

1 **Letter:**

2 **Equitable mitigation to achieve the Paris Agreement goals**

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16

17 **Manuscript.**

18 **Introductory paragraph:**

19 Benchmarks to guide countries in ratcheting-up ambition, climate finance, and support in an
20 equitable manner are critical but not yet determined in the context of the Paris Agreement¹. We
21 identify global cost-optimal mitigation scenarios consistent with the Paris Agreement goals and
22 allocate their emissions dynamically to countries according to five equity approaches. At the
23 national level, China's Nationally Determined Contribution (NDC) is weaker than any of the five
24 equity approaches suggests, India's NDC is aligned with two, and the EU's and the USA's with
25 three. Most developing countries' conditional (Intended) NDCs (INDCs) are more ambitious
26 than the average of the five equity approaches under the 2°C goal. If the G8 and China adopt the
27 average of the five approaches, the gap between conditional INDCs and 2°C consistent pathways
28 could be closed. Equitable, cost-optimal, achievement of the 1.5°C target allocates the G8 and
29 China combined 21% emissions lower in 2030 (relative to 2010 levels) than for 2°C, and 39%
30 lower for remaining countries. Equitably limiting warming to 1.5°C rather than 2°C requires that
31 individual countries achieve mitigations milestones, such as peaking or reaching net-zero
32 emissions, around a decade earlier.

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34 **Main text:**

35 To achieve its global mitigation objectives (Fig. 1a), the Paris Agreement binds countries to
36 periodically take stock of collective progress “in light of equity and the best available science”¹,
37 starting in 2018. The Agreement did not indicate national mitigation targets aligned with the
38 long-term goals and “notes with concern that the estimated aggregate greenhouse gas emissions
39 levels in 2025 and 2030 resulting from the intended nationally determined contributions do not
40 fall within cost-optimal 2°C scenarios”¹. Indeed, the current “bottom-up” situation, whereby
41 countries determine their own mitigation targets, results in projected annual global emissions of
42 52.5 GtCO₂eq (ref. 2) in 2030 (average of 49.4 GtCO₂eq and 55.6 GtCO₂eq, respectively the
43 ‘high-ambition’ and ‘low-ambition’ estimates of ref. 3, SAR GWP-100, Methods), inconsistent
44 with Integrated Assessment Models’ (IAMs) cost-optimal trajectories to 2°C or 1.5°C (ref. 4,
45 Fig. 1a).

46 In 1992, under the United Framework Convention on Climate Change (UNFCCC), all countries
47 agreed to pursue mitigation efforts according to their “Common but Differentiated
48 Responsibilities and Respective Capabilities”⁵ (CBDR-RC), with efforts differentiated between
49 developed (Annex I) and developing countries. The Paris Agreement moved to a sliding scale of
50 self-differentiation on emissions mitigation. While co-benefits and self-interest can drive rapid
51 mitigation actions⁶, current contributions are insufficient to match the ambition of the Paris
52 Agreement. Therefore, equity is still central for the ratcheting process and when discussing the
53 adequate magnitude of climate finance and support⁷. All ratifying Parties must communicate
54 successive NDCs that represent a progression and reflect the “highest possible ambition” in

55 relation to their CBDR-RC. The Paris Agreement still invites developed countries, without
56 naming them⁸, to take the lead in reducing economy-wide emissions and mobilizing climate
57 finance.

58 Historically, few countries have indicated which guiding principle⁹⁻¹¹ or formula¹² could be used
59 to ensure equitable mitigation contributions. Instead, most countries merely declared their
60 INDCs to be “fair and ambitious”, either explicitly (e.g. India and the USA¹³) or implicitly by
61 stating their contribution. Here we inform the question of fairness by quantifying national
62 emissions allocations using five ‘equity approaches’. Unlike most earlier studies, we use a
63 methodology that aligns aggregate emissions allocations with IAM global emissions scenarios
64 that are consistent with the Paris Agreement’s long-term goals.

65 Several studies have modelled equity principles to allocate 2°C-consistent emissions scenarios
66 across countries^{12,14-24}. The IPCC’s Fifth Assessment Report (IPCC-AR5) grouped the
67 distributive justice concepts of over 40 studies in five equity categories^{18,25} (Table 1). Most of
68 these studies allocate emissions of different global scenarios that are not always cost-optimal;
69 comparing allocations at a specific point in time is therefore difficult. More recent studies
70 developed frameworks that allocate emissions from a unique global scenario across countries
71 following multiple equity approaches, and derived national GHG (ref. 21,24) or CO₂ only^{20,23}
72 scenarios consistent with the 2°C limit. However, national equitable emissions allocations
73 consistent with the 1.5°C goal have not yet been assessed in the literature.

74 We use the five IPCC-AR5 equity categories²⁵ to define five equity approaches²⁴ (Table 1).
75 These allocation approaches are applied to cost-optimal scenarios selected from the database
76 accompanying the IPCC-AR5 and ref. 26 that have net-zero emissions by 2100 and at least a
77 likely (>66%) chance to limit warming to 2°C (Methods). We explore five ‘sets’ of GHG
78 emissions scenarios based on this selection (Table 1): (i) 32 scenarios peaking by 2020 (‘2°C-
79 pre2020peak’), (ii) 39 peaking by 2020 with a more likely than not (>50%) chance to return to
80 1.5°C in 2100 (‘1.5°C-pre2020peak’), (iii) 6 scenarios peaking in 2030 (‘2°C-2030peak’), (iv) a
81 custom ‘2°C-statedINDCs’ scenario with interpolated emissions between 2030 pledged INDC
82 levels³ and, from 2050 onwards, the average of the ‘2°C-2030peak’ scenarios, and (v) a ‘2°C-
83 fairINDCs’ scenario equal to global scenario (iv) but with allocations starting in 2010 (Fig. 1a).
84 The ‘2°C-2030peak’ scenarios are only loosely consistent with the Paris Agreement (Methods).
85 Emissions allocations of all sets start in 2010, except for (iv), which starts in 2030 at national
86 INDCs levels.

87 [TABLE 1]

88 The ‘2°C-pre2020peak’ scenario set has a 2030 average of 39.7 GtCO₂eq, similar to the Paris
89 decision indicative target of 40 GtCO₂eq, and becomes net-zero as early as 2080 (Fig. 1a). The
90 ‘1.5°C-pre2020peak’ set averages at 32.6 GtCO₂eq in 2030 and becomes negative between 2059
91 and 2087. Average annual global emissions reduction rates over the 2030-2050 period, as a
92 fraction of 2010 levels, are 1.6%/y for early-action ‘2°C-pre2020peak’ scenarios (reaching
93 2.1%/y in 2025), 2.2%/y for 1.5°C scenarios (reaching 2.3%/y in 2039), and 3.2%/y for delayed-
94 action ‘2°C-2030peak’ scenarios (reaching 3.5%/y from 2040 to 2050).

95 The selected cost-optimal scenarios rely on the IAM’s assumptions of harmonized international
96 policies and emissions trading systems that are currently not in place. However, the Paris
97 Agreement has recognized the voluntary “use of internationally transferred mitigation outcomes
98 towards nationally determined contributions”¹. The emissions allocations determined here could
99 be met through a combination of domestic mitigation, internationally traded emissions
100 mitigation¹ and international financial contributions toward global mitigation²⁴. Under any of our
101 modelled equity approaches, the national emissions scenarios are not cost-optimal if applied
102 domestically. However, they are consistent with a global cost-optimal scenario if countries
103 choose the right mix of domestic mitigation and transfer of support for additional mitigation
104 elsewhere. National mitigation costs are allocated indirectly through the allocation of emissions
105 allowances. A fair distribution of mitigation costs could be used to derive equitable emissions
106 allocation when comprehensive national-level mitigation cost estimates are available.

107 We allocate to all countries GHG emissions scenarios that add up, under each of the five equity
108 approaches (Supplementary Tables), to global cost-optimal IAM scenarios – excluding emissions
109 from Land Use, Land-Use Change and Forestry (LULUCF), and international shipping and
110 aviation (Methods).

111 At the regional level (Fig. 1c-l), Middle East and Africa’s aggregated (I)NDCs are consistent
112 with all approaches except the CER under all scenario-sets. Asia’s aggregated (I)NDCs are not
113 consistent with any allocation under early-action scenarios, while the OECD’s are consistent
114 with the GDR and CER under the ‘2°C-pre2020peak’ and with none under ‘1.5°C-pre2020peak’.

115 Only the aggregated (I)NDCs of the Middle East and Africa are consistent with some 1.5°C
116 allocations (with great disparities at the sub-regional level, Supplementary Discussion).
117 At the national level (Fig. 1c-g), all equity approaches require China's emissions to peak earlier
118 and lower than its current NDC. The USA's and the EU's NDCs are in line with the CER
119 allocation and the higher end of the '2°C-pre2020peak' range under the GDR or EPC allocations.
120 India's NDC is consistent with the CPC and EPC allocations of '2°C-pre2020peak' scenarios,
121 and the CPC allocation averaged over the '1.5°C-pre2020peak' scenarios lies within the NDC
122 assessment's uncertainty range (Fig. 1b, other countries in Supplementary Tables and provided at
123 at: www.paris-equity-check.org).

124 [FIGURE 1]

125 Combining multiple visions of equity – using weighting factors²⁰ or a leadership based
126 approach²² – is not necessarily equitable by design but can represent a political compromise²⁰,
127 and is useful to compare national allocations under different global goals or scenarios sets. The
128 fairness of the CER, or 'grandfathering', approach is criticized in the literature^{23,27} and not
129 supported as such by any Party. However, we include CER in the average because it represents
130 one of the five IPCC equity categories, stressing national circumstances regarding current
131 emissions levels, and is implicitly followed by many of the developed countries^{23,24}. The average
132 allocation of the EU and the USA becomes negative close to mid-century under both the '1.5°C-
133 pre2020peak' and '2°C-pre2020peak' sets. China's average allocation becomes negative 20
134 years later, and India's only at the end of the century.

135 [TABLE 2]

136 Recent studies using alternative implementation²⁴ or modelling^{21,22} of similar equity approaches
137 towards 2°C find significant differences in some national emissions allocations, but generally
138 reach similar conclusions (Supplementary Discussion). Overall, literature focusing on CO₂
139 emissions de-facto ignores other GHG^{20,23}, and often allocates carbon budgets²⁰ impossible to
140 compare with single-year (I)NDCs.

141 Reflecting the global scenarios, equitable national allocations towards 1.5°C require earlier
142 mitigation than for 2°C (Fig. 2, results per-approach in the Supplementary Discussion). To
143 achieve the 1.5°C goal ‘major economies’ (G8 and China as a group) need to lower their 2030
144 emissions targets by an additional 21 percent-points relative to 2010 emissions, compared to the
145 ‘2°C-pre2020peak’ case, and other countries (‘other economies’) altogether by 39 additional
146 percentage-points (Fig. 2a). However, increasing current (I)NDCs by these additional
147 percentages would not result in fair contributions towards the 1.5°C goal. Indeed, the aggregated
148 (I)NDCs of the ‘major economies’ should already be 39 percentage-points more stringent than
149 they currently are to be in line with their averaged allocation under the ‘2°C-pre2020peak’ case
150 (Fig. 2b). In contrast, the aggregated (I)NDCs of the ‘other economies’ are only 8 percentage-
151 points above ‘2°C-pre2020peak’ average allocations. Consequently, pledges in line with the
152 1.5°C goal should be respectively 60 and 46 percentage-points more stringent than current
153 (I)NDCs for ‘major economies’ and ‘other economies’ respectively (Fig. 2c).

154 In order to compare the relative fairness of (I)NDCs under the current global ambition (52.5
155 GtCO₂eq for 2030), we compare (I)NDCs ('2°C-statedINDCs' set) with the '2°C-fairINDCs'
156 allocations (Fig. 2d). We find that the (I)NDCs of 'other economies', of the USA, and of the EU
157 are more ambitious or aligned with their average allocation under current international 2030-
158 ambition, while the (I)NDCs of Canada, of Japan, and especially of Russia and of China are
159 substantially less ambitious.

160 Emissions budgets and timing for peaking or net-zero emissions may constitute more easily
161 actionable targets than temperature goals²⁸. Figures 2e-g compare the average timing when
162 emissions allocations peak or reach net-zero under the five equity approaches for '1.5°C-
163 pre2020peak' and '2°C-pre2020peak'. Net-zero emissions are allocated five years earlier
164 towards 1.5°C for developing countries, and ten years earlier for developed countries (i.e. around
165 2055-2060). Developing countries' allocations peak about ten years earlier and up to 40% lower
166 towards 1.5°C than 2°C, which implies lower domestic emissions or lower revenues from
167 emissions-trading. Overall, aiming at 1.5°C rather than towards 2°C requires earlier but not
168 faster or deeper mitigation at the national level (Supplementary Discussion).

169 [FIGURE 2]

170 The lower emissions-end of our (I)NDC quantification ('high-ambition' target) is set by the
171 conditional targets and sometimes by the quantification uncertainty. Hence, in most countries,
172 these 'high-ambition' targets have implicitly been identified as feasible. The implementation of
173 these 'high-ambition' (I)NDCs³ would lead to 2030 emissions of 48.9 GtCO₂eq and leave an 8.8

174 GtCO₂eq gap with the average of ‘2°C-pre2020peak’ scenarios and a 20.4 GtCO₂eq gap with the
175 ‘1.5°C-pre2020peak’ average (excluding LULUCF and bunkers emissions, Methods). The
176 aggregated ‘high-ambition’ (I)NDCs of ‘other economies’ are collectively slightly more
177 ambitious than the average of their allocations (Fig. 3 and Supplementary Discussion), although
178 some individual (I)NDCs are less ambitious (e.g. Iran, Saudi-Arabia and Turkey). Therefore, the
179 ‘other economies’ altogether could meet their average ‘fair’ allocation by increasing their current
180 unconditional contribution to the aggregate level of their conditional (I)NDCs. The average ‘fair’
181 allocations of ‘major economies’ is 9.6 GtCO₂eq below their current aggregated ‘high-ambition’
182 (I)NDCs. Put simply, the average ‘fair’ allocation of ‘major economies’ alone closes the global
183 2030 mitigation gap to 2°C, provided that other countries achieve their ‘high-ambition’ (I)NDC
184 targets. Closing the 2030 gap to average ‘1.5°C-pre2020peak’ scenarios requires most countries
185 to increase their ambition beyond their current conditional (I)NDCs.

186 [FIGURE 3]

187 Current aggregate (I)NDCs fall substantially short of meeting either the 2°C or 1.5°C goals^{2,4}.
188 The ratchet mechanisms established by the Paris Agreement¹ need to achieve an additional 13
189 GtCO₂eq reduction in 2030 to align with 2°C cost-optimal scenarios, and 20 GtCO₂eq for 1.5°C
190 (Fig. 1a). We derived ‘Equitably Determined Contributions’ consistent with the five IPCC equity
191 approaches towards 2°C or 1.5°C goals (Supplementary Tables). Averaging across the five
192 concepts of equity assigns the effort, beyond current conditional (I)NDCs, required for the 2°C
193 goal to the G8 and China. Equitably meeting the 1.5°C goal, and avoiding the additional climate
194 impacts of a 2°C warmer world²⁹, means that almost all national contributions should be

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195 enhanced substantially, with key milestones, such as peaking or reaching net-zero emissions,
196 brought forward by a decade or more.

197 **Additional information**

198 Supplementary information is available in the online version of the paper. Correspondence
199 should be addressed to Y.R.d.P.. The equitable emissions allocations of all countries are included
200 in the Supplementary Tables in the online version of the paper and can be visualized at:
201 www.paris-equity-check.org.

202 **Acknowledgments**

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207 **Author contributions**

208 All authors contributed to discussing the results and writing the manuscript. Y.R.d.P. led the
209 study and performed the calculations. M.L.J. modelled the GDR approach. J.G. downscaled to
210 the national level global RCP8.5 emissions scenarios using SSP data. Y.R.d.P. and M.M.
211 suggested the study. J.G., M.L.J. and M.M. updated and managed the composite PRIMAP
212 database.

213 **Competing financial interests**

214 The authors declare no competing financial interests.

215 **Figure legends**

216 **Figure 1 | Global, national and regional emissions consistent with the Paris Agreement and**
217 **five equity principles compared to current pledges. a,** IAM scenarios consistent with the Paris
218 Agreement under ‘1.5°C-pre2020peak’ (red), ‘2°C-pre2020peak’ (blue) and ‘2°C-2030peak’
219 cases (purple), and their averages (thicker lines). Scenarios consistent with the 2030 Paris
220 decision target (green circles) are more opaque. **b,** Comparison with IPCC-AR5 database
221 scenarios (grey lines). **c-g,** National emissions allocations excluding LULUCF compared to
222 (I)NDCs (black circles). Coloured patches and lines show allocation ranges of global ‘2°C-
223 pre2020peak’ scenarios, and averages over the range of global ‘1.5°C-pre2020peak’ scenarios,
224 respectively. **h-i,** Regionally aggregated 2030 allocations and (I)NDCs.

225 **Figure 2 | Comparisons of national emissions change under different global goals. a-d,**
226 Relative changes between ‘1.5°C-pre2020peak’, ‘2°C-pre2020peak’, ‘2°C-statedINDC’ and
227 ‘2°C-fairINDC’ cases over the 2010-2030 period (excluding LULUCF). **e-f,** Comparison of
228 timing of first net-zero emissions and peaking national emissions averaged over the five equity
229 approaches for the ‘1.5°C-pre2020peak’ and ‘2°C-pre2020peak’ cases. **g,** Average of peaking
230 emissions levels versus average peaking emissions years for ‘1.5°C-pre2020peak’ and ‘2°C-
231 pre2020peak’ cases. Disk sizes are proportional to 2010 emissions levels. Colours indicate world
232 regions. G8+China (larger disk) and the rest of the world (smaller disk) are shown in grey.

233 **Figure 3 | Gaps between equitable mitigation allocations and conditional (I)NDCs in 2030.**

234 Countries following individual approaches (tip of coloured patches), or their average (black

235 lines) under the 2°C (panel **a**) or 1.5°C goals (panel **b**), reduce or increase the projected 2030
236 global emissions levels (excluding LULUCF and bunker emissions) compared to aggregated
237 conditional (I)NDCs. Countries are sorted left to right in decreasing order of 2010 emissions
238 (proportional to bar width). The global gaps (grey arrow) between current aggregated conditional
239 (I)NDCs and the average scenarios consistent with the Paris 2°C or 1.5°C goals (grey bar) are
240 shown in each panel.

241

242 **Tables**

243 **Table 1 | Allocation approaches and global scenario set descriptions.** The allocation

244 framework modelling and parameterization follow those of ref. 24. More details on the scenario

245 selection in the Supplementary Methods.

| Allocation name | Allocation type | IPCC category | Allocation characteristics |
|-------------------|-------------------------------|--------------------------------|--|
| CAP | Capability | Capability | High mitigation for countries with high GDP per capita. |
| EPC | Equal per capita | Equality | Convergence towards equal annual emissions per person. |
| GDR | Greenhouse Development Rights | Responsibility-capability-need | High mitigation for countries with high GDP per capita and high historical per capita emissions. |
| CPC | Equal cumulative per capita | Equal cumulative per capita | Populations with high historical emissions have low allocations. |
| CER | Constant emissions ratio | Staged approaches | Maintains current emissions ratios. |
| Scenario set | Scenario type | IPCC category | Scenarios characteristics |
| 1.5°C-pre2020peak | 1.5°C scenarios | 39 P1P2 scenarios | More likely than not (>50%) chance to return to 1.5°C in 2100. Global emissions peaking by 2020. National emissions allocated from 2010 onwards. |
| 2°C-pre2020peak | 2°C early action scenarios | 32 P1P2 scenarios | Likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking by 2020. National emissions allocated from 2010 onwards. |
| 2°C-2030peak | 2°C delayed action scenario | 6 P3 scenarios | Likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2010 onwards. |
| 2°C-statedINDC | 2°C delayed action scenario | 1 P3 custom scenario | De-facto likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2030 (I)NDC levels onwards. |
| 2°C-fairINDC | 2°C delayed action scenario | 1 P3 custom scenario | De-facto likely (>66%) chance to stay below 2°C by 2100. Global emissions peaking in 2030. National emissions allocated from 2010 onwards. |

246

247 **Table 2 | Mitigation targets, timing of peaking and net-zero emissions, and emissions**

248 **budgets of selected countries for the ‘1.5°C-pre2020peak’ and ‘2°C-pre2020peak’ cases,**

249 **averaged over the five equity allocations.** Target ranges indicate the extrema across the five

250 approaches' averages. Emissions from LULUCF and bunkers are excluded. Data for all countries
 251 available in the Supplementary Tables. Emissions budgets are accounted from 2010.

| Country | Goal | 2030 change to 2010 levels (in %) | | 2050 change to 2010 levels (in %) | | Peaking year | Net-zero year | Budget to 2050 in GtCO ₂ eq | Budget to 2100 in GtCO ₂ eq |
|--------------------|-------|-----------------------------------|--------------|-----------------------------------|---------------|--------------|---------------|--|--|
| World (no bunkers) | 2°C | -5 | | -47 | | 2020 | 2082 | 1523 | 1749 |
| | 1.5°C | | | | | Immediate | | | |
| China | 2°C | -27 | [-59 to 6] | -70 | [-95 to -44] | Immediate | 2075 | 1134 | 1156 |
| | 1.5°C | -48 | [-71 to -19] | -88 | [-102 to -76] | Immediate | 2075 | 329 | 345 |
| USA | 2°C | -44 | [-66 to -5] | -89 | [-119 to -47] | Immediate | 2065 | 254 | 237 |
| | 1.5°C | -64 | [-80 to -33] | -109 | [-144 to -78] | Immediate | 2067 | 154 | 104 |
| EU | 2°C | -38 | [-62 to -5] | -86 | [-122 to -47] | Immediate | 2057 | 109 | 57 |
| | 1.5°C | -62 | [-84 to -33] | -106 | [-149 to -78] | Immediate | 2068 | 114 | 94 |
| India | 2°C | 72 | [-5 to 155] | 40 | [-47 to 152] | 2033 | 2057 | 80 | 54 |
| | 1.5°C | 30 | [-33 to 102] | -24 | [-78 to 63] | 2022 | 2087 | 162 | 236 |
| | C | | | | | | 2081 | 122 | 161 |

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313 **Methods:**

314 **Scenario selection**

315 We selected global emissions scenarios from the IPCC-AR5 database (hosted at the International
316 Institute for Applied Systems Analysis and available at: tntcat.iiasa.ac.at/AR5DB/) and ref. 26
317 that feature negative GHG emissions by the end of the century and a chance equal to or higher
318 than 66% to limit global warming to 2°C over the entire 21st century, or equal to or higher than
319 50% to return to 1.5°C in 2100 compared to pre-industrial levels.

320 **IPCCAR5 scenarios**

321 The temperature likelihood response to 523 of these 846 Kyoto-GHG scenarios from the IPCC-
322 AR5 database was projected using the simple carbon cycle and climate model MAGICC6^{30,31},
323 under a probabilistic set-up³² (data visualization available at: [https://www.pik-potsdam.de/paris-
324 reality-check/ar5-scenario-explorer/](https://www.pik-potsdam.de/paris-reality-check/ar5-scenario-explorer/)). First, we selected from the database 155 scenarios that
325 have net negative emissions in 2100. Of these 155 scenarios, a sub-selection was made of the 40
326 scenarios with a likely ($\geq 66\%$) chance to stay below 2°C throughout the 21st century. Of these 40
327 scenarios, 2 had a more likely than not ($>50\%$) chance to result in a warming below 1.5°C in
328 2100. The number of scenarios matching each or a combination of these three criteria – negative
329 emissions in 2100, 2°C ($\geq 66\%$ over 2010-2100) and 1.5°C ($>50\%$ in 2100) – are shown in
330 Supplementary Table 1 (Supplementary Information). All the selected scenarios that have a more
331 likely than not chance of warming being below 1.5°C in 2100, also have a likely chance to
332 remain below 2°C over the 2010-2100 period. Only 2 of the 5 scenarios that have a more likely

333 than not chance to be below 1.5°C in 2100 also have negative emissions in 2100. The model and
334 study names of these scenarios are shown in Supplementary Table 2 (Supplementary
335 Information).

336 The ‘2°C-2030peak’ scenarios have higher emissions levels than the ‘2°C-pre2020peak’ but still
337 have a likely chance to limit warming to 2°C and do not result in higher maximal temperature
338 over the century. However, these ‘2°C-2030peak’ scenarios are from the MERGE-ETL_2011
339 model (Supplementary Information) that uses exogenous sulfate forcing³³ and feature higher SO₂
340 – an aerosol with a cooling effect – concentrations than other IPCC-AR5 Working Group 3
341 scenarios³⁴. These aerosol emissions are outside the ranges consistent with the underlying CO₂
342 path³⁵. Moreover, the ‘2°C-2030peak’ scenarios do not peak as soon as possible, as defined in
343 Article 2 of the Paris Agreement.

344 **Additional 1.5°C scenarios**

345 To this selection of 40 IPCC-AR5 scenarios, we added the 37 scenarios from ref. 26 that have a
346 more likely than not (>50%) chance to have warming below 1.5°C in 2100. All of these
347 scenarios have negative emissions in 2100. These 37 scenarios are from the MESSAGE or
348 REMIND modelling frameworks and the scenario names and descriptions are available in Table
349 4 of the supplementary information of ref. 26.

350 The average of all selected 1.5°C scenarios that peak between 2010 and 2020 is 32.6 GtCO₂eq in
351 2030. The UNEP gap report³⁶ identified a 39 GtCO₂eq goal for 2030, which corresponds to the

352 median of the 1.5°C scenarios (from the same source as our study) with emissions peaking in
353 2020 only.

354 **(I)NDC scenario**

355 In addition to the selected emissions scenarios, we construct a global emissions scenario that is in
356 line with current aggregated (I)NDC targets. Between 2010 and 2030, this global ‘2°C-
357 statedINDC’ scenario follows the global emissions from the “(I)NDC factsheets”³ (for ‘high-
358 ambition’ or ‘low-ambition’ assessments, and the average of both), that include emissions
359 projections of all countries, national Land-Use, Land-Use Change and Forestry (LULUCF), and
360 international shipping and aviation (‘bunker emissions’) emissions until 2030. Beyond 2030, the
361 global ‘2°C-statedINDC’ emissions are a 20-year linear interpolation to reach the level of the
362 average of the global ‘2°C-2030peak’ scenarios (including LULUCF emissions). Beyond 2050,
363 the global ‘2°C-statedINDC’ scenarios follows the averaged of global ‘2°C-2030peak’ scenarios.
364 The ‘2°C-statedINDC’ scenario is expected to have a likely chance of limiting global warming to
365 2°C – with the same limitations regarding SO₂ concentrations as the ‘2°C-2030peak’ scenarios.
366 Indeed, the ‘2°C-statedINDC’ scenario (whether it follows the INDC’s ‘high-ambition’, ‘low-
367 ambition’ assessments, or the average of both) has lower emissions than the average of ‘2°C-
368 2030peak’ scenarios until 2050, and is equal to the average of ‘2°C-2030peak’ scenarios beyond
369 2050 (see Fig 1).

370

371 Scenario preparation

372 We used the Potsdam Real-time Integrated Model for the probabilistic Assessment of emission
373 Paths (PRIMAP)¹⁷ to model allocations approaches. This model contains population, GDP, and
374 GHG emissions historical and projected data from composite sources as detailed in ref. 24.
375 Kyoto-GHG emissions are aggregated following the ‘SAR-GWP-100’ (Global Warming
376 Potential for a 100 year time horizon) as reported in the Second Assessment Report of the
377 IPCC³⁷ and used under the UNFCCC.

378 All these global scenarios, shown in Fig. 1a, are harmonized to the PRIMAP¹⁷ database’s 2010
379 emissions of 47.7 GtCO₂eq (including LULUCF, and international shipping and aviation
380 emissions). To do so, emissions are multiplied by a vector that is an interpolation between the
381 2010 PRIMAP emissions levels divided by the respective 2010 scenarios values, and 1 in
382 2040^{24,37}.

383 In this study, we allocate emissions of ‘bunker-free’ scenarios that are in line with the global
384 scenarios selected and constructed as described above, and that exclude LULUCF emissions as
385 follows. Emissions of the LULUCF sector are not considered by all parties as part of the
386 emissions scope to be negotiated. Moreover, no universal accounting method of positive or
387 negative LULUCF emissions is currently in place. Therefore, we exclude LULUCF emissions
388 from the global scenarios before allocating their emissions across countries.

389 For the IPCC-AR5 scenarios, we excluded the corresponding LULUCF emissions. For the 37
390 1.5°C scenarios of ref. 26, where no specific LULUCF emissions were available, we excluded

391 the CO₂ emissions that do not come from fossil fuels combustion. We then subtracted from these
392 IPCC-AR5 and ref. 26 scenarios international shipping and aviation emissions from the
393 QUANTIFY project³⁸ coherent with the IPCC-SRESB1 scenario that limits global warming to
394 1.8°C compared to the 1980-1999 average^{24,39}. Shipping emissions are 3.9 times higher in 2100
395 compared to 2010 levels, and aviation emissions double over that same period, but peak in 2062.
396 While the mitigation targets agreed in Article 4 apply to all GHG, the Paris Agreement contains
397 no specific reference to bunker emissions. The lack of current policies does not leave ground to
398 project strong mitigation scenarios^{40,41}. Lower emissions from this sector would reduce the
399 mitigation burden on all countries.

400 We also constructed a version of the ‘2°C-statedINDC’ without bunker and LULUCF emissions
401 following the methodology employed to construct the ‘2°C-statedINDC’ scenario that includes
402 bunker and LULUCF emissions. This bunker-free ‘2°C-statedINDC’ emissions scenario is the
403 sum of all national emissions from ref. 3 over the 2010-2030 period. Beyond 2030, the bunker-
404 free ‘2°C-statedINDC’ emissions follow a 20-year linear interpolation to reach the level of the
405 2050 average of the bunker-free ‘2°C-2030peak’ scenarios (excluding bunker and LULUCF
406 emissions). Beyond 2050, the bunker-free ‘2°C-statedINDC’ scenario follows the average of the
407 bunker-free ‘2°C-2030peak’ scenarios. The bunker-free ‘2°C-statedINDC’ scenario is allocated
408 across countries using our allocation framework from 2030 onwards, when countries have the
409 emission level of their (I)NDC target⁴. The ‘2°C-fairINDC’ global scenario is equal to the ‘2°C-
410 statedINDC’ scenario, both with and without LULUCF and bunker emissions. At the national

411 level, the emissions allocation of the ‘2°C-fairINDC’ scenario begins in 2010 and therefore
412 differs from the national emissions of the ‘2°C-statedINDC’ scenario.

413 All these bunker-free scenarios are harmonized to the PRIMAP¹⁷ database’s 2010 emissions of
414 42.5 GtCO₂eq (excluding LULUCF, international shipping and aviation emissions). To do so,
415 national emissions are multiplied by a vector that is an interpolation between the 2010 PRIMAP
416 national emissions levels divided by the respective 2010 bunker-free scenarios values, and 1 in
417 2040^{24,37}. These bunker-free scenarios, excluding LULUCF and international shipping and
418 aviation emissions are shown in Supplementary Figure 1 (Supplementary Information).

419 The allocation of the scenarios’ bunker-free emissions follows the methodology and the
420 parameterization described in the supplementary information of ref. 24. The only exception is the
421 ‘2°C-statedINDC’ case whose allocation starts in 2030, starting at estimated national (I)NDC
422 levels. All other cases have emissions allocations starting in 2010 at national historical levels¹⁷.

423 The GDR allocation approach requires business-as-usual emissions projections. We use RCP8.5,
424 downscaled using the SSP2 scenario (<https://tntcat.iiasa.ac.at/SspDb/>) from the Shared
425 Socioeconomic Pathways framework^{42,43}. More details are available in ref. 24. The business-as-
426 usual emissions projections used in the ‘2°C-statedINDC’ beyond 2030 national (I)NDC levels
427 case follow the growth rates of RCP8.5 over the 2030-2100 period.

428 The modelling and the parameterization of the equity approaches follow those of a previous
429 study²⁴. Notably, a 30-year linear transition period is implemented between national 2010
430 emissions and the allocations under the CAP and EPC approaches. Therefore, in 2030 this

431 transition period still slightly favours countries with allocations lower than their 2010 levels –
432 usually developed countries, and slightly disfavours countries with allocations higher than their
433 2010 levels. Historical emissions are accounted since 1990 under the GDR and CPC approaches.
434 The CPC approach applies a 1.5% annual discount rate to emissions before 2010 and achieves
435 equal cumulative per capita emissions in 2100. The GDR approach allocates emissions
436 reduction, compared to business-as-usual scenarios, to country’s citizens earning over \$7500 (in
437 purchase power parity) annually.

438 The distribution of regional mitigation action as represented in least-cost mitigation pathways is
439 not necessarily equitable. Our results show how pathways that achieve the global Paris
440 Agreement mitigation goals at lowest cost can be aligned with equity principles at the national
441 scale.

442 The (I)NDC assessment used in this study is an average of the ‘high-ambition’ and ‘low-
443 ambition’ cases from ref. 3, except in Fig. 3 that uses ‘high-ambition’ (I)NDC assessment. The
444 ‘high-ambition’ assessment uses conditional (I)NDCs when available as well as the most
445 ambitious end of the uncertainty associated with the (I)NDC assessment (based on GDP,
446 population, energy demand projections). The ‘low-ambition’ assessment reflects the lower
447 ambitions end of the uncertainty associated with the assessment of unconditional (I)NDCs. The
448 assessments used in this study^{2,3} used in this study are based on original (I)NDCs, before their
449 conversion to NDCs.

450 Countries with missing data

451 Deriving the CAP and GDR allocations requires national projections of GDP. The PRIMAP
452 database does not contain such projections for all countries due to a lack of available data.
453 Countries with some missing data ('missing countries' whose ISO-Alpha 3 country codes are:
454 'AFG', 'AGO', 'ALB', 'AND', 'ARE', 'ATG', 'COK', 'DMA', 'FSM', 'GRD', 'KIR', 'KNA', 'LIE',
455 'MCO', 'MHL', 'MMR', 'MNE', 'NIU', 'NRU', 'PLW', 'PRK', 'QAT', 'SMR', 'SSD', 'SYC', 'TUV',
456 'ZWE') are mostly developing countries whose emissions allocation could represent a significant
457 fraction of global 2030 emissions, under the CAP allocation in particular given their low GDP
458 per capita (<https://www.imf.org/external/pubs/ft/weo/2015/01/weodata/download.aspx>). We
459 excluded the countries with missing data from the allocations and the remaining countries share
460 the global 'bunker-free' scenarios' emissions. Figure 3 displays the aggregated conditional
461 (I)NDCs excluding these 'missing countries'. As a consequence, the mitigation gaps between the
462 aggregated (I)NDCs and the aggregated average allocations are affected by the exclusion of
463 countries' 2030 (I)NDC emissions (and is greater or smaller depending on how the sum of
464 average allocations of these countries would compare to the sum of their conditional (I)NDCs).
465 The gap between that sum of all countries' conditional (I)NDCs – 49.8 GtCO₂eq including the
466 'missing countries' (51.4 GtCO₂eq with bunker emissions), excluding LULUCF emissions – and
467 the sum of available average allocations – 40.1 GtCO₂eq – would be 9.6 GtCO₂eq instead of 8.8
468 GtCO₂eq. As a reminder, the gap between the 'major economies' (G8 plus China) aggregated
469 conditional (I)NDCs and their aggregated allocation is of 9.6 GtCO₂eq. The conclusions of
470 Figure 3 are still valid in this configuration. Note that the aggregate level of all 'high-ambition'

471 (I)NDCs including LULUCF emissions (including the ‘missing countries’) is 49.4 GtCO₂eq, and
472 47.8 GtCO₂eq excluding bunker emissions.

473 **Method's references**

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