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# Current level and rate of warming determine emissions budgets under ambitious mitigation

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# Supplementary Information for "Current level and rate of warming determine emissions budgets under ambitious mitigation"


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This Supplementary Online Material provides four additional figures illustrating points and supporting arguments made in the main text and Methods.

Fig. S1 shows three idealised anthropogenic warming scenarios and their associated carbon dioxide forcing equivalent ($CO_2$-fe) emissions. Anthropogenic warming to the present-day (computed as described in Fig. 1) is extended in three different ways: by keeping the rate of warming constant, increasing at $T_0' = 0.2$°C/decade; by stabilising warming at 1.5°C with a quadratic profile ($T(t) = T_0 + T_0'(t - t_0) - T_0'(t - t_0)^2/(2(t_1 - t_0))$ for $t_0 \leq t \leq t_0 + t_1$); and by stabilising warming at 1.5°C with an exponential profile of $T(t) = T_0 + T_1(1 - e^{-(t-t_0)/\rho}$ for all $t \geq t_0$). We then diagnose $CO_2$-fe emissions for these three profiles with the FAIR model[1,2] with parameters identical to those indicated by the best-estimate anthropogenic warming and forcing to date. This then illustrates the physical meaning of $\rho$ – it is the time until the constant warming rate profile exceeds 1.5°C (25 years in this schematic); half the time required for a quadratic profile to stabilise (since $T(t_1) - T(t_0) = \Delta T = T_0'(t_1 - t_0)/2$, hence $\rho = \Delta T/T_0' = (t_1 - t_0)/2$); or the decay constant for an exponential stabilisation profile*. From the $CO_2$-fe emissions in panel b it is clear that quadratic temperature stabilisation is approximately equivalent to a linear reduction in $CO_2$-fe over $2\rho$ years. We note in panel b that with this set of parameters in FAIR, TCRE declines slightly under steadily increasing forcing due to the logarithmicity of $CO_2$ radiative forcing, hence the emissions required to maintain a constant warming rate increase by about 10% by the time temperatures reach 1.5°C, but this is not the case in general nor with many more complex models.

*shown as follows: for general exponential stabilisation, $T'(t) = T'(t_0)e^{-(t-t_0)/\lambda} = rE(t)$; thus $\int_{t_0}^{\infty} E(t)dt = \lambda E(t_0)$; since $\Delta T = r\int_{t_0}^{\infty} E(t)dt$, $\lambda = \Delta T/T_0' = \rho$.

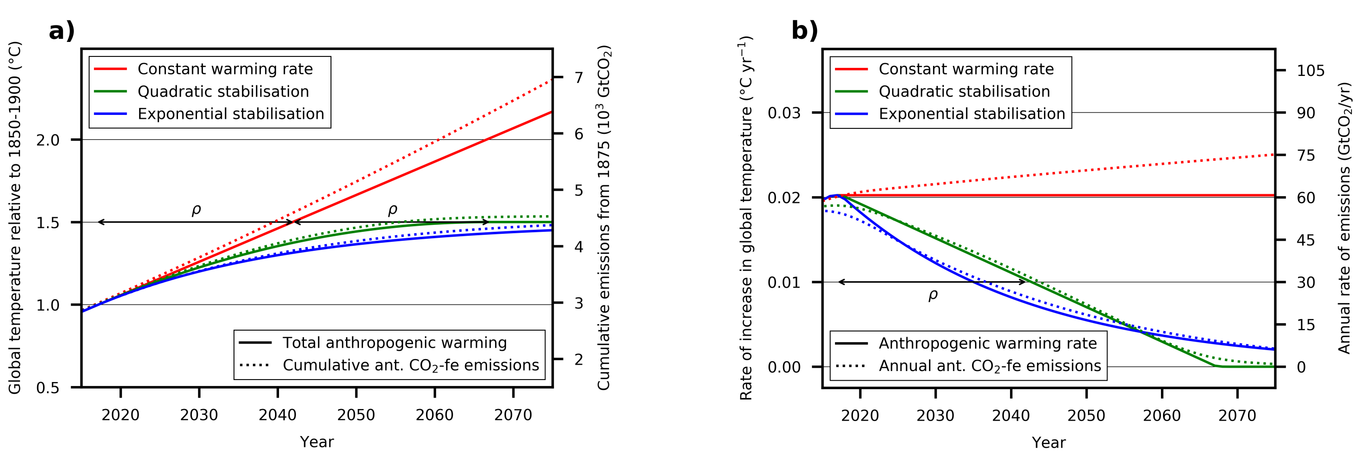


Figure S1: **Illustrating the mitigation timescale, $\rho$, under different temperature scenarios. a)** Anthropogenic temperature scenarios and corresponding cumulative $CO_2$-fe emissions. Red lines show a scenario in which rate of change of warming remains constant from the present day. Green lines show a scenario in which the temperature gradient is reduced linearly to zero such that temperature stabilises at 1.5°C. Blue lines show a scenario in which temperature stabilises at 1.5°C with an exponential profile. **b)** Rates of change of the quantities plotted in panel a. Black arrows in both panels indicate the $\rho$ timescale.

Fig. S2 clarifies our step in filtering the AR5 WG3 scenarios[3] to retain only mitigation pathways consistent with present-day $CO_2$ emissions and non-$CO_2$ radiative forcing (many pathways in the database assume aggressive global mitigation starting in 2010). We preselect scenarios in which temperatures reach a peak value before 2100, which are the most relevant to relatively high levels of mitigation. We then filter these by two criteria: that annual $CO_2$ emissions are within 5-95% of observed[4] in 2016; and that the rate of change of non-$CO_2$ forcing is within 5-95% of the rate of increase in observed forcing,[5] updated, in 2016. We have shown these criteria in panels a and b through an errorbar showing the 5-95% range of observed $CO_2$ emissions in 2016 in panel a, and the two black lines in panel b, which have gradients equal to the $5^{th}$ and $95^{th}$ percentiles of rate of change of observed non-$CO_2$ forcing in 2016. The uncertainty in absolute non-$CO_2$ forcing is too large to constrain these scenarios. These filtration steps reduce the number of applicable scenarios from 524 to 94. Panel c supports the statements made in the main text regarding the fractional contribution of non-$CO_2$ to total forcing; it shows that for the majority of all scenarios, except those in which non-$CO_2$ forcing is already falling rapidly through the 2010s, contrary to observed trends, this contribution increases, and for many of the most ambitious mitigation scenarios that we select as being realistic relative to the present day, after 2020 this contribution remains relatively stable. As the AR5 WG3 scenarios report only non-$CO_2$ radiative forcings only, we assume these are indicative of the changes in effective radiative forcing.

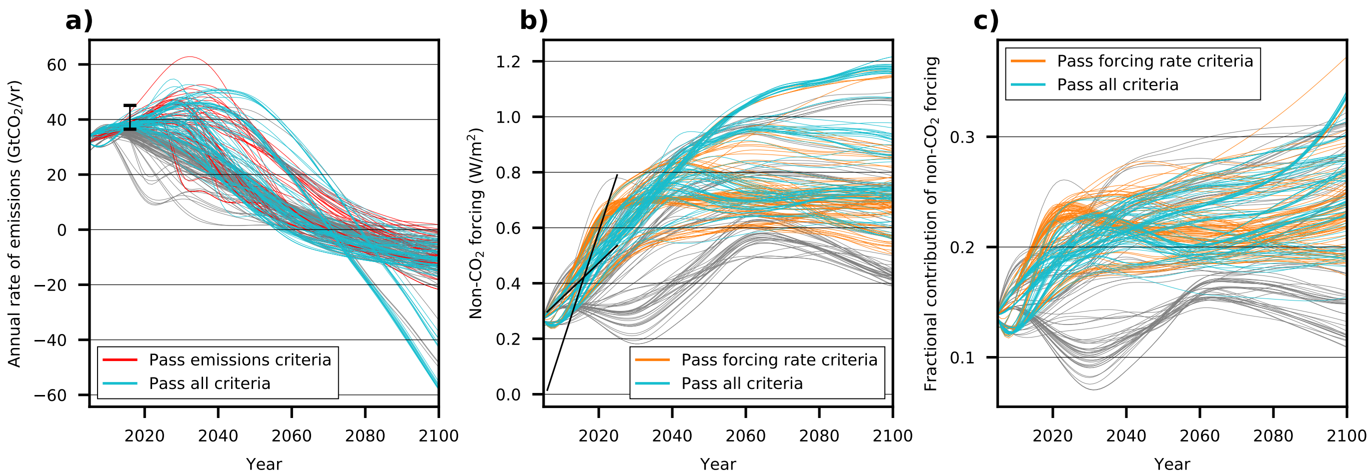


Figure S2: **AR5 WG3 database scenario filtration step. a)** $CO_2$ emissions in the AR5 WG3 scenarios. Grey lines show scenarios in which temperatures peak before 2100 but did not pass either other criterion, red lines show scenarios that pass the $CO_2$ emissions level criteria, and turquoise lines show scenarios that pass CO2 emissions level and non-$CO_2$ forcing rate criteria. The black errorbar indicates the range of emissions which we have filtered over. **b)** Non-$CO_2$ forcing in the AR5 WG3 scenarios. Grey lines show scenarios that did not pass any criteria, orange lines show scenarios that pass non-$CO_2$ forcing-rate criteria, and turquoise lines show scenarios that pass both criteria. The black lines indicate the gradient range which we have filtered over. **c)** Fractional contribution of non-$CO_2$ to total anthropogenic forcing in the AR5 WG3 scenarios. Line descriptions as panel b.

Fig. S3 compares mitigation timescales for smoothed (Gaussian filter, $\sigma = 5$ years) CMIP5 and EMIC model output global mean surface temperature (GMST) with attributable warming diagnosed from the unsmoothed model output using the "multi-fingerprinting" method described in Methods, as introduced in Otto et al. (2015)[6] and updated as the "Global Warming Index" in Haustein et al. (2017).[7] In panels a and b attributable warming is calculated from a regression of FAIR model responses to anthropogenic and natural observational forcing,[5] against raw model GMST output in the RCP2.6 and 8.5 experiments.[8,9] In panels c and d attributable warming is calculated from a regression of CMIP5 model GMST onto the estimated[1] responses to smoothed (gaussian filter, sigma = 10) CMIP5 anthropogenic forcings diagnosed from individual models and standard natural forcings.[10] We have included uncertainty due to internal variability (50 variations, from the CMIP5 pre-industrial control ensemble) in all attributable warming ensembles, while forcing uncertainty is additionally included in panels a and b. The present-day rate of warming is calculated as the gradient of the linear regression line for the temperature period 2013-2017, as in Fig. 3. We note that in panels c and d, the uncertainties in model-simulated radiative forcings are an important additional unknown, and their inclusion would likely extend the 5-95% errorbar in the attributable warming ranges. Note that both versions of the HadGEM2 model have anomalously strong aerosol forcing in the late 20[th] century, while the GFDL-ESM2G model has an anomalously low current rate of warming. Given these anomalies, the fraction of models outside the 5-95% uncertainty ranges is as expected for such a 'perfect model', 'imperfect forcings' test.

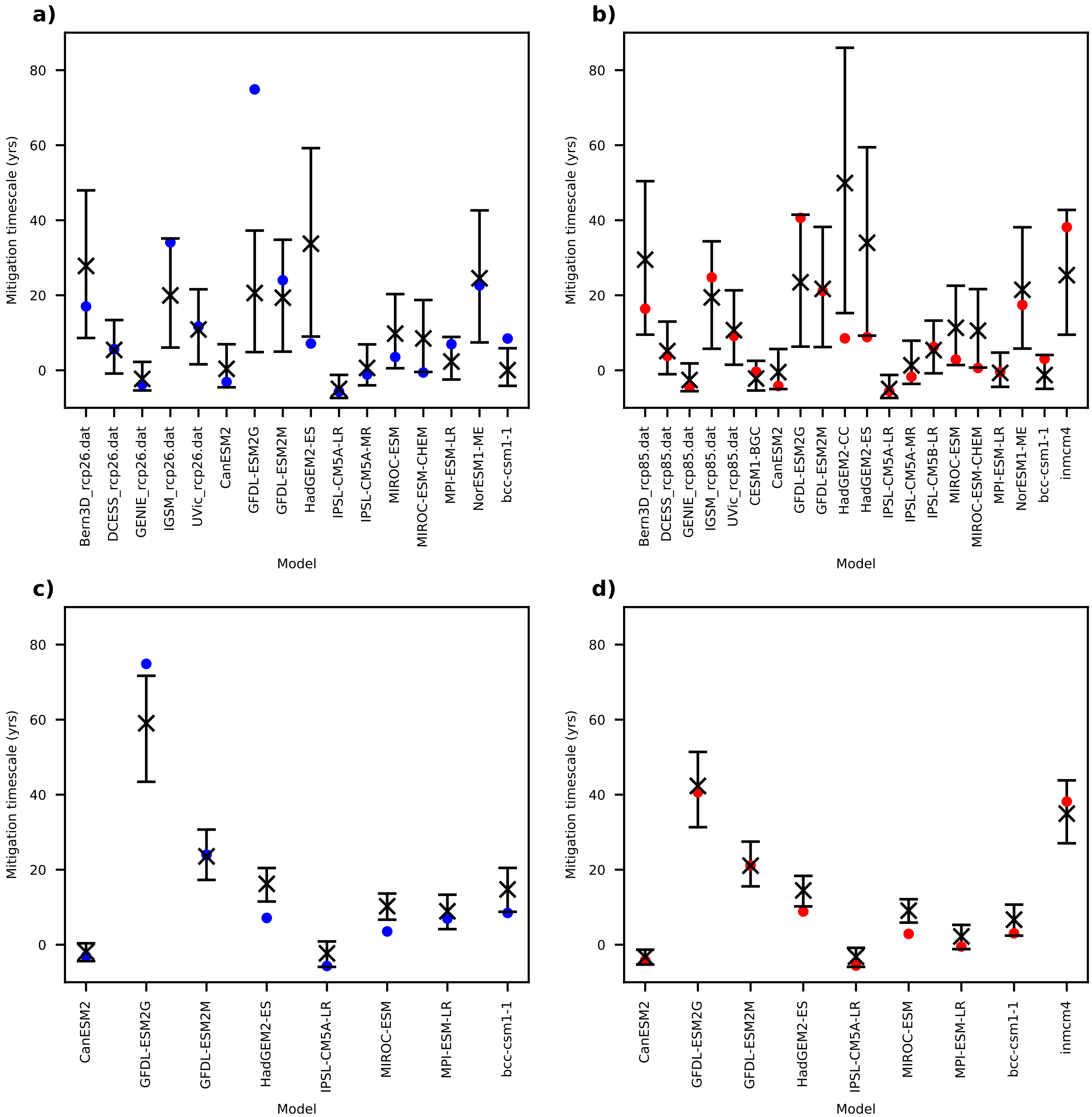


Figure S3: **Mitigation timescales in CMIP5 GCMs and EMICs: attributing warming from model output GMST. a) - d)** Blue and red dots show present-day (2017) mitigation timescale, $\rho$, estimated directly from smoothed model output from RCP2.6 and 8.5 experiments respectively. **a) and b)** Black errorbars display 5-95% timescale range for attributable warming in each model experiment, calculated from anthropogenic and natural observational forcing response ensemble, including internal variability uncertainty. **c) and d)** Black errorbars display 5-95% timescale range for attributable warming in each model experiment, calculated similarly from anthropogenic forcings diagnosed from individual models and CMIP5 standard natural forcings, including internal variability uncertainty only.

Fig. S4 shows the magnitude of contributions from natural variability (volcanoes, ENSO and solar incoming radiation) on the present-day warming trend. We use the multiple regression method introduced in Foster and Rahmstorf (2011),[11] which allows for lags between the individual regressors to obtain the best fit. Volcanic and solar forcing is updated from AR5. The secular warming trend is assumed to be linear, which is broadly correct for the 1979-2017 period considered here. The resulting temperature time series with natural factors being removed has a warming trend of 0.18 ($\pm$0.04)°C/decade, which is the remaining attributable warming trend due to anthropogenic influence. We note that the trend is very close to the estimate obtained in Haustein et al. (2017)[7] for the same period, although these data are too noisy to detect an acceleration without further information (as provided by forcing series in Haustein et al., 2017). The regression method effectively filters out most of the multi-annual temperature deviations associated with volcanic eruptions and ENSO. While the residuals (noise term) do show peak amplitudes for unexplained internal variability $\sim$0.3°, there is no evidence of unaccounted-for multi-decadal variability. This is also true for the removed natural variability which does not support the notion of strong multi-decadal variability.

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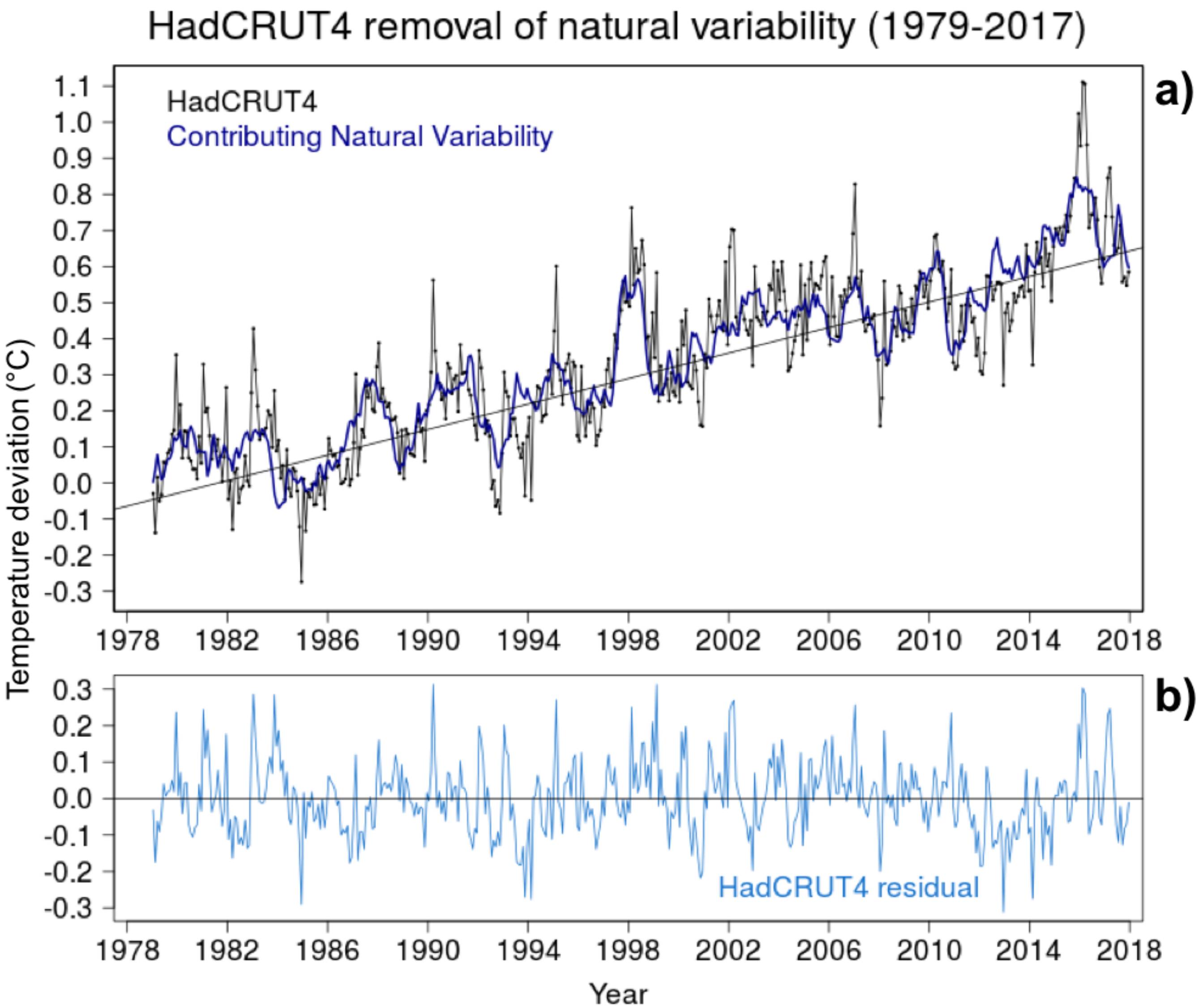


Figure S4: **Removal of natural (non-anthropogenic) factors from the HadCRUT4 temperature time series for the 1979-2017 period.** **a)** The black dotted line shows the original monthly HadCRUT4 data. The thick dark blue line shows the natural contributions from volcanic eruptions, El Niño Southern Oscillation (ENSO) and varying solar incoming radiation. A multiple regression method[11] is applied that allows for lags in the temperature response. The black trend line corresponds to the linear trend between 1979-2018, which is 0.18 (±0.04)°C/decade. **b)** Residual "noise" in the HadCRUT4 time series with trend and natural contributions removed (difference between black and blue line in panel a).