Steering the climate system: Comment[*][†]

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Abstract

Lemoine and Rudik (2017) argue that it is efficient to delay reducing carbon emissions, due to supposed inertia in the climate system's response to emissions. This conclusion rests upon misunderstanding the relevant Earth system modelling: there is no substantial lag between CO_2 emissions and warming. Applying a representation of the Earth system that captures the range of responses seen in complex Earth System Models invalidates the original article's implications for climate policy. The least-cost policy path that limits warming to 2 °C implies that the carbon price starts high and increases at the interest rate. It cannot rely on climate inertia to delay reducing and allow greater cumulative emissions.

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Lemoine and Rudik (2017) (hereafter LR17) explore the implications of inertia[1] in the climate system for cost-effective paths to hold global warming to a target level, notably 2 °C above the pre-industrial level, an interpretation of the 2015 Paris Agreement (UNFCCC, 2015). LR17 make a logical point and derive policy implications from it. The logical point is that if there is a substantial lag between CO_2 concentrations and the resulting warming, then leveraging on this inertia allows limiting warming to less than 2 °C at a much lower cost than standardly concluded. However, their model uses a carbon cycle and climate response formulation not aligned with standard approaches of atmospheric science. These two factors jointly lead to quantitative results on the optimal timing of climate change mitigation and carbon prices that are not robust, which invalidates the policy-relevance of the logical point.[2] LR17 assume simple exponential decay functions to characterize both the response of atmospheric CO_2 concentrations to emissions and the time dependence of warming in response to CO_2 increases. Rather than rising at the interest rate according to Hotelling's rule (van der Ploeg, 2018), the least-cost carbon price in LR17 follows a hump-shaped path and grows much more slowly than the interest rate throughout the 21st century. Their cost-effective path delays emissions reductions for decades and, in their baseline case, keeps carbon prices near zero until 2075.

[1]Inertia is understood by LR17 to be between CO_2 concentration and warming, see below.

[2]Other aspects of LR17 may be questionable, but are beyond scope of our comment: Carbon budgets have superseded concentration targets as the standard approach to limiting warming (IPCC, 2014b), as they are more relevant for temperature targets such as expressed in the Paris Agreement. Most Integrated Assessment Models (IAMs) compute least-cost carbon prices subject to a constraint on cumulative CO_2 emissions or equivalent formulations because of the carbon budget approach. Also note that simple minimization of abatement costs leads to an optimal carbon price that is too low at the start and too high in the future, relative to maximization of welfare when both abatement and damages are included, because simply minimizing abatement costs is indifferent to the timing of the damages (Dietz and Venmans, 2019).

These conclusions differ markedly from findings in mainstream economic analysis, such as Golosov et al. (2014). They also differ from the conclusions of recent policy syntheses (Stiglitz and Stern, 2017; IPCC, 2014a), according to which cost-effective global carbon prices start high (in the range US$50-100 per metric ton of CO_2 in 2030) and rise quickly and with the interest rate to keep warming beneath 2 °C. By contrast, the cost-effective carbon price in LR17 is close to zero until 2030 (their Figure 1, Panel D).

The simple calibration used by LR17 involves lags between emissions and peak warming that are ten times as long as those in standard climate models (see Figure 1).[3] LR17's incomplete representation of the Earth system is the key to the difference between their and other policy conclusions mentioned above. While LR17 are correct to state that the "climate system displays substantial inertia, warming only slowly" (p. 2948), this statement only relates to the atmospheric *concentration* (i.e. the stock) of CO_2.[4] Their statement does not hold for the climate system's direct response to CO2 *emissions* since there is no significant time lag between *emissions* (i.e. the flow) of CO_2 and resulting warming, the more important relationship for economic policy relevance. The absence of a substantial lag between CO_2 emissions and resulting warming has been established in Earth System Models for more than a decade (IPCC, 2013;

[3]LR17 reference Solomon et al. (2009) in support of the claim of substantial time lag between emissions and warming, but the statement in Solomon et al. (2009) is focused on warming after the *cessation* of emissions and this should not be confused with the substantial prompt warming that occurs *while* emissions are occurring (see also Matthews and Solomon, 2013); results in Solomon et al. (2009) also show a rapid response of warming to CO_2 emissions.

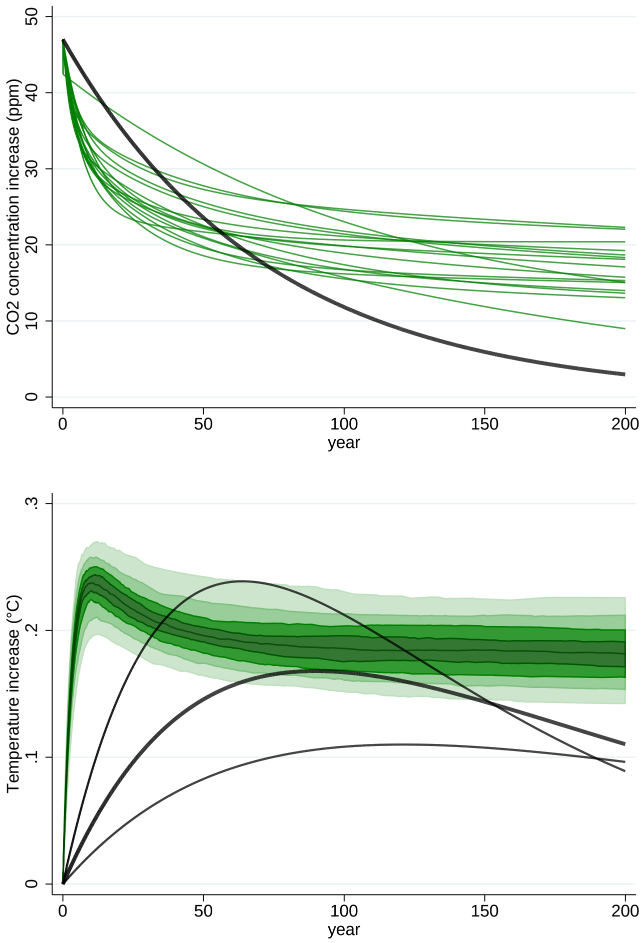
[4]Not-to-exceed concentration targets are no longer widely studied in climate science and politics because they have been superseded by the carbon budget approach (Allen et al., 2009; Matthews et al., 2009). If one thought that concentration targets were a useful starting point, one could believe that both LR17 and this piece support the claim that efficient mitigation policy to limit warming should be less stringent than policy limiting not-to-exceed carbon concentrations. But concentration targets are no longer relevant for climate policy.

Joos et al., 2013; Matthews and Caldeira, 2008; Matthews et al., 2009; Matthews and Zickfeld, 2012; Matthews and Solomon, 2013; Ricke and Caldeira, 2014).

Reassessing the LR17 climate model LR17 neglect two critical aspects of climate system inertia. First, the carbon cycle response to CO_2 emissions does not follow a simple exponential decay function, as assumed in LR17's carbon equation (1). Representing the carbon cycle with a single (finite) decay timescale implicitly assumes an infinite and unchanging capacity of the Earth system to absorb our CO_2 emissions. This neglects the well-known feature that the carbon cycle's ability to absorb our emissions will weaken with time. It means that delayed emissions reduction will impose a new penalty that will manifest as a decreased ability for the Earth system to absorb CO_2 emission in the future. Second, LR17's equation for the attendant warming (2) is again incorrect because it ignores the well-known behavior of the climate system that temperature responses to emissions or increased CO_2 concentrations display both fast and slow components, which cannot be accurately captured by LR17's single first-order expression (Held et al., 2010). Figure 1 illustrates the important discrepancies in time dependencies between state-of-the-art models versus LR17's simple expressions for carbon and temperature responses. It shows the response to a one-off pulse emission of 100 GtC CO2 as simulated in LR17 (black) and using decay functions representing combinations of carbon cycle and thermal responses as simulated by complex Earth System models (Joos et al., 2013; Geoffroy et al., 2013; Ricke and Caldeira, 2014) – see online appendix for underlying equations and details.[5]

[5] The Fifth Assessment Report of the Intergovernmental Panel on Climate Change contains a related model for the global warming potential of greenhouse gases (IPCC, 2013, ch. 8).

Figure 1: The decay of atmospheric CO_2 from a pulse of 100 Gt carbon emissions and the global temperature effect of such a CO_2 emission pulse



Temperature response in LR17 is too slow and too low. Black lines represent the climate representation in LR17 for their high, medium (bold) and low inertia scenarios. The green lines in the upper panel represent calibration to 16 independent, more sophisticated models of the carbon cycle model in Joos et al. (2013). The colored distribution in the lower panel marks the deciles of the distribution of response under combinations of Earth System Models consistent carbon-cycle and thermal response functions; see online appendix for notes on the sources of the data and details.

As Figure 1 shows, Complex Earth System model consistent climate representations first warm quickly in response to CO_2 emissions, followed by a long period in which temperatures remain nearly constant, because two different natural processes roughly cancel each other out. First, when emissions stop, the atmospheric concentration of CO_2 gradually decays, as carbon is absorbed by natural ocean and land sinks, but the changing shape of this decay illustrates that multiple decay times are involved, not just one as assumed in LR17. Second, the climate system very slowly approaches a thermal equilibrium with higher levels of atmospheric CO_2.[6] The first process (CO_2 decay) reduces future temperatures that would have occurred had concentrations remained at their peak value; the second process (thermal inertia) increases future temperatures. To a first order, the timescales and magnitudes of these two processes compensate each other, leading warming to plateau about 10 years after emissions stop and remain approximately constant thereafter (Matthews et al., 2009; Ricke and Caldeira, 2014; Solomon et al., 2010). Thus, ignoring the structure of the CO_2 decay function and the thermal response function[7] can lead to the false inference that the very long time it takes for the climate system to reach thermal equilibrium with a higher atmospheric CO_2 *concentration* implies a similarly long lag between CO_2 *emissions* and warming. This is not the case.

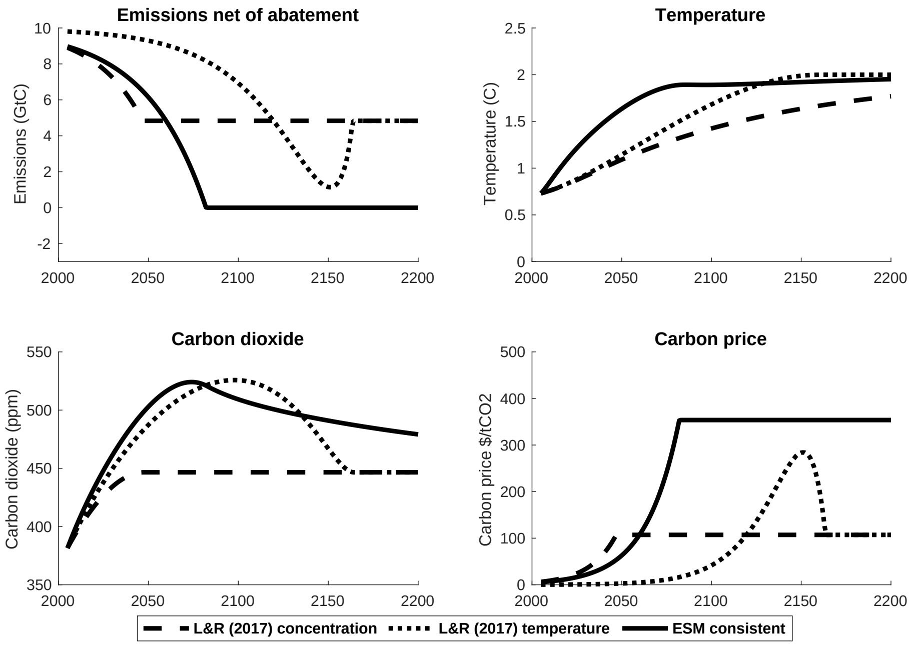
The climate representation used in LR17 is based on the DICE model, in which long-term warming in response to CO_2 emissions is also too slow when compared to more complex physical models (Nordhaus and Sztorc, 2013; Dietz and Venmans, 2019).[8] Sensitivity and robustness checks to the form of the

[6]LR17 use a thermal response function with a level of inertia that is an order of magnitude too large compared to more complex climate models, see Figure 3 in the Online Appendix.

[7]For an accurate thermal response function, it is crucial to introduce two heat reservoirs, one for the warming of the atmosphere and the upper ocean, and the other for the deep ocean, see Equations (2-3) in the Online Appendix.

[8]However, because DICE has multiple timescales, whereas LR17's model has only a single time scale, it will behave differently on any periods longer or shorter than the calibration

Figure 2: Trajectories of the optimal paths



Optimal mitigation paths with state-of-the-art atmospheric science. The two dashed paths shown correspond to the 2 °C and concentration targets of LR17 (reproducing their Figure 1, i. e. with the climate representation of LR17). The black path shows the optimal trajectory to reach 2 °C with an Earth System Model consistent climate representation, see online appendix. The four panels show emissions net of abatement, temperature, atmospheric CO_2 and the carbon price. Economic parameters are as in LR17.

climate representation are detailed in Mattauch et al. (2018). A sensitivity analysis with respect to an alternative carbon cycle used by LR17, which is based on Golosov et al. (2014) is included in the Online Appendix to this comment. Again, this variant in LR17 is inconsistent with state-of-the-art climate representations.[9]

period.

[9]Note while Figure D1 of LR17 has similar emissions trajectories to our Figure 2, their variant produces warming that is markedly too slow.

Implications for climate policy We show that introducing climate dynamics that are aligned to those simulated by full-complexity Earth System Models to LR17's analysis invalidates their policy conclusions. Carbon prices cost-effectively keeping warming below a target level start around an order of magnitude higher than found in LR17, as a result of this change alone. Prices grow approximately at the interest rate, consistent with Hotelling (1931), and much faster than in LR17.

Figure 2 shows the outcome of replacing the climate representation of LR17 with the best fit for the Earth System Model representation from the distribution shown in Figure 1. The economic analysis is conducted identically to that in LR17 (for details see Mattauch et al. (2018)). Simply updating the climate representation in LR17 to be approximately representative of the response of Earth System models changes the core policy finding of LR17, with the initial carbon price needed to minimize the cost of meeting a 2 °C target at around 5.6 $\$/tCO_2$, rather than being effectively zero. The subsequent evolution of the optimal carbon price then follows a qualitatively different path to the least-cost carbon price in LR17, rising at the interest rate, rather than, as in LR17, slowly rising over the 21st century before eventually rising fast, peaking and declining.[10] Near-zero emissions of CO_2 are required in order to stabilize global temperature, consistent with recent assessments of the Intergovernmental Panel on Climate Change (IPCC, 2018), and contrasting sharply with that found in LR17.

[10] In Mattauch et al. (2018), we check that this holds for a wide range of calibrations beyond LR17's main scenario. See also Mattauch et al. (2018) for additional parameters used and calibration of initial values.

Conclusion LR17 model a climate system that is not consistent with the response of global temperature to CO_2 emissions as simulated by complex Earth System Models. The artificial inertia introduced into the climate system by their simple first-order response formulation leads LR17 to find an optimum trajectory with delayed CO_2 emissions abatement. It also leads to their claim of other studies that "[b]y failing to take advantage of the climate system's inertia, these modelled policies undertake more total abatement than necessary and ramp up policy faster than necessary" (LR17, p. 2956). As we have shown in this comment, these conclusions are artifacts of using climate and carbon representations at odds with current understanding of the climate system.

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Online Appendix

Here we compare the physical climate model of LR17 with the model we derived from Joos et al. (2013) and Geoffroy et al. (2013) and which was employed by IPCC (2013, ch. 8).

Let us first look at the decay of atmospheric CO_2, then temperature inertia. LR17 model the decay of atmospheric CO_2 as

$$\dot{M}_t = E - \delta M_t,$$

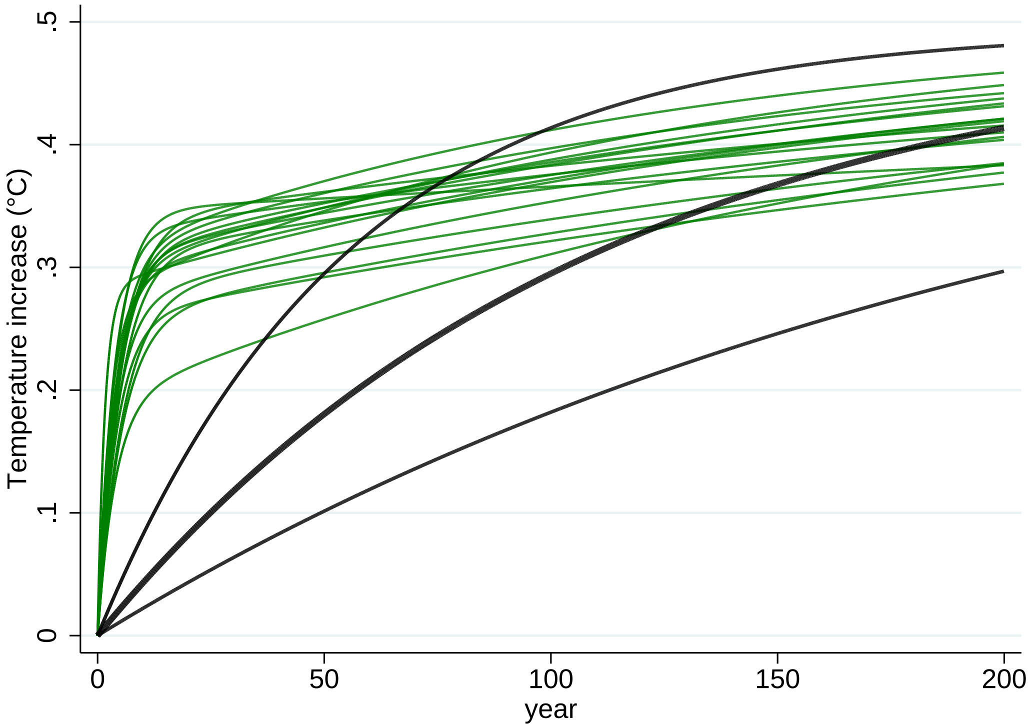
where M_t is the increase in the atmospheric CO_2 concentration from the preindustrial level, δ the decay rate and E is the baseline flow of CO_2 emissions into the atmosphere. The difficulty facing this simple representation of the decay of atmospheric CO_2 is that the global carbon cycle has multiple timescales and a significant fraction of CO_2 emissions will remain in the atmosphere for many thousands of years. This can be represented by

$$\dot{M}_t = \sum_{i=0}^{3} \dot{M}_t^i = \sum_{i=0}^{3} a_i E - \delta_i M_t^i \tag{1}$$

with $\sum_{i=0}^{3} a_i = 1$ and $\delta_0 = 0$ and $M_t = \sum_{i=0}^{3} M_t^i$. Following the use of this specification in IPCC (2013), we use the best fit of Equation (1) to 16 independent, more sophisticated models of the carbon cycle (Joos et al., 2013). This allows us to compare LR17's climate dynamics with a set of more physically realistic carbon-cycle models.

Second, consider the treatment of temperature inertia in response to the atmospheric concentration of CO_2 in LR17. This is modelled as an exponential

Figure 3: Increase in temperature for a constant increase in CO_2 concentration by 47 ppm



Black lines represent the climate representation in LR17 for their high, medium (bold) and low inertia scenarios. The green lines represent calibration to 16 independent, more sophisticated models of the temperature response in Geoffroy et al. (2013).

process towards a steady-state temperature,

$$\dot{T}_t = \phi(sF(M_t) - T),$$

with T being global mean surface warming above the pre-industrial level, F the radiative forcing (W/m^2) resulting from elevated atmospheric CO_2, and s a transformation of the parameter known as climate sensitivity, i.e. the long-run equilibrium warming that would result from a doubling of the CO_2 concentration.[11] ϕ is the crucial thermal inertia parameter.

A single response timescale is insufficient to characterize the response of the surface climate system to radiative forcing, as shown in Held et al. (2010) and see Figure 3. A more representative model comprises two heat reservoirs, one for the warming of the atmosphere and the upper ocean T, and one for the warming of the deep ocean T^o :[12]

$$\dot{T}_t = \frac{1}{c}(F(M_t) - bT_t) - \frac{\gamma}{c}(T_t - T^o_t) \tag{2}$$

$$\dot{T}^o_t = \frac{\gamma}{c_o}(T_t - T^o_t). \tag{3}$$

IPCC (2013, ch. 8) employs this simple model, calibrated on the outputs of 16 independent, more sophisticated climate models by Geoffroy et al. (2013), and we do likewise. The calibrations were based on behaviour of the more sophisticated models under an instantaneous quadrupling of atmospheric CO_2 concentrations, which are then held fixed.[13]

Comparison to Golosov carbon cycle We examine the alternative specification of the carbon cycle due to Golosov et al. (2014), which was employed by

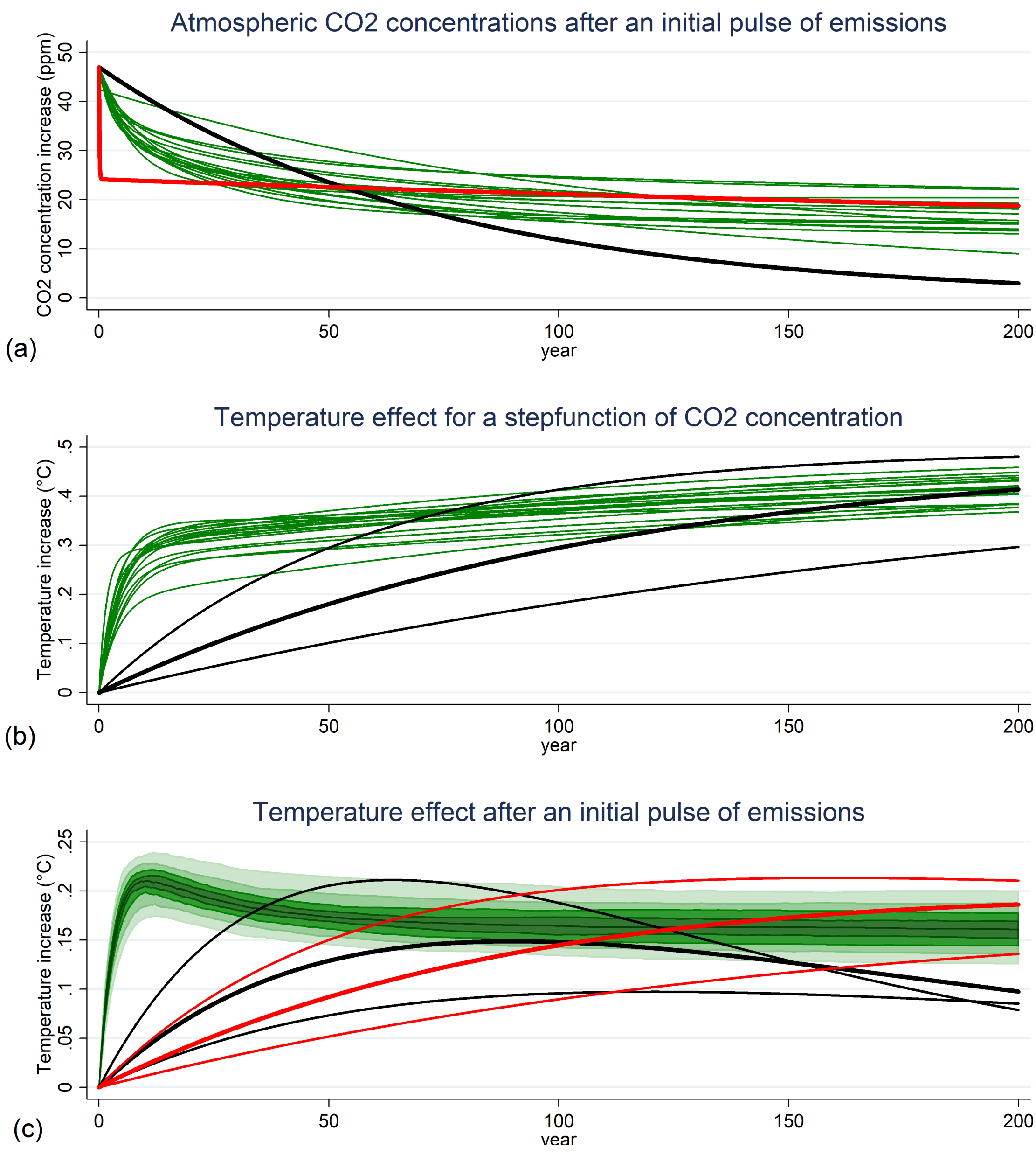
[11] Here, sF, for doubled CO_2 concentration, corresponds to the equilibrium climate sensitivity.

[12] Here c and c_0 are effective heat capacities per unit area, λ is a radiative feedback parameter per unit area for an additional degree of warming and γ is a heat exchange coefficient representing the transfer of heat for a difference of 1 degree between upper and lower ocean, see Geoffroy et al. (2013).

[13] Further, we assume the same formula for radiative forcing as LR17: $F(M) = \alpha \ln((M + M_{pre})/M_{pre})$. Defining climate sensitivity cs as steady state warming for a doubling of atmospheric carbon emissions, allows to easily compare our formulation of temperature response $\dot{T} = b/c(cs/\ln 2 * \ln((M + M_{pre})/M_{pre}) - T) - \gamma/c(T - T)$ with LR17's expression $\dot{T} = \phi(cs/\ln 2 * \ln((M + M_{pre})/M_{pre}) - T)$, with M_{pre} the pre-industrial concentration level. These formulas were used to set different climate sensitivities in Geoffroy et al. (2013) to 3 °C for Figures 1 and 3.

LR17 in their Online Appendix D. Figure 4 shows the results from substituting in the carbon decay model of Golosov et al. (2014). When the model of Golosov et al. (2014) is put in, the disparity with the IPCC models is even greater.

Figure 4: The effect of a CO_2 emission pulse, including Golosov et al. decay



In addition to Figure 1 and 3, red lines represent the climate model in Online Appendix D of LR17, based on Golosov et al. (2014), for their high, medium and low temperature inertia scenarios.