¹ Adaptive emission reduction approach to reach

² any global warming target

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20 The parties of the Paris Agreement agreed to keep global warming well below 2°C and pursue efforts to 21 limit it to 1.5°C. A global stocktake is instituted to assess the necessary emissions reductions every five 22 years. Here, we propose an adaptive approach to quantify successively global emissions reductions that 23 allow reaching a temperature target within ±0.2°C – solely based on regularly updated observations of 24 past temperatures, radiative forcing, and emissions statistics and not on climate model projections. 25 Testing this approach using an Earth System Model of Intermediate Complexity demonstrates that 26 defined targets can be reached following a smooth emissions pathway. The adaptive nature makes the 27 approach robust against inherent uncertainties in observational records, climate sensitivity, 28 effectiveness of emissions reduction implementations, and the metric to estimate CO₂ equivalent 29 emissions. This approach allows developing emission trajectories for CO₂, CH₄, N₂O, and other agents 30 that iteratively adapt to meet a chosen temperature target.

31 Human-made emissions of greenhouse gases (GHG) and other radiative forcing agents have led to global 32 warming of around 1.2°C by 2020¹ with already observable negative impacts on the world's climate and ecosystems^{2,3}. To limit the impact from further warming^{4,5}, 191 countries signed the Paris agreement to 33 "keep global warming well below 2°C and to pursue efforts to limit it to 1.5°C" by reducing GHG 34 emissions⁶. As a central part of the agreement, a regular five-year stocktake process was instituted to 35 36 assess collective progress in reducing emissions over the previous five-year period and to reassess the 37 necessary global emission reductions for the following five years and beyond. Each signatory country 38 provides its nationally determined contributions (NDCs) to the globally necessary GHG emissions 39 reductions.

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These necessary reductions to reach a chosen temperature target are often derived using the concept of 41 a remaining emissions budget (REB)^{2,7-9}. Such a REB quantifies the total allowed emissions that can still be 42 43 emitted from the present-day onwards before a temperature target is reached. In the past, REBs usually only included CO2⁸⁻¹². Non-CO2 forcing agents were generally included as prescribed, scenario-dependent, 44 climate forcing, bringing an additional uncertainty into the remaining carbon budget⁸⁻¹³. To consider 45 emissions of different radiative forcing agents and precursors in one budget, the concepts of Global 46 Warming Potential (GWP)¹⁴ and CO₂-forcing equivalent (CO₂-fe) emissions^{7,15,16} can be used. The GWP for 47 48 a time horizon of 100 years (GWP-100) is the metric applied by the parties of the Paris Agreement, 49 although GWP-100 equivalent emissions from different gases do not result in identical forcing trajectories 50 and climate impacts^{7,15,17–19} and other metrics can be additionally used for reporting²⁰. CO₂-fe emissions 51 are defined as the amount of CO_2 emissions that would cause the same radiative forcing trajectory as 52 emissions from a non-CO₂ agent (e.g., methane). Thus, the CO₂-fe metric is best suited to compare 53 emissions from different agents in the context of forcing and temperature stabilization pathways. 54 However, even when non-CO₂ emissions are transferred to CO₂-fe emissions and added to the total REB

and not treated as an additional uncertainty of the remaining carbon emissions budget, estimations of
the REB in 2020 that allows reaching the 1.5°C temperature target still *likely* vary by a factor of more than
two (130–300 Pg C)^{7,21}.

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This range mainly stems from uncertainties in the global temperature response to changes in radiative forcing agents and precursors^{8,22–25}, historical CO₂-fe emissions⁷, historical anthropogenic warming^{26–29}, change in temperatures after net zero CO₂-fe emissions are reached³⁰, and future sources and sinks of CO₂ and other agents^{30–36}. Furthermore, natural interannual-to-decadal variability in temperature^{37–39}, and land and ocean carbon and heat sinks^{33,40} may mask effects of GHG emissions reductions^{41,42}.

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The large REB uncertainties may hamper efforts to establish ambitious NDCs and could potentially lead to insufficient global emission reductions, large global warming, and severe consequences for natural and human systems^{2,43,44}. Therefore, emissions reductions should be estimated at each stocktake using approaches that side-step these uncertainties and allows smoothly approaching a temperature target. Such approaches should be transparent, verifiable, and, to the extent possible, objective to foster their acceptance as well as the implementation of the implied near-term emissions reduction measures. Such a science-based approach to guide near-term emission reduction policies is currently missing.

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73 The Adaptive Emissions Reduction Approach (AERA)

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Here, we propose an Adaptive Emissions Reduction Approach (AERA) to estimate the necessary emission
reductions until temperature stabilization successively every five years (e.g., 2025, 2030, ...) as foreseen
by the stocktake mechanism. By adapting emissions every five years, the AERA works like a control system
that corrects emissions based on the realized warming to eventually approach a prescribed temperature

target within a narrow range (±0.2°C). For example, a temperature target of 1.75°C may be chosen to estimate the emissions for keeping "global warming well below 2°C". At a future stocktake, the temperature target can be re-defined, for example "to pursue efforts to limit it to 1.5°C".

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The AERA only relies on global surface temperature observations, radiative forcing (RF), and emissions data, and does not rely on any Earth system model projections. Its adaptive nature ensures that emission reductions are quantified that allow meeting the foreseen temperature target, irrespective of uncertainties in understanding the climate system. Such adaptive learning and stepwise adjustment of the emission reduction target has been shown to help reducing costs⁴⁵ and to avoid strong negative outcomes for the economy and the environment⁴⁴.

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90 The AERA consists of three main steps: (1) determining the past anthropogenic warming and hence the 91 remaining warming allowed, (2) estimating the remaining CO_2 -fe emission budget, and (3) proposing a 92 future CO2-fe emission curve until temperature stabilization (Figure 1; see Methods). First, the 93 anthropogenic warming is calculated from observed global mean surface temperature (GMST) time-series using the past RF of all relevant forcing agents (labelled as 'Step 1' in Figure 1)⁴⁶. This approach removes 94 95 temperature changes from natural variability and non-anthropogenic forcing, such as volcanic eruptions and changes in solar activity, by fitting an Impulse-Response Function^{47,48} to the RF and GMST time-series, 96 97 only leaving the anthropogenic contribution to the observed warming. Alternatively, natural, interannualto-decadal variability in GMST may also be removed by applying a smoothing spline or another low pass 98 filter^{49,50}. Once the realized anthropogenic warming is determined, the remaining warming between the 99 100 temperature target and the realized anthropogenic warming is estimated by difference.

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105 Fig. 1. Schematic of the Adaptive Emission Reduction Approach to limit global warming. The three steps are 106 repeated at the year of each stocktake (indicated on the left) to determine allowable emissions for the next five-107 year period (red numbers on the right) from temperature observations and forcing and emissions statistics. The 108 approach is illustrated using results from one Bern3D-LPX simulation with ECS=3.2°C as a surrogate for future 109 observations (black lines in insets). Step 1: Estimation of the anthropogenic warming (red lines in inset) at the time 110 of the stocktake from past time-series of GMST (black line) and anthropogenic radiative forcing. Step 2: Estimation 111 of the remaining CO₂-fe emissions budget (REB; space between dashed red lines) based on the observed linear 112 relationship between anthropogenic warming (ΔT_{ant}) and cumulative CO₂-fe emissions (black line). Step 3: Allocation 113 of the REB over the next five years and beyond using a cubic function with minimal slope changes (red line). The 114 approach stabilizes ΔT_{ant} close to the given target, here 1.5°C, as illustrated in the bottom left inset.

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Second, the REB of CO₂-fe emissions is estimated using the transient climate response to cumulative emissions (TCRE)^{51,52}, determined as the ratio of past warming and past cumulative CO₂-fe emissions (Step 2 in Figure 1). Mathematically, the REB is estimated as the remaining warming until the temperature target divided by TCRE. Therefore, we rely here on the near-linear relationship between cumulative CO₂fe emission and warming over the past and the assumption that this relationship holds for the nearfuture^{14,53}.

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124 When quantified, the REB of CO_2 -fe emissions is distributed over the future years (Step 3 in Figure 1). 125 Many possible future CO₂-fe emission curves may exist for one specific REB with different lengths and economic and political assumptions⁵⁴. For simplicity, we use a cubic polynomial function and chose the 126 127 parameters of the cubic function and its length, i.e., the time until the REB is exhausted, by minimizing 128 the curvature. Thereby, we assume that smaller changes in the trend of CO₂-fe emission curves are easier 129 to implement. It may happen that the curve with the smallest curvature has positive emissions that are 130 later compensated by negative emissions, which would result in a temporary temperature overshoot that could be harmful to the economy^{55,56} and ecosystems^{57,58}. To reduce the risk of such an overshoot, we also 131 132 minimized exceedance emissions, i.e., negative emissions if the REB is still positive or positive emissions 133 if the REB is negative. A negative REB can occur if the anthropogenic warming or the TCRE turns out to be 134 larger than estimated in the previous stocktakes.

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The three steps of the AERA are intended to be repeated every five years at each stocktake (Figure 1). At each stocktake, the determined future CO₂-fe emission curve until temperature stabilization can be split into contributions from CO₂, CH₄, and N₂O emissions, as well as contributions from other non-CO₂ forcing agents. This split may be achieved using a metric of choice, for example CO₂-fe emissions, which captures the temperature change per CO₂-fe emissions precisely^{7,15–17} or GWP-100^{18,19,59}, which is simpler and can

nevertheless lead to relatively good results in terms of mitigation costs and climate outcomes^{60,61}. 141 142 Independent of the metric to split the CO₂-fe emissions into CO₂ and non-CO₂ emissions, the AERA adjusts 143 the future CO₂-fe emission curve every five years based on the most up-to-date observations of GMST, RF, and CO₂-fe emissions. If the anthropogenic warming will turn out to be larger or smaller than 144 anticipated by the time of the next stocktake, the adaptive nature of the AERA will adjust this successively, 145 146 much like a control system with a feedback loop. These regular adaptations successively correct for 147 inherent uncertainties of the respective system, here the estimation of the realized anthropogenic 148 warming and the response of GMST to anthropogenic emissions.

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150 Testing the AERA with an Earth System Model

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152 Uncertainties are not explicitly considered in a control system, c.f., the AERA, but they determine how 153 well the control system is functioning. We demonstrate that the AERA allows to reach a chosen 154 temperature level, also those well below 2°C, within the uncertainty with which the anthropogenic warming can be determined (±0.2°C)²⁶⁻²⁹, independent of uncertainties in the Earth's temperature 155 156 sensitivity to GHGs and other agents, the strength of the land and ocean carbon sinks, radiative forcing 157 estimates, the split-up of CO₂-fe emissions in CO₂, CH₄, and N₂O emissions and the applied method (CO₂-158 fe or GWP-100), and under deviations between emission reductions quantified by the AERA versus those 159 implemented. To that end, we used the Earth System Model of Intermediate Complexity Bern3D-LPX^{62,63} 160 under nine different configurations with varying atmospheric sensitivity to atmospheric forcing agents 161 and varying ocean mixing (see methods). These configurations cover the range of estimates of the transient climate response $(1.3-2.5^{\circ}C)^{24}$ and equilibrium climate sensitivities $(1.9-5.7^{\circ}C)^{24}$ (see Methods). 162 163 Depending on the configuration, the simulated anthropogenic warming in 2020 with prescribed historical 164 CO₂ emissions and non-CO₂ radiative forcing ranges from 0.64 to 1.48°C versus 1.23±0.20°C from

observations (Extended Data Figure 1). The remaining warming in the ensemble would deviate from the observational estimate when prescribing a fixed target in the model. To address the uncertainty in remaining emissions, the remaining warming in 2020 is set to the observational estimate (0.27°C for the 1.5°C target, see Methods) regardless of their simulated warming up to 2020.

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170 Here, we tested the AERA for two fixed temperature targets (1.5°C and 2.0°C) and for a peak and decline 171 case with a temperature target of 1.75°C until 2050 to "keep global warming well below 2°C", but from 172 2050 onwards, the target is reduced at each stocktake by 0.025°C and reaches 1.5°C in 2100 "to pursue efforts to limit it to 1.5°C"⁶. The target could be further reduced to avoid any exceedance of the 1.5°C 173 174 limit. The choice to which extent emissions are reduced by reducing CO₂ emissions versus reducing emissions of any other agents are not dictated by the AERA. We exemplify trade-offs in emissions by 175 176 exploring different choices, e.g., regarding GHG and aerosol emissions reductions. In the standard 177 simulation, CO₂, CH₄, and N₂O emission curves evolve proportional in time after 2025 (Figure 2d-f). An 178 updated reduced form chemistry model⁶⁴ is used to calculate non-CO₂ GHG and aerosol radiative forcing 179 from emissions (see Methods). Eventually, the emission curves for individual agents are chosen for which 180 the resulting CO_2 -fe emissions from all forcing agents match best the CO_2 -fe emissions from the AERA. 181 Atmospheric CO₂ and GMST for the next five-year period are then simulated by the Bern3D-LPX model 182 using the AERA-estimated CO₂ fossil fuel emissions, non-CO₂ forcing, and CO₂ emissions from land use 183 change.

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The simulations demonstrate that the AERA allows reaching a chosen temperature level almost exactly at the end of the 22^{nd} century and already within the uncertainty to which anthropogenic warming can be determined $(\pm 0.2^{\circ}C)^{26-29}$ in the second half of the 21^{st} century independent of the model's configuration (Figure 2a). A temporal, small overshoot may occur if the REB was initially overestimated.



190 Fig. 2. Globally averaged surface atmospheric temperature anomaly with respect to 1850-1900, CO₂-fe emissions, their annual rate of change, as well as CO₂, 191 CH₄, and N₂O emissions following the adaptive emission reduction approach. (a) Temperature anomalies with respect to 1850-1900, (b) CO₂-fe emissions, and 192 (c) their annual rate of change if the AERA is applied every five years starting in the year 2025 for the 1.5°C target (blue) and the 2.0°C target (orange), as well as 193 the AERA-calculated emission curves for the proportionally evolving (d) CO₂, (e) CH₄, and (f) N₂O are shown. CH₄, and N₂O emissions cannot descend below the thresholds 30 Tg CH₄ yr⁻¹ and 5.3 Tg N₂O yr⁻¹, respectively, due to the difficulty in abating CH₄ and N₂O emissions from agricultural and livestock sectors (see 194 195 Methods for the choice of these thresholds). Temperature and emission curves are also shown if the AERA is applied with a temperature target of 1.75°C until 196 2050 and from 2050 onwards this target is stepwise reduced at each stocktake to 1.5°C in 2100 (green). The thick solid lines show the average of the 8 simulations 197 with varying magnitude and timing of added inter-annual temperature variability of the Bern3D-LPX model configuration with an ECS of 3.2°C, the thin solid lines 198 show the same for the remaining 8 configurations covering ECS from 1.9 to 5.7°C, and the shaded area shows the range of all configurations that fall within the 199 likely range of ECS as defined by Sherwood et al. $(2020)^{24}$. The grey shading in (a) indicates the uncertainty with which the anthropogenic warming can be determined $(\pm 0.2^{\circ}C)^{26-29}$ for the 1.5°C and 2.0°C targets. 200

201 For the fixed 1.5°C target case, the resulting CO₂-fe emissions curves descend quickly (blue lines in Figure 202 2b), reach zero CO₂-fe emissions by 2038 (2033-2048, the central estimate is the mean over 8 simulations 203 with different superimposed interannual variability (see methods) from the ECS=3.2 model configuration, 204 and the range is the spread of the ensemble means across the remaining 8 model configurations with ECS varying from 1.9°C to 5.7°C), become negative afterward, peak at -2.7 (-4.0 to -1.6) Pg C yr⁻¹, and eventually 205 206 converge to zero emissions after 2150. If CH₄ and N₂O emissions decrease strongly (Figures 2e,f), net 207 negative CO₂ emissions are not necessary to limit warming to 1.5°C, but CO₂ emissions still approach zero 208 emissions (Figure 2d).

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210 For the fixed 2.0°C target, the resulting CO₂-fe emissions curves (orange lines in Figure 2b) descend less 211 rapidly, reach zero emissions by 2070 (2050-after 2300), and peak at negative emissions of -0.4 (-3.5 to 212 +1.0) Pg C yr⁻¹. The cumulative CO₂ equivalent emissions for the 2°C target, using GWP-100, are 310 Pg C 213 until 2050 and 543 Pg C until 2100, estimated from the AERA-derived CO₂, CH₄, and N₂O emissions. These 214 CO₂ equivalent emissions are similar to estimates by the Climate Action Tracker⁶⁵ when assuming that all 215 national pledges and targets are implemented (313 Pg C in 2050 and 513 Pg C in 2100), confirming that stabilizing warming at 2.0°C is possible in this optimistic scenario⁶⁶. Maximum annual CO₂-fe emission 216 217 reductions for the 2.0°C target are considerably smaller than the necessary reductions for the 1.5°C target 218 (Figure 2c). Furthermore, the timing when zero CO_2 -fe emissions need to be reached are in line with 219 previous estimates based on the time of the peak of radiative forcing⁶⁷.

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The peak and decline case demonstrates that the AERA can also be applied with a temperature target that changes over time (green lines in Figure 2). In the case where the temperature target is reduced from 1.75°C in 2050 to 1.50°C in 2100, the 2°C warming is never exceeded. Negative CO₂-fe emissions are needed until the beginning of the 22nd century. These negative CO₂-fe emissions are realized by negative CO₂ emissions because CH₄ and N₂O emissions have already reached their assumed minima due to the difficulty in abating CH₄ and N₂O emissions from agricultural and livestock sectors (see Methods). This peak and decline simulation shows that net-zero emissions in the second half of the 21st century (Article 4.1 of the Paris Agreement⁶) would be sufficient to "keep global warming well below 2°C, if strong emission reductions were implemented in the first half of the 21st century.

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231 The relative smoothness of the emission curves (Figure 2b, d-f) demonstrates that the projected CO₂-fe 232 emission curves as well as the associated CO₂, CH₄ and N₂O emissions curves by the AERA will need only 233 relatively small adjustments every five years. Therefore, the longer-term projections of CO₂-fe emission 234 curves were reliable and less frequent adjustments may be sufficient. Even if CO₂-fe emission curves were 235 adjusted by the AERA only every 10 years, the resulting CO₂-fe emission curves look almost identical 236 (Extended Data Figure 2). However, small changes at every stocktake are still unavoidable as the REB 237 remains uncertain. The initial REB guess can be different from the final emissions budget because the 238 linearity between warming and cumulative emissions does not hold strictly in all configurations when 239 emissions approach zero, partly due to unrealized warming (or cooling) from past CO₂-fe emission (i.e., the zero-emission commitment³⁰) that varies between model configurations. For Bern3D-LPX, 240 temperatures decrease slightly in the decades after zero emissions are reached³⁰. This decrease is 241 242 automatically corrected by the AERA by slightly increasing CO_2 -fe emissions. Despite these uncertainties 243 in the initial estimate of the REB, the adaptive nature of the AERA allows reaching the temperature target 244 while keeping changes in the CO₂-fe emission curve as small as possible.

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Furthermore, we tested the robustness of the AERA under varying pathways of CH_4 and N_2O emission curves and aerosol radiative forcing, by performing three more simulations for the 1.5°C target (Figure 3 - violet, red, and ochre curves). Independent of the prescribed non-CO₂ emissions and radiative agents, 249 the respective CO₂-fe emission curves remain almost indistinguishable and temperature stabilization is 250 reached by the AERA in each case (Extended Data Figure 3). However, the necessary CO₂ emission 251 reductions (Figure 3a) depend strongly on the corresponding reduction in CH₄ and N₂O emissions and 252 aerosol radiative forcing. When the magnitude of the aerosol forcing decreases faster (violet curves), 253 slightly stronger reductions in CO₂, CH₄, and N₂O emissions are needed. In an idealized 'solar radiation 254 management' case where aerosols are artificially emitted in the atmosphere after 2025 (red curves), CO₂, 255 CH_4 , and N_2O emissions reductions would only need to start 10-15 years later than in the standard case 256 (blue curves), while the necessary reduction rates of CO₂, CH₄, and N₂O emissions would remain similar. 257 Moreover, once the solar radiation management would stop (not simulated here), strong reductions in CO₂, CH₄, and N₂O emissions would be necessary immediately^{68,69}. In the extreme case, where only 258 259 emissions from non-CO₂ gases may be reduced but CO₂ remains constant, temperature cannot be 260 stabilized (Extended Data Figure 4). Although reductions of non-CO₂ emissions can compensate for 261 reductions in CO₂ emissions for some decades, continuing CO₂ emissions will lead to further increases 262 atmospheric CO₂ and hence the global temperature.



264 Fig. 3. Emissions of CO₂, CH₄, and N₂O, and aerosol radiative forcing following the adaptive emission reduction approach for the 1.5°C temperature target 265 using different assumptions for non-CO₂ radiative forcing agents. (a) CO₂ emissions, (b) CH₄ emissions, (c) N₂O emissions, and (d) the total radiative forcing of 266 anthropogenic aerosols (stratospheric and tropospheric) for five different idealized cases: aerosol radiative forcing decreases exponentially and CO₂, CH₄, and 267 N₂O emissions evolve proportionally (blue), aerosol radiative forcing decreases exponentially and CO₂, CH₄, and N₂O emissions evolve proportionally but GWP-268 100 is used to split CO₂ equivalent emissions instead of the CO₂-fe approach (brown), aerosol radiative forcing decreases stronger due to strong CO₂ emissions 269 cuts^{71,72} and CO₂, CH₄, and N₂O emissions evolve proportionally (violet), aerosol radiative forcing decreases exponentially but CH₄, and N₂O emissions follow SSP1-270 2.6 after 2025 and only CO₂ evolves dynamically (ochre), and aerosol radiative forcing remains constant after 2025 and CO₂, CH₄, and N₂O emissions evolve 271 proportionally (red, idealized solar radiation management). The thick solid lines show the average of the 8 simulations with varying magnitude and timing of

- added inter-annual temperature variability of the Bern3D-LPX model configuration with an ECS of 3.2°C and the shaded area shows the range of all configurations
- that fall within the likely range of ECS as defined by Sherwood et al. (2020)²⁴. The corresponding temperature curves, CO₂-fe emissions, and CO₂-e emissions for
- each simulated case are shown in Extended Data Figure 3.

275 The almost identical temperature curves and associated CO₂-fe emission curves across these four 276 scenarios with varying CH₄, and N₂O emissions as well as varying radiative forcing from aerosols (Extended 277 Data Figure 3) highlights the robustness of the CO₂-fe approach for transferring contributions from different radiative forcing agents to CO₂ equivalent emissions^{7,15–17}. However, as the GWP-100 approach 278 279 is widely used, e.g., in the Paris Agreement, we tested the AERA using GWP-100 by repeating the standard 280 simulations but using the GWP-100 and not the CO₂-fe metric to transfer CH₄ and N₂O emissions to CO₂ 281 equivalent emissions (brown curves in Figure 3). The AERA stabilizes the temperature at the given target when using GWP-100 (Extended Data Figure 5). However, the limitations^{7,15,17–19} of the GWP-100 metric 282 283 lead to an overcorrection at first of the CO₂, CH₄, and N₂O emissions reductions by the AERA by up to 78% for CO₂ (maximum relative difference in emissions reductions since 2025) and 46% for CH₄ and N₂O that 284 285 is later corrected by positive CO_2 -fe emissions (brown curves in Figure 3 and Extended Data Figure 5b-f). 286 However, when the usage of GWP is envisioned, better results may be achieved by using temperature 287 change potentials⁷⁰ or adjustments to the GWP over time⁶¹.

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289 The behavior of the AERA was further investigated assuming precautionary "over-compliance" (using a 290 REB that is smaller than the central estimate, i.e., 67th and 83rd percentile instead of the 50th percentile) or "under-compliance" (using a REB that is higher than the central estimate, i.e., 17th and 33rd percentile). 291 292 In the case of "under-compliance", the target temperature is still reached, but at the cost of a larger 293 temperature overshoot (Extended Data Figures 6 and 7). In the case of "over-compliance", the 294 temperature target is also reached, and the temperature overshoot can be avoided or reduced (for the 295 highest ECS). Overall, the AERA thus provides a robust and working tool to estimate the necessary 296 emission reductions to minimize the risk of temperature overshoot and the risk to surpass a given 297 temperature limit, e.g., of 2°C.

299 Applying the AERA in 2020

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301 Having demonstrated the robustness and fidelity of the AERA in the model world, the question arises what 302 rate of emission reductions the AERA would have estimated for the 1.5°C and 2.0°C temperature targets 303 based on available observations and emissions statistics in 2020, when 186 parties had communicated 304 their first NDCs to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat. 305 Applied to observational data until 2020, step one of the AERA yields an anthropogenic warming of 1.23°C 306 resulting in a remaining warming of 0.27°C for the 1.5°C target and 0.77°C for the 2.0°C target. In step 2, 307 the ratio of the anthropogenic warming of 1.23°C and past cumulative CO₂-fe emissions of 749 Pg C results in an REB of 167 Pg C for 1.5°C and 472 Pg C for 2.0°C. These remaining CO₂-fe emissions are divided over 308 309 the coming years in step 3 of the AERA assuming a cubic polynomial function with minimum changes of 310 its slope. The so estimated reduction of annual CO₂-fe emissions from 2020 to 2025 is 3.7 Pg C for the 311 1.5°C temperature target (from 13.7 Pg C yr⁻¹ in 2020 to 10.0 Pg C yr⁻¹ in 2025) and 1.0 Pg C for the 2.0°C 312 temperature target (from 13.7 Pg C yr⁻¹ in 2020 to 12.6 Pg C yr⁻¹ in 2025). Beyond 2025, CO₂-fe emissions would have to drop to 7.0 Pg C yr⁻¹ in 2030 to reach the 1.5°C target, further decrease to 0.5 Pg C yr⁻¹ in 313 314 2050 and become lightly negative after 2055 (up to -0.5 Pg C yr⁻¹) until reaching zero CO₂-fe emissions in 2085. For the 2.0°C target, CO₂-fe emissions would have to reach 11.3 Pg C yr⁻¹ in 2030, 7.2 Pg C yr⁻¹ in 315 316 2050 and zero CO_2 -fe emissions by 2110. While the estimates of past warming, TCRE, REB, and necessary 317 emission reductions have uncertainties, the AERA side-steps these uncertainties. The successive 318 adaptation of the CO₂-fe emissions every five years allows to correct the emission pathway over time if the initial estimates were not exact. Estimates are based on the median (50th percentile) value in these 319 320 example calculations for year 2020. Other percentiles may be used, as in the "overcompliance case" 321 described previously, for considering the precautionary principle of the UNFCCC.^{71,72}

323 Discussion

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325 The AERA allows estimating future CO₂-fe emission pathways to reach the desired temperature target 326 within the uncertainty to which anthropogenic warming can be determined (±0.2°C)^{26–29}. Climate 327 projections by Earth System Models using the AERA could be incorporated into the periodical IPCC 328 Assessment Reports and provide an alternative to the often-used approach of applying pre-defined 329 emissions or concentration pathways (such as SSPs). Such pathways are generally designed a priori to be 330 consistent with a given radiative forcing or warming level (e.g., SSP1-1.9 for 1.9 W m⁻² and 1.5°C by 2100), not knowing the actual response of the Earth system to these emissions pathways⁷³. AERA-based warming 331 332 simulations from different models would be directly comparable in terms of impacts under equal 333 warming. However, the sociotechnical feasibility of the pathways is not informed by the AERA but could 334 be assessed by coupling these simulations to a cost-effectiveness integrative assessment model in a 335 recursive dynamic setup. The approach may hence guide a valuable and highly policy-relevant 336 complementary set of simulations for the next generation of CMIP models that result in a range of emission curves that all result in the same warming in the long term as opposed to current simulations 337 338 with the same emission or concentration curves that can result in very different levels of warming.

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In the Paris Agreement, the 2°C warming limit represents an upper threshold that should not be passed. The AERA applied with the median observation-based estimates allows to devise pathways that keep warming to within about 0.2°C of prescribed warming targets. For keeping warming below temperature limits that have been set as upper ceilings for global warming allowable to society, the AERA can be applied with a temperature target about 0.2°C lower than such limits or by using a lower than the median estimate for the REB as in the "overcompliance case". In future efforts, the approach could be further refined by applying the AERA within a fully observation-constrained probabilistic framework^{12,13} to estimate the necessary emission reductions with associated likelihoods.

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349 The AERA presents policy makers transparent science- and observation-based emission reductions that 350 would be necessary to limit global warming to any chosen temperature level without the need to make 351 climate projections with Earth System Models. With many simulations, substituting for future real-world 352 outcomes, we have shown that this approach is robust across a vast number of possible developments. 353 Policy makers may wish to use the information from the AERA to regularly update near- and long-term 354 emission reduction goals, including additional socio-economic considerations such as equity, mitigation 355 versus adaptation costs, and risks of not meeting a target. The AERA can thereby help to successfully "keep global warming well below 2°C and to pursue efforts to limit it to 1.5°C"⁶. 356

358	Data a	vailability								
359	The	Bern3D-LPX	model	output	is	available	publicly	available	via	SEANOE
360	(<u>https:</u>	//doi.org/10.17	<mark>/882/9090</mark> 1	<u>L</u>) ⁷⁴ . All oth	ner dat	a are availat	ole in the m	ain text or th	e supp	lementary
361	materi	als.								
362										
363	Code a	availability								
364	The AE	RA code is pub	licly availat	ole via <u>http</u>	s://git	hub.com/Jet	e90/AERA ⁷⁵ .			
365										
366	Ackno	wledgements								
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562		

563 Methods

564

- 565 Adaptive Emission Reduction Approach
- 566

567 The Adaptive Emission Reduction Approach (AERA)⁷⁵ is designed to estimate a future trajectory of CO_2 568 forcing equivalent (CO_2 -fe) emissions to reach a temperature target. The AERA is formulated as part of a 569 control system with a feedback loop. In a control system, the output of a system is controlled by regularly 570 adjusting the input to the system based on the deviation between the actual and target value of a process 571 variable. An example is a regulation of room temperature with a heating-cooling unit. The room 572 temperature is measured to estimate the deviation between the actual and target temperature. The flow 573 of heat between the unit and the room is then adjusted by the "controller" based on the deviation and 574 the median available estimate of the response in room temperature to heat flow. This procedure is 575 repeated, e.g., every minute, to adjust the room temperature towards and to track the target 576 temperature. Similarly, the AERA, when implemented with real-world emissions, will control the evolution 577 of anthropogenic warming by adjusting CO₂-fe emissions. Here, emissions are foreseen to be adjusted 578 every five years, based on the median observational estimate of the deviation between actual and target 579 anthropogenic warming and the median observation-based estimate of the Earth system's response to 580 emissions. Implementing the regularly updated emissions reductions following the AERA will allow the 581 temperature to converge towards the target temperature, despite uncertainties in our understanding of 582 the Earth System.

583

As input, the AERA requires past global time-series of three variables: (i) global mean surface temperature (GMST), (ii) total anthropogenic radiative forcing (RF), and (iii) total CO₂-fe emissions from CO₂, non-CO₂ GHGs, precursors, aerosols, and land-use change combined (see CO₂-fe emissions calculation below). The 587 AERA contains three steps. First, internal variability from the GMST record is removed by calculating anthropogenic warming from the GMST timeseries⁴⁶. Second, the Remaining CO₂-fe Emission Budget 588 (REB)^{2,7-9} is estimated based on the near-linear relationship between past CO₂-fe emissions and warming 589 (i.e., the transient climate response to cumulative carbon emission)^{51,52}, and the remaining temperature 590 591 gap before the target temperature will be reached. Third, this REB is distributed over the future years 592 using a cubic polynomial function. The three steps are to be repeated every five years. Therefore, the 593 future CO₂-fe emission curve may be adjusted every five years based on the most up-to-date observations 594 of GMST, RF, and CO₂-fe emissions.

595

In the first step, the natural internal and external (i.e., volcanoes, solar activity) variability is removed from the observed, historical GMST resulting in a temperature curve (T_{ant}) that only changes due to anthropogenic forcing. T_{ant} is determined following Otto et al.⁴⁶ by fitting an Impulse-Response Function (IRF)^{47,48} to the observed GMST(t). The IRF features three characteristic timescales, τ_i , and coefficients, a_i : 600

$$601 T_{ant}(t) = T_{ant}(1850) + c \int_{1850}^{t} I_{RF}(t') \left(a_1 \left(1 - e^{\frac{-(t-t')}{\tau_1}} \right) + a_2 \left(1 - e^{\frac{-(t-t')}{\tau_2}} \right) + a_3 \left(1 - e^{\frac{-(t-t')}{\tau_3}} \right) \right) dt' (1)$$

602

Eq. 1 relates the sum of step-like changes in RF (impulses $I_{RF}(t')$, defined as the change in RF in year t') over the past observed period to $T_{ant}(t)$. The constant c is a scaling and unit conversion factor, and the integral is approximated by the sum of annual values. The seven free parameters of Eq. 1 (timescales τ_1 , τ_2 , and τ $_{3}$; coefficients a_1 , a_2 ; c; T_{ant} (1850) are determined to best fit the observation-based GMST by minimizing the root-mean-square-deviations between $T_{ant}(t)$ and GMST(t). The parameters are determined at each stocktake to account for possible feedbacks from the warming of the climate and cumulative CO₂ uptake that may change the shape of the IRF⁷⁶. The free parameters were constrained a priori to ease the fitting. The timescales are limited to 1.5-2.0 years (for τ_1), 15-30 years (τ_2), and 100-600 years (τ_3) and the coefficients are limited to 0.2-0.4 (a_1), 0.3-0.5 (a_2). a_3 is calculated by $a_3 = 1 - a_{1} - a_2$. Implicitly, a_3 is thus limited to 0.1-0.5. These broad constraints are enforced to ensure physically meaningful parameters. From the anthropogenic temperature time-series $T_{ant}(t)$, the anthropogenic temperature anomaly (ΔT_{ant}) is calculated by subtracting the mean *GMST(t)* over the reference period 1850-1900 from T_{ant} :

616
$$\Delta T_{ant}(t) = T_{ant}(t) - \overline{GMST(1850 - 1900)}$$
(2)

617

The Remaining Emission Budget (REB) of CO₂-fe emissions is estimated at the time of the stocktake, t_{st} (years 2025, 2030, ...) exploiting the near-linearity between warming and cumulative CO₂ emissions discussed by the Intergovernmental Panel on Climate Change^{14,53}. The REB (t_{st}) is determined by multiplying the remaining anthropogenic temperature anomaly until the target temperature is reached with the ratio of cumulative CO₂-fe emissions since 1850 ($\int_{1850}^{t_{st}} E_{fe}^{CO_2}(t') dt'$) and the realized anthropogenic warming anomaly $\Delta T_{ant}(t_{st})^{51,52}$:

624

625
$$REB(t_{st}) = \left(\Delta T_{ant}^{target} - \Delta T_{ant}(t_{st})\right) \frac{\int_{1850}^{t_{st}} E_{fe}^{CO_2}(t')dt'}{\Delta T_{ant}(t_{st})},$$
 (3)

626

627 with ΔT_{ant}^{target} being the temperature target, e.g., 1.5°C or 2°C.

628

The emission pathway for the five years following the stocktake is determined by distributing the
 remaining CO₂-fe emission budget over the future years using a cubic polynomial function:

631

632
$$E_{fe}^{CO_2}(t) = at^3 + bt^2 + ct + d$$
 for $t_{target} \ge t \ge t_{st}$, (4)

with *t* referring to the time after the year of the stocktake (t_{st}) and t_{target} being the year when the temperature target should be reached. The t_{target} is not an a priori fixed year^{61,70} but continuous to evolve over time and will be adapted here to ensure that the change of the slope of CO₂-fe emissions remains as small as possible (see paragraph below). The parameters *a*, *b*, *c*, and *d* are chosen to determine an emission curve with a small curvature using the following boundary conditions:

640 1) $E_{fe}^{CO_2}(t_{st})$ equals the CO₂-fe emissions at the year of the stocktake.

641 2) Changes in $E_{fe}^{CO_2}$ in the year before the stocktake are as close as possible to changes in $E_{fe}^{CO_2}$ at 642 the year of the stocktake:

643
$$\frac{\partial E_{fe}^{CO_2}}{\partial t}(t_{st}) = \frac{\partial E_{fe}^{CO_2}}{\partial t}(t_{st}-1) + \eta,$$
(5)

644 with η being a change in the slope.

645 3)
$$E_{fe}^{CO_2}(t_{target})$$
 equals zero.

646 4) $E_{fe}^{CO_2}$ remains constant after the target year is reached $\left(\frac{\partial E_{fe}^{CO_2}}{\partial t}(t_{target})=0\right)$

647

648 Condition 1) enforces the polynomial function to match emissions at the time of the stocktake. Condition 649 2) minimizes the changes in the emissions trend around the stocktake, thereby implicitly accounting for 650 inertia in the socio-economic system that makes it difficult to 'abruptly' change trends. Conditions 3) and 651 4) imply that CO_2 -fe emissions are zero when the target is reached and stay zero afterward in the absence 652 of any trend change in emissions. These boundary conditions leave two free parameters t_{target} and η . For 653 each combination of these two parameters one emission curve exists. The maximum length of the time series (t_{max}) varies dynamically depending on the REB and the CO₂-fe emissions in the year of the stocktake:

656

657
$$t_{max} = 30yr + 90yr \times e^{\left(-\frac{|max(REB-30PgC, 0PgC)|}{50PgC}\right)} + min\left(\left|E_{fe}^{*CO_2}(t_{st})\right|, \ 10 \ \frac{PgC}{yr}\right)^2 \times \frac{yr^3}{(PgC)^2}.$$
 (6)

658

659 Each term in equation (6) is rounded to its nearest integer. This dynamic definition keeps the time until 660 which the temperature target should be reached (t_{max}) relatively short (close to 30 years, first term in 661 equation (6)) so that the temperature does not remain off target for too long. However, in two cases, it is 662 preferable that the REB is distributed over a longer time. The first case occurs when the anthropogenic 663 warming is close to the temperature target. In that case, a short t_{max} leads to abrupt short-term changes 664 in CO₂-fe emissions because a small REB (< \sim 100 Pg C) is forced into a small number of years 665 (Supplementary Figure 1). To avoid such an oscillation, t_{max} increases by up to additional 90 years when 666 the REB becomes small (term 2 in equation (6)). The second case occurs when the REB is large, but annual 667 emissions are still high (> \sim 5 Pg C yr⁻¹). These high emissions will already be correcting the temperatures 668 over time. A reduced t_{max} would force the large REB into a small number of years, and cause even higher 669 emissions in the first years, which need to be reduced shortly afterwards (Supplementary Figure 1). The third term in equation (6), with $E_{fe}^{*CO_2}(t_{st})$ being equal to $E_{fe}^{CO_2}(t_{st})$ if the REB and $E_{fe}^{CO_2}(t_{st})$ have the 670 671 same sign and being zero otherwise, increases t_{max} by up to 100 years. Overall, the choice of the different timescales does not rely on theoretical assumptions, but it is a result of tests across a wide range of 672 673 timescales.

674

For determining the free parameters t_{target} and η , we systematically varied them in steps of 1 year and 0.1 Pg C yr⁻² within the following limits: 5 years < (t_{target} - t_{st}) < t_{max} ; -2.5 Pg C yr⁻² < η < 2.5 Pg C yr⁻². The 'best' choice out of these emission curves is chosen in three steps: First, all curves are excluded whose integrated emissions from t_{st} to t_{target} do not agree with the REB within ± 5 Pg C ($|\xi| < 5$ Pg C): 680

681
$$\xi = \int_{t_{st}}^{t_{target}} E_{fe}^{CO_2}(t') dt' - REB,$$
(7)

682

with ξ being the difference between the REB and the integral of the CO₂-fe emission curve. In our tests, at every stocktake at least one CO₂-fe emissions curve with a REB that lies within ±5 Pg C of the REB determined by the AERA is found. In the potential cases where a curve within the REB limit cannot be found, the curve with the smallest $|\xi|$ would be chosen.

687

688 Second, among the remaining curves, all curves are excluded with exceedance emissions (ε) being larger 689 than 10 Pg C. Exceedance emissions are defined as follows:

690

691
$$\int_{t_{st}}^{t_{target}} \left| E_{fe}^{CO_2}(t') \right| dt' - \int_{t_{st}}^{t_{target}} E_{fe}^{CO_2}(t') dt' < 2\varepsilon$$
(8)

692

693 The left side of equation (8) describes the difference between the integral of the absolute emissions over time and the emissions integral. Although this difference is ideally zero, it can diverge if $E_{fe}^{CO_2}(t')$ changes 694 its sign between t_{st} and t_{target} . This can for example be the case if $E_{fe}^{CO_2}(t_{st})$ is still positive and $T_{ant}(t_{st})$ is 695 696 already larger than the temperature target. Thus, the still emitted positive emissions before emissions 697 become negative increase the exceedance of T_{ant} further and are therefore called 'exceedance emissions'. 698 They are later compensated by the roughly similar amount of negative emissions, hence the factor 2 on the right side of equation (8). Several studies^{77–80} have shown that the global warming response to positive 699 and negative CO₂ emissions is indeed approximately symmetrical for moderate amounts of negative 700 701 emissions and under ambitious climate targets.

In 99.95% of the cases a CO₂-fe emissions curve with exceedance emissions smaller than 10 Pg C is found. In the remaining 0.05% cases, the curve with the smallest exceedance emissions is chosen. In the 99.95% of the cases where the limits for $|\xi|$ and exceedance emissions are met, the curve is retained with the combination of t_{target} and η that results in the smallest curvature (sum of absolute changes in emissions change). The smallest curvature is calculated by minimizing the sum of each curve's (absolute) second derivates from year t_{st} -1 to year t_{target} .

708

709 <u>CO₂-fe emissions from non-CO₂ agents</u>

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The historical CO_2 -fe emissions from non- CO_2 agents are estimated based on the radiative forcing timeseries of non- CO_2 agents. This annual time series is translated into CO_2 -fe emissions¹⁷:

713

714
$$\alpha E_{CO_2 - fe}(t) = \frac{dF_{non - CO_2}(t)}{dt} + \rho F_{non - CO_2}(t), \qquad (9)$$

with F_{non-CO_2} (t) being the radiative forcing of non-CO₂ agents, $E_{CO_2-fe}(t)$ being CO₂-fe emissions from non-CO₂ agents, with ρ being the rate of decline of radiative forcing over these timescales under zero emissions (0.33%), and α being a constant representing the forcing impact of ongoing CO₂ emissions (1.08 W m⁻² per 1,000 GtCO₂).

719

720 Applying the AERA to observations until 2020

721

The necessary emission reductions in 2020 are quantified using the AERA. As input, we used the historical GMST data from HadCRUT5 (https://crudata.uea.ac.uk/cru/data/temperature/), historical CO₂ concentrations from Meinshausen et al. (2017)⁸¹ until 2014 and from NOAA GML from 2015 to 2020 (https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_gl.txt), historical radiative forcing from non-CO₂ radiative agents from the RCP database, assuming RCP2.6 from 2005 to 2020 (https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome)^{82–90}, historical CO₂ fossil fuel and land-use change emissions from the Global Carbon Project³³, and historical CO₂-fe emissions from non-CO₂ forcing agents derived from the non-CO₂ radiative forcing from the RCP database.

730

731 The estimated warming in 2020, past cumulative CO₂-fe emissions, and the remaining CO₂-fe emissions budgets to limit global warming to 1.5°C and 2°C and the estimated time when zero CO₂-fe emissions need 732 733 to be reached based on this data lie within previous estimates. Previous estimates of the anthropogenic warming are $1.0 \pm 0.2^{\circ}$ C in 2017², 1.07 (0.8-1.3)°C for the period from 2010-2019²⁹, and 1.20°C in 2020²⁶. 734 735 In comparison, the AERA-derived temperature is 1.15°C in 2017, 1.08°C from 2010 to 2019, and 1.23 in 736 2020, in agreement with the three previous estimates. The resulting remaining CO₂-fe budget, when scaled to the remaining warming in 2020 (0.27°C), was estimated to be 117–270 Pg C^{7,21}. This estimation 737 738 encompasses the here presented REB estimate of 168 Pg C.

739

740 <u>Supplementary Methods</u>

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Additional information about the methods that are used throughout this study is made available as Supplementary Information. The Supplementary Information includes a detailed description of the AERA testing wit Bern3D-LPX, the reduced form atmospheric chemistry model, and the AERA robustness tests.

745

747 References – Methods

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790 Extended Data Figure 1. Historical and simulated globally averaged surface atmospheric 791 temperature anomaly with respect to 1850-1900 for different model configurations. (a-i) Global 792 mean surface temperature (GMST) from 1850 to 2020 for 9 model configurations with varying ECS 793 without the superimposed inter-annual variability. The blue lines show the simulated GMST, and the 794 orange lines show the determined anthropogenic warming. The diapycnal diffusivity coefficients are 1x10⁻⁵, 2x10⁻⁵ and 1x10⁻⁴ m² s⁻¹ (from top to bottom) and the different numbers for the internal Bern3D 795 796 model parameter that accounts for climate feedbacks, which are not explicitly represented in the model, are 0.1, -0.5, and -0.8 W m⁻² K⁻¹ (from left to right). The HadCRUT5 observation-based GMST 797 798 time-series is shown in black in all panels.

799



801 Extended Data Figure 2. Globally averaged surface atmospheric temperature anomaly with respect to 1850-1900, CO₂-fe emissions, their annual rate of 802 change, as well as CO₂, CH₄, and N₂O emissions when applying the adaptive emission reduction approach every ten years. (a) Temperature anomalies with 803 respect to 1850-1900, (b) CO₂-fe emissions, and (c) their annual rate of change if the AERA is applied every ten years starting in the year 2025 for the 1.5°C target (blue) and the 2.0°C target (orange). In addition, the AERA-calculated emission curves for (d) CO₂, (e) CH₄, and (f) N₂O are shown. As compared to figure 804 805 2 in the main text, here the CO₂ emissions are forced to remain constant while only CH₄, N₂O, VOC, NOx, and CO emissions evolve proportionally. The thick 806 solid lines show the average of the 8 simulations with varying magnitude and timing of added inter-annual temperature variability of the Bern3D-LPX model configuration with an ECS of 3.2°C, the thin solid lines show the same for the remaining 8 configurations covering ECS from 1.9 to 5.7°C, and the shaded area 807 shows the range of all configurations that fall within the likely range of ECS as defined by Sherwood et al. (2020)¹⁷. The grey shading in (a) indicates the 808 uncertainty with which the anthropogenic warming can be determined $(\pm 0.2^{\circ}C)^{53-56}$. 809

810



812 Extended Data Figure 3. Adaptive CO₂-fe emissions and resulting temperature anomaly for 1.5°C and 813 2.0°C target for different non-CO₂ GHG emissions and aerosol radiative forcing. (a, c, e, g) Temperature anomalies with respect to 1850-1900 and (b, d, f, h) corresponding CO₂-fe emissions if 814 815 the AERA is applied every five years starting in the year 2025 for the 1.5°C target (blue) and the 2.0°C 816 target (orange) for four different idealized cases: (a, b) aerosol radiative forcing decreases 817 exponentially and CO_2 , CH_4 , and N_2O emissions evolve proportionally, (c, d) aerosol radiative forcing 818 decreases according to the CO_2 emissions and CO_2 , CH_4 , and N_2O emissions evolve proportionally, (e, 819 f) aerosol radiative forcing decreases exponentially but CH_4 , and N_2O emissions remain constant after 820 2025 and only CO_2 evolves dynamically, and (g, h) aerosol radiative forcing remains constant after 2025 821 and CO_2 , CH_4 , and N_2O emissions evolve proportionally. The thick solid lines show the average of the 8 822 simulations with varying magnitude and timing of added inter-annual temperature variability of the 823 Bern3D-LPX model configuration with an ECS of 3.2°C and the shaded area shows the range of all 824 configurations that fall within the likely range of ECS as defined by Sherwood et al. (2020)¹⁷. The grey 825 shading in (a, c, e, g) indicates the uncertainty with which the anthropogenic warming can be 826 determined (±0.2°C)^{53–56}. The corresponding CO₂, CH₄, and N₂O emissions and aerosol forcing for each 827 simulated case are shown in Figure 3.



828

829 Extended Data Figure 4. Globally averaged surface atmospheric temperature anomaly with respect to 1850-1900, CO₂-fe emissions, their annual rate of 830 change, as well as CO₂, CH₄, and N₂O emissions following the adaptive emission reduction approach when forcing CO₂ emissions to remain constant. (a) 831 Temperature anomalies with respect to 1850-1900, (b) CO₂-fe emissions, and (c) their annual rate of change if the AERA is applied every five years starting in the year 2025 for the 1.5°C target (blue) and the 2.0°C target (orange). In addition, the AERA-calculated emission curves for (d) CO₂, (e) CH₄, and (f) N₂O are 832 833 shown. As compared to figure 2 in the main text, here the CO₂ emissions are forced to remain constant while only CH₄, N₂O, VOC, NOx, and CO emissions 834 evolve proportionally. The thick solid lines show the average of the 8 simulations with varying magnitude and timing of added inter-annual temperature 835 variability of the Bern3D-LPX model configuration with an ECS of 3.2°C, the thin solid lines show the same for the remaining 8 configurations covering ECS 836 from 1.9 to 5.7°C, and the shaded area shows the range of all configurations that fall within the likely range of ECS as defined by Sherwood et al. (2020)¹⁷. The grey shading in (a) indicates the uncertainty with which the anthropogenic warming can be determined $(\pm 0.2^{\circ}C)^{53-56}$. 837



838

Extended Data Figure 5. Globally averaged surface atmospheric temperature anomaly with respect to 1850-1900, CO₂-e emissions, their annual rate of 839 840 change, as well as CO₂, CH₄, and N₂O emissions following the adaptive emission reduction approach using GWP-100 instead of CO₂-fe to split CO₂-e 841 emissions. (a) Temperature anomalies with respect to 1850-1900, (b) CO_2 -e emissions, and (c) their annual rate of change if the AERA is applied every five 842 years starting in the year 2025 for the 1.5°C target (blue) and the 2.0°C target (orange). In addition, the AERA-calculated emission curves for (d) CO₂, (e) CH₄, 843 and (f) N₂O are shown. As compared to figure 2 in the main text, here the GWP-100 approach was used to calculate CO₂ equivalent emissions from CH₄ and 844 N₂O emissions and the CO₂-fe emissions approach was applied to calculate CO₂ equivalent emissions from the remaining forcing agents. The thick solid lines 845 show the average of the 8 simulations with varying magnitude and timing of added inter-annual temperature variability of the Bern3D-LPX model configuration with an ECS of 3.2°C, the thin solid lines show the same for the remaining 8 configurations covering ECS from 1.9 to 5.7°C, and the shaded area shows the 846 range of all configurations that fall within the likely range of ECS as defined by Sherwood et al. (2020)¹⁷. The grey shading in (a) indicates the uncertainty with 847 which the anthropogenic warming can be determined (±0.2°C)^{53–56} 848



850 Extended Data Figure 6. Adaptive emissions and resulting temperature anomaly for 1.5°C and 2.0°C target with varying compliance. Temperature from 2020 to 2300 for three model configurations with 851 852 varying ECS (1.9°C (a, d, g, j), 3.2°C (b, e, h, k), 5.7°C (c, f, i, l)) averaged over four simulations each with 853 different inter-annual variability for the (a-c) 1.5°C and (g-i) 2.0°C temperature target and (d-f, j-l) the respective CO₂-fe emission curves with different compliance, i.e., at each stocktake the 17th (orange), 33rd 854 (blue), 50th (green), 67th (red), or 83rd percentile (violet) was implemented. The percentiles are scaled at 855 856 each stocktake based on the percentiles of the REB in 2020 from Table 5.8 of the IPCC AR6 WG1 report⁸⁹. 857 The grey shading in (a, b, c, g, h, i) indicates the uncertainty with which the anthropogenic warming can be determined $(\pm 0.2^{\circ}C)^{53-56}$. 858



Extended Data Figure 7. Overshoot cumulative intensity for 1.5°C and 2°C temperature targets dependent on compliance and model configuration. Overshoot cumulative intensity (°C years), defined as the sum of the overshoot temperatures in each year, in dependence of model configuration (ECS from 1.9°C to 5.7°C) and the REB that was used in the AERA (17th, 33rd, 50th, 67th, and 83rd percentile) for (a) 1.5°C and (b) 2°C target.

Supplementary Information

Testing the AERA with Bern3D-LPX

The AERA was tested using the Bern3D-LPX model, version $2.0^{62,63}$ with nine model configurations with combinations of three ocean diapycnal mixing coefficients ($1e^{-4}$, $2e^{-5}$, $1e^{-5}$ m² s⁻¹) and three temperature sensitivities to radiative forcing. These three sensitivities to radiative forcing are created by varying an internal Bern3D model parameter that accounts for climate feedbacks, which are not explicitly represented in the model (-0.7, -0.3, 0.1 W m⁻² K⁻¹). These nine configurations cover the ECS range from 1.9 to 5.7 °C and the TCR range from 1.3 to 2.5 °C. This range represents the range of TCR/ECS estimates based on multiple lines of evidence²⁴.

For each configuration, the same set of simulations were performed. In these simulations, land-use change CO₂ emissions were interactively simulated by the biosphere component of the Bern3D-LPX model⁶³ by prescribing land-use area. More specifically, over the historical 1750-2014 period, historical land-use area was prescribed⁹¹. From 2015 to 2100, land-use area was assumed to follow the low-emissions pathway SSP1-2.6, and from 2100 to 2300 land-use area was assumed to be constant. The corresponding land-use change CO₂ emissions were diagnosed by the difference in air-land CO₂ flux between a simulation with constant land-use area and one with changing land use as prescribed above. Both simulations had the same atmospheric CO₂ concentrations, following historical records until 2014 and SSP1-2.6 afterward⁸¹. Historical non-CO₂ radiative forcing from 1850 to 2004 was prescribed by values from the RCP database (https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome)^{83–90,92}, and non-CO₂ radiative forcing from 2005 to 2025 follows the SSP1-2.6 scenario as described in the SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10)^{93,94}. After 2025, the non-CO₂ radiative forcing was either develop dynamically depending on the AERA-prescribed CO₂-fe emissions or was prescribed as a time-series. Before 1850, the non-CO₂ radiative forcing is held

constant at the values from 1850. Historical fossil fuel CO₂ emissions are prescribed from 1765 to 2019 based on the Global Carbon Project³³, and in 2020 based on Le Quéré et al. (2021)⁹⁵. Prescribed fossil fuel CO₂ emissions from 2021 to 2025 are assumed to evolve proportionally to the estimated CO₂-fe emissions that were estimated from the Nationally Determined Contributions (NDC) (Climate Action Tracker⁶⁵).

The different ECSs in each configuration lead to a range of $\Delta T_{ant}^{model}(2020)$ of 0.64 to 1.48°C. Due to this difference, ΔT_{ant}^{target} is defined for each configuration so that $\Delta T_{ant}^{target} - \Delta T_{ant}^{model}(2020)$ equals the $\Delta T_{ant}^{target} - \Delta T_{ant}^{obs}(2020)$ calculated from observations. Thus, for each model configuration the remaining warming from 2020 onwards is the same and differences in the emission curves after 2020 result solely from the differences in ocean mixing and temperature sensitivity and not from differences in the already realized model warming. The historical $\Delta T_{ant}(2020)$ calculated as described above is 1.23°C, leaving an allowable warming of 0.27°C for the 1.5°C target and 0.77°C for the 2°C target.

From 2025 onward, CO₂-fe emissions are calculated by the AERA every 5 years starting in 2025 to mimic the global stocktake process (UNFCCC 2015⁶). For the first step of the AERA, the historical time-series of temperature and RF are needed to calculate the anthropogenic warming at the time of the stocktake. The historical temperature timeseries is directly taken from the simulated model output for each configuration. In addition, an artificial temperature anomaly was added to the simulated temperature in Bern3D, as the modelled inter-annual variability is strongly underestimated. The added anomaly is derived from observed GMST (HadCRUT5) from 1920 to 2019 by subtracting a 3rd order polynomial fit. This 100-year time series is added periodically. To create different anomalies, the anomaly was also added with different phasing (25, 50, and 75 years) and also with a changing sign, resulting in 8 different temperature time series for each model configuration. The past RF is a combination of the CO₂ and non-CO₂. The non-CO₂ RF is directly taken from the prescribed RF to Bern3D-LPX. The CO₂ RF is calculated following IPCC AR6, Table 7.SM.1⁹⁶ using the dynamically simulated atmospheric CO₂ in the respective simulation and prescribed atmospheric N₂O based on the RCP and SSP databases following SSP1-2.6. In the second step, the REB is estimated based on the anthropogenic warming from step one and the past CO₂-fe emission curve. The past CO₂-fe emission curve is the sum of the dynamically adapted fossil fuel CO₂ emissions, the emissions from prescribed land-use area (smoothed with a 21-year running mean due to its relatively large inter-annual variability), and the non-CO₂ forcing agent emissions that are derived from the prescribed non-CO₂ radiative forcing (smoothed with a 5-year running mean to avoid artificially steps in the emissions that arise from the radiative forcing data that is only provided every 10 years). The CO_2 equivalent emissions from non-CO₂ forcing agents are derived from the prescribed non-CO₂ radiative forcing using the CO₂fe emissions approach¹⁷. In the last step of the AERA, the REB is distributed over the following years. In the standard case, the CO₂ equivalent emissions are split using the CO₂-fe emissions approach¹⁷. When testing the AERA with the GWP-100 approach (Extended Data Figure 5), the equivalent CO_2 emissions from CH₄ and N₂O emissions for the period after the stocktake are calculated using GWP-100, while the CO₂-fe emissions approach is used to transfer the radiative forcing from the remaining non-CO₂ forcing agents (aerosols, halogens, ...). The effect of CH₄ on tropospheric ozone is accounted for by GWP-100 and only the remaining radiative forcing by ozone, which is mainly caused by CO, VOC, and NOx, and to a small extend by stratospheric ozone, is transferred via the CO₂-fe emissions approach (Supplementary Figure 2).

After the AERA is applied, the future adapted CO₂-fe emission curve is again divided into different components (CO₂ fossil fuel emissions, land use change CO₂ emissions, non-CO₂ emissions). First, the prescribed land-use change CO₂ emissions are subtracted from the CO₂-fe emission curve that was determined from the AERA. The radiative forcing and CO₂-fe emissions from non-CO₂ radiative agents are calculated using a reduced form atmospheric chemistry model⁶⁴ updated with the latest information from IPCC AR6. The reduced form atmospheric chemistry model takes time series of CH₄, N₂O, CO, VOC, and NOx emissions, as well as time series of radiative forcing of aerosols and halogens,

as input to calculate future fossil fuel CO₂ emissions and the radiative forcing from non-CO₂ radiative agents from which the corresponding non-CO₂ CO₂-fe emissions are calculated. In the standard case (Figure 2), CO₂, CH₄ and, N₂O emissions after 2025 evolve proportionally and are chosen so that fossil fuel CO₂ emissions and CO₂-fe emissions from non-CO₂ radiative agents fit the prescribed CO₂-fe emissions by the AERA (minus the land use change CO₂ emissions). However, CH₄, and N₂O emissions cannot descend below the thresholds 30 Tg CH₄ yr⁻¹ and 5.3 Tg N₂O yr⁻¹, respectively, due to the difficulty in abating CH₄ and N₂O emissions from agricultural and livestock sectors. The N₂O emissions threshold is chosen as the minimum N₂O emissions across the 21st century and across the range of SSPs from the SSP database. The minimum CH₄ emissions prescribed here are below the minimum CH₄ across all SSPs and present the most optimistic future for possible CH₄ reductions. Recent estimates quantify the potential reduction in CH4 emissions until 2030 to be 45-54% (Emissions Gap Report 2021⁹⁷ and the Global Methane Initiative (https://www.globalmethane.org/documents/gmimitigation-factsheet.pdf)). Here, we assumed that 45% is possible until 2030 and another 45% is possible until 2300. While this is clearly optimistic, large-scale negative CO₂ emissions are also optimistic. In alternative cases (Figure 3 & Extended Data Figure 3), CH₄ and N₂O emissions after 2025 are prescribed and only fossil fuel CO₂ emissions after 2025 are dynamically chosen so that fossil fuel CO_2 emissions and CO_2 -fe emissions from non- CO_2 radiative agents fit the prescribed CO_2 -fe emissions by the AERA (minus the land use change CO_2 emissions) (Supplementary Figure 2).

Reduced form atmospheric chemistry model

The reduced form atmospheric chemistry model calculates the effective radiative forcing for non-CO₂ radiative forcing agents based on prescribed emissions, as well as time series of radiative forcing of aerosols and halogens⁶⁴ with updated equations and constants. The reduced chemistry model is initialized in 2019 from observational data and evolves over time as follows:

• Anthropogenic CH₄ and, N₂O emissions are prescribed as input.

- Natural CH₄ and, N₂O emissions are supposed to be constant over time and are set to 218 Tg CH₄ yr⁻¹ and 9.7 Tg N yr⁻¹, respectively. Natural N₂O emissions are taken from Tian et al. (2020)³⁶ and natural CH₄ emissions are calculated from the change in atmospheric CH₄ mixing ratio from 2000 to 2017 from NOAA (<u>https://gml.noaa.gov/ccgg/trends_ch4/</u>), anthropogenic CH₄ emissions from 2000 to 2017 from the Global Methane Budget³¹, and an atmospheric lifetime CH₄ of 9.1 years (based on Tab 6.2 IPCC AR6 and associated text)⁹⁸.
- CO, VOC, and NO_x emissions in 2019 are initialized based on the respective emissions in 2020 in the SSP database following SSP1-2.6 (763.5 Tg CO yr⁻¹; 128.6 Tg VOC yr⁻¹; 123.6 Tg NO₂ yr⁻¹). After 2019, these CO, VOC, and NO_x emissions are assumed for simplicity to evolve proportional to CO₂ emissions, although these emissions are linked to a range of sources such as fossil fuel burning, N-fertilizer use, or biomass burning and their relationship with CO₂ emissions may change through time. These emissions are assumed to not be able to drop below their respective emissions in 2100 following SSP1-2.6: 307.2 Tg CO yr⁻¹; 38.4 Tg VOC yr⁻¹; 32.4 Tg NO₂ yr⁻¹.
- Preindustrial and 2019 atmospheric mole fractions of CH₄ (731.41 and 1825.00 ppb) and N₂O (273.87 and 330.50 ppb) are prescribed based on tables 7.5 and 7.SM.1 and chapter 7 of IPCC AR6⁹⁶. After 2019, atmospheric mole fractions of CH₄ and N₂O evolve dynamically as explained below.
- CH₄ mole fraction is calculated forward every year as follows:

(10)

$$CH_4(t+1) = CH_4(t) + \frac{ppb}{2.75 \, Tg \, CH_4} \left(E_{nat}^{CH_4}(t+1) + E_{ant}^{CH_4}(t+1) \right) - \frac{CH_4(t)}{\tau_{CH_4}(t)}$$

with $CH_4(t)$ being the CH₄ mole fraction (ppb) in year t, $E_{nat}^{CH_4}$ being the natural CH₄ emissions (Tg CH₄), $E_{ant}^{CH_4}$ being the anthropogenic CH₄ emissions (Tg CH₄), $\frac{ppb}{2.75 Tg CH_4}$ being the conversion factor from the IPCC AR6 report ⁹⁹, and $\tau_{CH_4}(t)$ being the life time of CH₄ (yr) that is calculated as follows:

$$\tau_{CH_4}(t) = \left(\frac{r_{OH}}{11yr} + \frac{1}{52.4 yr}\right)^{-1},$$
(11)

with lifetimes based on Tab 6.2 in IPCC AR6 Chapter 6^{96} and Prather et al. (2012)¹⁰⁰ and rOH being the relative change in tropospheric OH with respect to year 2019:

$$\ln(rOH) = \ln\left(\frac{OH(t)}{OH(2019)}\right) =$$

$$-0.32 * \ln\left(\frac{CH_4(t)}{CH_4(2019)}\right) + 0.0042 * \left(\frac{E_{NO_X}(t)}{E_{NO_X}(2019)}\right) - 0.000105 * \left(\frac{E_{CO}(t)}{E_{CO}(2019)}\right) - 0.000313 * \left(\frac{E_{VOC}(t)}{E_{VOC}(2019)}\right), (12)$$

with $E_{NO_X}(t)$, $E_{CO}(t)$, and $E_{VOC}(t)$ being the emissions from CO, VOC, and NO_X.

• N₂O concentrations change is calculated forward every year as follows:

$$N_2 O(t+1) = N_2 O(t) + \frac{ppb}{4.79 \, Tg \, N} \Big(E_{nat}^{N_2 O}(t+1) + E_{ant}^{N_2 O}(t+1) \Big) - \frac{N_2 O(t)}{\tau_{N_2 O}(t)} \gamma r,$$
(13)

with $N_2O(t)$ being the N₂O concentrations (ppb) in year t, $E_{nat}^{N_2O}$ being the natural N₂O emissions (Tg N), $E_{ant}^{N_2O}$ being the anthropogenic N₂O emissions (Tg N), $\frac{ppb}{4.79 Tg N}$ being the conversion factor from Prather et al. (2012)¹⁰⁰, and $\tau_{N_2O}(t)$ being the lifetime of N₂O (yr)⁶⁴:

$$\tau_{N_{2}O}(t) = 116 \ yr * \left(\frac{E_{ant}^{N_{2}O}(t)}{E_{ant}^{N_{2}O}(2019)}\right)^{-0.055},$$

(14)

with the mean lifetime (116 years) being based on chapter 5 of IPCC AR6⁹⁹.

- The stratospheric adjusted radiative forcing for CH₄ and N₂O is calculated as described in chapter 7 of IPCC AR6, Table 7.SM.1⁹⁶. From that, the effective radiative forcing is calculated using adjustment factors (0.86 for CH₄ and 1.07 for N₂O) from chapter 7 of IPCC AR6⁹⁶.
- Effective radiative forcing of tropospheric O₃ in 2019 is set to 0.34 W m⁻² and evolves over time as described in equation 7.SM.1.3 in IPCC AR6 CH7⁹⁶. The effective radiative forcing of tropospheric O₃ in 2019 is within the uncertainty range given in Figure 7.6 in IPCC AR6 CH7⁹⁶. Although the best estimate is 0.47 W m⁻², we have reduced the effective radiative forcing so that the total non-CO₂ radiative forcing in 2025 that is estimated by the reduced atmospheric chemistry model is consistent with the prescribed non-CO₂ radiative forcing in Bern3D based on the RCP and SSP databases following SSP1-2.6 that was used until 2025. The effective radiative forcing of stratospheric O3 is of the order of -0.05 W m⁻² and included in the remaining effective radiative forcing (see below).
- Total halogen effective forcing radiative forcing in 2019 is set to 0.41 W m⁻² (Figure 7.6 in IPCC AR6 CH7⁹⁶) is divided into short-lived halogens with a lifetime of 12 years (0.08 W m⁻²), medium-lived halogens with a lifetime of 40 years (0.09 W m⁻²), long-lived halogens with a lifetime of 100 years (0.21 W m⁻²), and 'eternal' halogens (0.03 W m⁻²) based on table 7.SM.1.3 in IPCC AR6 CH7⁹⁶. The halogen radiative forcing is assumed to decay depending on the lifetime with no source of halogens.
- The aerosol effective radiative forcing is set to -1.1 W m⁻² in 2019 following Figure 7.6 in IPCC AR6 Chapter 7⁹⁶. After 2019, the aerosol forcing decays exponentially in the standard case. Half of it is assumed to decline with a half-life of 20 years and half is assumed to decay with a half-life of 250 years to approximate an aerosol forcing that co-evolves with the strong reductions in CO₂ emissions that need to be achieved to limit warming to temperatures between 1.5°C and 2°C.

• Effective radiative forcing of stratospheric water vapor $(ERF_{H_2O}(t))$ is calculated based on the atmospheric CH₄ mixing ratio in the respective year $(CH_4(t))$ and the preindustrial atmospheric CH₄ mixing ratio $(CH_4^{pi})^{64}$:

$$ERF_{H_20}(t) = \alpha_{H_20} \left(\sqrt{CH_4(t)} - \sqrt{CH_4^{pi}} \right),$$

(15)

With α_{H_20} set to 0.0031 $\frac{W}{m^2 pp b^{\frac{1}{2}}}$ so that $ERF_{H_20}(2019)$ is 0.05 $\frac{W}{m^2}$ as in Figure 7.6 in IPCC AR6

Chapter 7⁹⁶.

Remaining effective radiative forcing (albedo, stratospheric O₃, contrails, ...) is for simplicity assumed to stay constant at -0.07 W m⁻² based on Figure 7.6 in IPCC AR6 CH7⁹⁶.

AERA robustness tests

The AERA was tested for robustness within the Bern3D-LPX model framework. These tests are made with the standard version (CO₂-fe approach and CO₂, CH₄, and N₂O emissions evolving proportional after 2025) and include varying the allowed difference to the REB (ξ) and the allowed integrated exceedance emissions (ε) when fitting the future total CO₂-fe emissions curve, and testing the algorithm when Bern3D has been used with different non-CO₂ GHG radiative forcing than that 'seen' by the AERA to ensure that the AERA still works even if the past radiative forcing estimates are incorrect.

The sensitivities towards the allowed difference to the REB (ξ) and the allowed exceedance emissions (ε) were tested with three model configurations (ECS=1.9°C, 3.2°C, 5.7°C) with 4 instead of 8 different temperature anomalies superimposed in each case for computational reasons. Simulations were made

with half and twice the amount of ξ and ε . CO₂-fe emissions from 2025 to 2300 are on average not different from the standard version when ξ is halved or doubled (0.0 ± 0.1 Pg C yr⁻¹), but minimum CO₂-fe emissions in the 21st century are marginally less pronounced if ξ is halved and more pronounced if ξ is doubled (Supplementary Figure 3). The temperature curves are also indifferent. When exceedance emissions are halved, temperature curves remain almost unchanged, whereas CO₂-fe emissions become less smooth when the temperature anomaly is close to the temperature target (Supplementary Figure 4). In such a situation, a fast change in the sign of the REB between two stocktakes due to natural variability in the temperature likely causes the abrupt changes in the CO₂-fe emissions curve. When ε is doubled, the temperature overshoot in the 21st century becomes larger for the high ECS configuration by up to 0.06°C but leaves temperature curves for the other configurations unchanged. In return, the CO₂-fe emissions curves become slightly smoother. Overall, the chosen best parameters for ξ and ε present the best compromise between the smoothness of the emission curves and the degree of a temperature overshoot.

To test the robustness of the AERA towards the estimate of the past radiative forcing, the radiative forcing from aerosols was adjusted in the model, whereas the non-CO₂ radiative forcing and the corresponding CO₂-fe that are 'seen' by the AERA are not adjusted. The radiative forcing of aerosols in 2011 was taken from the central estimate of the IPCC report WG1 2013⁵⁹. It was extrapolated back and forward (until 2025) in time using sulfur emissions as a proxy from the RCP and SSP databases. After 2025, the radiative forcing is calculated by the reduced form chemistry model. Once the aerosol radiative forcing time series is determined, this timeseries of aerosol forcing was adjusted by ±40%. The model was then run with 3 different configurations (ECS =1.9, 3.2 and 5.7°C). However, only a few combinations of ECS and adjusted aerosol forcing are credible, i.e., a small aerosol forcing in combination with a large ECS results in too strong warming over the historical period whereas a small ECS and a large cooling aerosol forcing results in almost no temperature rise over the same period. We then chose the combinations that represent the historical warming best: low ECS and low aerosol

forcing and high ECS and high aerosol forcing (Supplementary Figure 5). Overall, the AERA still works in both cases. If aerosol forcing is less strong than expected, a reduction of aerosols does not cause the expected warming and emissions reductions can be less pronounced. However, if aerosol forcing is underestimated, a reduction of aerosols over the 21st century will cause pronounced warming and an overshoot of 0.58°C to which the AERA reacts with strong emissions reductions. The AERA thus automatically corrects the underestimation of the aerosol forcing.



Supplementary Figure 1. Sensitivity of results to maximum length of the prescribed polynomic function in the AERA algorithm. (a-I) Temperature anomalies with respect to 1850-1900 and (m-x) corresponding CO₂-fe emissions for two ensemble members each if the AERA is applied every five years starting in the

year 2025 for the 1.5°C target (a-f, m-r) and the 2.0°C target (g-l, s-x). The lines show realizations for different maximum lengths of the prescribed polynomic function in the AERA algorithm: fixed maximum length at 30 years (orange), fixed maximum length at 250 years (blue), and dynamical maximum length (green) as described in the methods. The shaded area shows the range of all configurations that fall within the likely range of ECS as defined by Sherwood et al. (2020)¹⁷. The grey shading in (a) indicates the uncertainty with which the anthropogenic warming can be determined (±0.2°C)^{53–56}.



Supplementary Figure 2. Schematic of the implementation of the reduced atmospheric chemistry model. The reduced form atmospheric chemistry model is used to project non-CO₂ GHG concentrations and non-CO₂ (effective) radiative forcing from emissions of CO₂, CH₄, and N₂O, and of the precursors CO, VOC, and NOx. Here, radiative forcing from aerosols and from halogens is prescribed (see methods). When using the CO₂-fe approach to calculate CO₂ equivalent emissions (left), radiative forcing from all non-CO₂ agents considered is added to yield total non-CO₂ radiative forcing, which is converted to CO₂-fe emissions (Smith et al., 2021). When using the GWP-100 approach to calculate CO₂ equivalent emissions (right), CH₄ and N₂O emissions are transferred to CO₂ equivalent

emissions using GWP-100, while radiative forcing from all remaining non-CO₂ agents considered is added to yield the remaining non-CO₂ radiative forcing, which is converted to CO₂-fe emissions. Projected non-CO₂ radiative forcing (together with fossil CO₂ emissions, and land use) is prescribed to the Bern3D-LPX model to project CO₂ concentration and global warming. In the standard simulations in this manuscript, the CH₄, N₂O, CO, NOx, and VOC emissions evolve proportional to the CO₂ emissions in every year and the effective radiative forcing of aerosols and halogens are prescribed. In each year, the CO₂ emissions are chosen for which the resulting CO₂-fe emissions fit the prescribed CO₂-fe emissions by the AERA for that respective year.



Supplementary Figure 3. Adaptive emissions and resulting temperature anomaly for 1.5°C and 2.0°C target with varying allowed difference to the remaining emission budget. Temperature from 2020 to 2300 for three model configurations with varying ECS (orange = 5.7°C, blue = 3.2°C, and green = 1.9°C) averaged over four simulations each with different inter-annual variability for the (**a**, **e**) 1.5°C and (**b**, **f**) 2.0°C temperature target and (**c**, **d**, **g**, **h**) the respective CO₂-fe emission curves with the difference to the remaining emission budget (ξ) being (**a**-**d**) 2.5 Pg C (half of standard version) and (**e**-**h**) 10 Pg C. Temperature and emission curves are also shown for the standard version (ξ = 5 Pg C) (colored transparent lines). The grey shading in (**a**, **b**, **e**, **i**) indicates the uncertainty with which the anthropogenic warming can be determined (±0.2°C)^{53–56}.



Supplementary Figure 4. Adaptive emissions and resulting temperature anomaly for 1.5°C and 2.0°C target with varying allowed exceedance emissions. Temperature from 2020 to 2300 for three model configurations with varying ECS (orange = 5.7°C, blue = 3.2°C, and green =1.9°C) averaged over four simulations each with different inter-annual variability for the (**a**, **e**) 1.5°C and (**b**, **f**) 2.0°C temperature target and (**c**, **d**, **g**, **h**) the respective CO₂-fe emission curves with the allowed exceedance emissions (ϵ) being (**a**-**d**) 5 Pg C (half of standard version) and (**e**-**h**) 20 Pg C. Temperature and emission curves are also shown for the standard version (ϵ = 10 Pg C) (colored transparent lines). The grey shading in (**a**, **b**, **e**, **i**) indicates the uncertainty with which the anthropogenic warming can be determined (± 0.2 °C)^{53–56}.



Supplementary Figure 5. Adaptive emissions and resulting temperature anomaly for 1.5°C and 2.0°C target when the radiative forcing from aerosols is different than estimated. (a, b) temperatures and (c, d) associated CO₂-fe emissions averaged over four simulations each with different inter-annual variability (a, c) with ECS=5.7 and 40% increased simulated radiative forcing from aerosols and (b, d) with ECS=1.9 and 40% reduced simulated radiative forcing from aerosols. In each case, the AERA input for the radiative forcing from aerosols was not changed. Temperature observations based HadCRUT5 GMST time series are shown in comparison for the historical period.

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