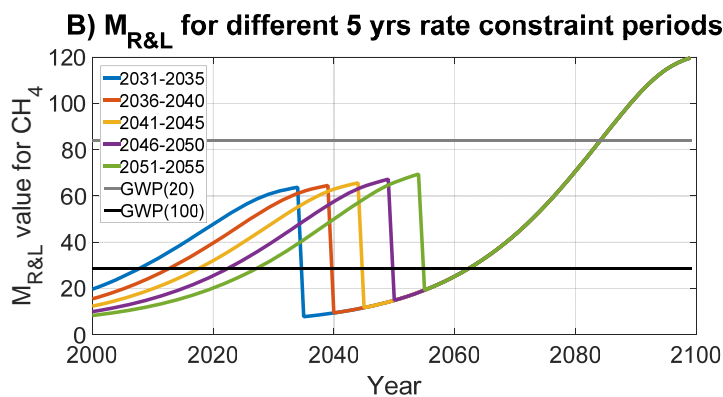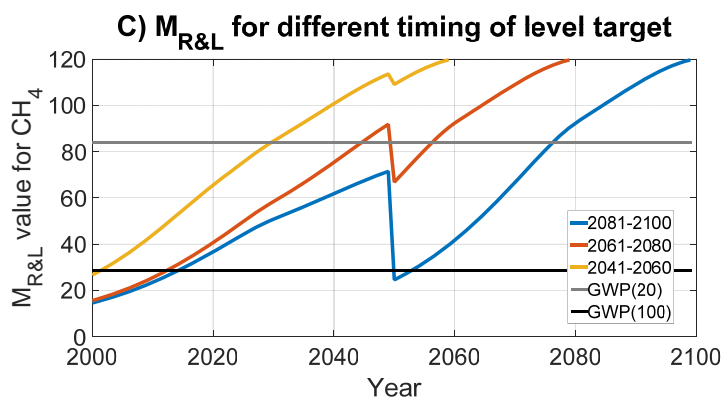
Figure 4: How changing the timing of the level and rate targets influence the combined metric values. For all figures, the length of the level constraint in years is identical to the length of the rate constraint period. All metric values are given based on a weighting of α=0.5. In A, the length of the period of binding rate constraint (5-40 years) varies with midpoint in 2050. B shows a 5 years period of binding rate constraint at different times. C shows a sensitivity test of the timing of the level target. GWP(20) and GWP(100) values are added to all figures as a reference.

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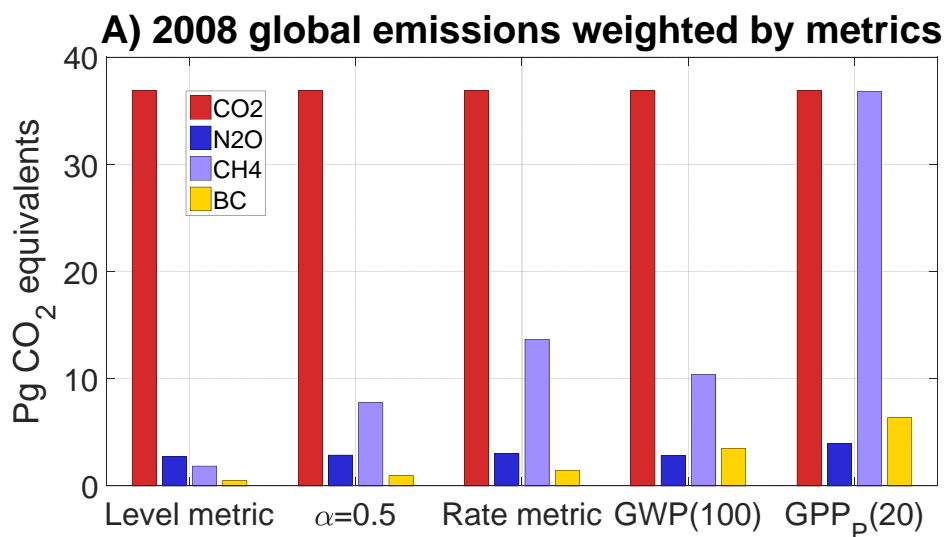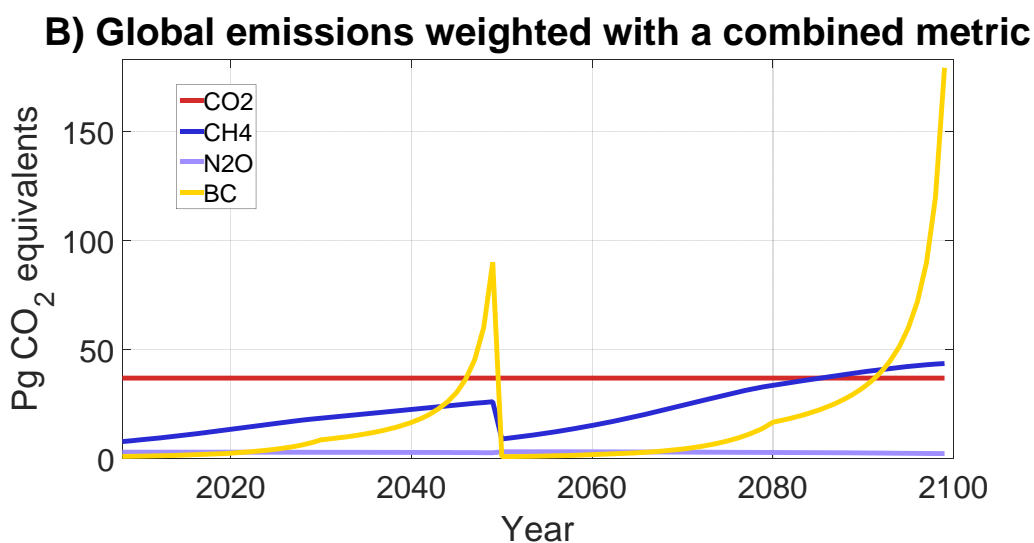**Figure 5: Metric values for investments that lead to constant emissions over a period of 20 years based on the baseline scenario. The weighting is α=0.5. GWP(20) and GWP(100) values are given as reference. For the rate metric (α=1), we apply the level metric after the period of binding rate constraint.**

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Figure 6: A shows the global 2008 emissions weighted by different emission metrics. The calculations is based on Fig. 3, with the rate constraint binding for the 2031-2050 period and level reached in 2081-2100. The level metric is here the same as α=0 and the rate metric equal to α=1. These metrics are given equal weight with α=0.5, while GWP(100) and GPP$_P$(20) are given for comparison. B is based on constant 2008 emissions for the rest of the century. The emissions are weighted with the combined metric (α=0.5).