

Future-proofing interpretations of the Paris Agreement's limit of well below 2 °C

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The Paris Agreement's 'well below 2 °C' target is often interpreted as holding warming below 2 °C with a probability in the 66–90% range. We argue that such interpretations are not future-proof as decreasing uncertainties with time will allow temperatures to approach 2 °C later in the century. We show how referring to median warming can resolve this issue and illustrate how past probabilistic target interpretations would translate to a median 1.65–1.8 °C warming limit range.

The Paris Agreement requires global warming to remain 'well below 2 °C' relative to pre-industrial levels while pursuing efforts to limit it to 1.5 °C, known as the Paris Agreement long-term temperature goal (LTTG)¹. As the prospect of keeping warming below 1.5 °C reduces², focus turns to understanding the well below 2 °C limit. The legal imperative of pursuing efforts to keep warming below 1.5 °C persists even if 1.5 °C is temporarily exceeded, with well below 2 °C seen as a stricter legal limit or ceiling that cannot be exceeded^{3–5}. The 'well below' language of the LTTG has no official definition, but policy documents implicitly interpret it as having a specific probability of keeping warming below 2 °C (refs. 6–8).

Policy documents commonly use probabilities of 66% or higher, consistent with the IPCC definition of 'likely'⁹. The 2015 United Nations Environment Programme (UNEP) Emissions Gap Report⁷ and the Sustainable Development Goals¹⁰ (adopted shortly before the Paris Agreement) referenced 'likely below 2 °C', an interpretation later adopted by the International Energy Agency (IEA)⁶. Statistics reflecting this LTTG interpretation are now cited in legal cases^{11,12} and parliamentary resolutions¹³. Some studies adopt higher probabilities, supported by several lines of reasoning. Notably, the earlier Cancún Agreements set a target of keeping warming 'below' 2 °C, which was broadly interpreted using a 66% probability^{14–18}. The subsequent strengthening of this language in climate policy decisions to 'well below' 2 °C thus implies a higher probability. Accordingly, some sources use 83% (corresponding to up to 1 s.d. above the median in remaining carbon budgets of the Intergovernmental Panel on Climate Change (IPCC)^{19,20}) or 90%, referring to the IPCC definition of 'very likely'^{8,21,22}.

The challenge with probabilistic targets is that uncertainty of future outcomes declines as those outcomes come closer. Over time, accumulating past emissions result in more warming while the remaining emissions compatible with a given temperature limit

reduce^{20,23}, shifting warming from projected to observable²⁴. This means that, even without new insights into Earth system physics, plausible estimates of future warming become increasingly constrained. Additional physics insights would further strengthen this effect. Figure 1a illustrates hypothetical temperature evolutions for an emissions pathway from 2015 (the year the Paris Agreement was adopted) designed to avoid 2 °C of warming with some probability >50%, say 90%. If this emissions pathway is pursued without adjustment, by 2060, the uncertainty in projected warming will be substantially reduced, even if temperatures were closer to 2 °C than they are today. Recalibrating the emissions pathway using updated uncertainty estimates and implied higher allowable emissions would therefore lead to warming approaching 2 °C itself. There is thus a clear distinction between the literal meaning of keeping global warming 'well below 2 °C' and this probabilistic interpretation. As uncertainty declines, median and 90% probability warming estimates converge to the updated median estimate. A similar effect occurs for other probabilities and temperature levels. That means that targets to return warming to below 1.5 °C with a probability other than 50% would also result in a convergence towards 1.5 °C. Acknowledging this broader applicability, the remainder of this paper focusses on 'well below 2 °C' target interpretations. For a discussion of other temperature limits, see Supplementary Information Section 3.

Realistically, emissions are regularly re-assessed as part of 5-yearly global stocktake cycles^{25,26}. Global warming could gradually approach 2 °C if updated probabilities of avoiding 2 °C are used as a proxy for alignment with the LTTG. Such an outcome is inconsistent with the ordinary meaning of 'well below' and would not align with expectations of how treaties should be interpreted (discussed in Supplementary Information Section 1). Allowing temperatures to approach 2 °C would more accurately be described as 'stabilizing warming at 2 °C',

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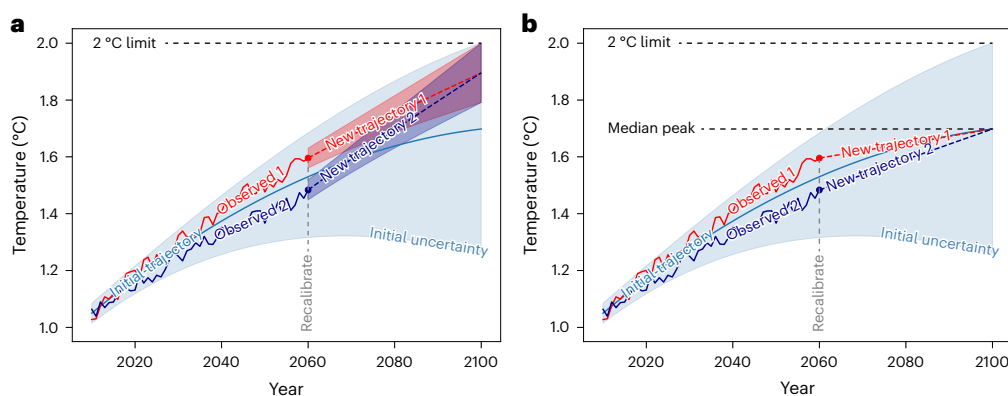


Fig. 1 | How uncertainty in temperature projections narrows over time and how different designs of trajectory adapt. **a**, An initial trajectory is designed to remain below 2 °C this century with some specific confidence, for example, 90%. The light blue shading represents the initial uncertainty with the median shown by the light blue line. At a later assessment point (2060 in this example, in practice more frequently), the warming up until that date becomes measurable, with some measurement uncertainty much smaller than the uncertainty of the original projection. We show two possible future realizations, in dark blue and

red. Uncertainty in future warming is also reduced as more warming is known observably. This reduction in uncertainty permits higher future emissions and therefore a final temperature much closer to 2 °C than initially envisioned (see dark blue and red dashed lines and uncertainty ranges), even if the observed future temperatures exceeds the initial median. **b**, Outcome for the same initial pathway and hypothetical observations when updated using a median temperature target rather than a probabilistic confidence interval.

Table 1 | Median peak warming (°C) in scenarios with a given chance of keeping global warming below 2 °C

Simple climate model	Calibration (Earth system uncertainties)	Median temperature (°C) with a given probability (66%, 83% or 90%) of keeping global warming below 2 °C		
		66%	83%	90%
MAGICC	AR6	1.852	1.666	1.574
FaIR	AR6	1.851	1.670	1.576
MAGICC	SR1.5 (AR5 knowledge)	1.827	1.631	1.537
FaIR	SR1.5 (AR5 knowledge)	1.844	1.653	1.546
Mean of MAGICC and FaIR	SR1.5 (AR5 knowledge)	1.836	1.642	1.541

Median peak warming estimates are calculated with either the SR1.5 scenario database⁴⁰ with the simple climate model calibrations representing the IPCC AR5 state of knowledge (2013–2014) or the IPCC AR6 database³⁹ with the simple climate model calibrations reflecting the AR6 state of knowledge (2021–2022). The MAGICC SR1.5 row is in bold as we consider it the most historically motivated.

an acknowledged risk in interpreting the Cancún Agreements that was explicitly rejected by Parties in adopting the Paris Agreement²⁷.

The surrounding text of the Paris Agreement adds richness to the interpretation of the ‘well below 2 °C’ language and places additional constraints on permissible scenarios. Importantly, the 1.5 °C target persists as a demand to minimize overshoot in spite of its likely exceedance^{3–5} and continues to be applied as a ceiling for end-of-century warming in many contexts (for example, UNEP 2025²⁸). Furthermore, Article 4.1 of the Paris Agreement, which requires achieving global net-zero GHG emissions this century, applies a further weak constraint on keeping warming below 2 °C and implies a gradual temperature reversal in pursuit of 1.5 °C (Supplementary Information Section 2; refs. 29,30).

The issue of convergence to a weaker end point can be avoided by interpreting the LTTG in terms of median or expected warming (Fig. 1b). Although uncertainty ranges may narrow over time, the expected position of the median remains unchanged. This approach avoids a gradual convergence towards 2 °C without requiring a revised legal interpretation of ‘well below’. Instead, it translates the level of uncertainty based on the best-available science at the time of adoption of the Paris Agreement into a median temperature target (Methods), allowing scientific updates to adjust emissions limits required without altering the ambition of the temperature goal itself.

There is a logistic relationship between median peak warming and the probability of peaking below 2 °C in many simple climate models (Extended Data Fig. 1). The MAGICC³¹ (v.6.0) and FaIR²² (v.1.3) models

are calibrated to reproduce Earth system behaviour as assessed in the IPCC Fifth Assessment Report (AR5), the most recent assessment available at the adoption of the Paris Agreement. These models ran a scenario ensemble collected for the IPCC Special Report on Global Warming of 1.5 °C (SR1.5)³³. Although some scenarios post-date the Paris Agreement, the resulting warming estimates remain consistent with the science available at its adoption. For comparison, we also present results using updated calibrations of both models³⁴ run on more recent scenarios used in AR6³⁵.

The logistic fits relate median peak warming to the initially pursued probability of remaining below 2 °C for each climate model and scenario database combination. Although the underlying scientific assessments are less than a decade apart, the values in Table 1 already illustrate the upwards creep in pursued median warming, an effect one would seek to avoid. Between the AR5 (SR1.5) and AR6 assessments, uncertainty in climate sensitivity and temperature projections decreased, partly due to additional observational data. Consequently, the expected warming associated with nominally equivalent probability-based interpretations of limiting warming below 2 °C increases. For example, targeting a 66% probability of keeping warming below 2 °C yields a median peak warming of 1.83 °C under MAGICC as calibrated for AR5 (SR1.5), rising to 1.85 °C under the AR6 calibration. This is similar to the IEA 2016 estimate of 1.84 °C for a 66% probability of staying below 2 °C (ref. 6).

Using the best-available science at specific points in time allows us to quantify the median warming implied by different probabilities

of remaining below 2 °C, as would have informed the Paris Agreement. The FaIR model was not yet available at the time and was still considered less established in SR1.5³³, which primarily reported MAGICC results. The MAGICC calibration and scenarios used in SR1.5, reflecting IPCC AR5 climate uncertainties, is most representative of knowledge during the Paris Agreement adoption (MAGICC SR1.5 in Table 1).

Table 1 shows that a 90% probability of remaining below 2 °C (both in 2015 and under current assessments) is not substantially weaker a target than pursuing a median 1.5 °C limit, given the difficulty in specifying recent temperature change to two decimal places³⁶. While this underscores the importance of the 1.5 °C target as a guardrail and focal point, it can exemplify constructed ambiguity³⁷ or that a near-equivalence of the two might not have been universally appreciated. Distinctions between global temperature metrics were also less widely appreciated; although our analysis uses GSAT, the results can be readily translated to GMST using a conversion factor³⁸, since the relationships we examine are approximately linear.

Most scenarios meeting a 1.5 °C end-century target have a currently assessed probability >66% of remaining below 2 °C throughout the century (Supplementary Fig. 2). Although scenarios can be constructed where this does not hold, the ‘well below 2 °C’ language of the Paris Agreement clearly signals greater stringency than the Cancún Agreements’ ‘below 2 °C’ framing. As the latter was widely interpreted with a 66% probability of avoidance, reasonable interpretations of the LTTG upper limit should adopt probabilities clearly above a 66% threshold. Such interpretation corresponds to a median warming level markedly below 1.83 °C. A reasonable choice with previous usage in this range is the up-to-one-standard deviation probability (83%), translating to a median warming of no more than 1.63 °C. This is broadly consistent with the IEA interpretation of a 66% probability of remaining below 1.8 °C, which translates to a median warming of about 1.65 °C (Supplementary Information Section 3). It is also stronger than a median warming of 1.8 °C even without future-proofing. The 1.7 °C median warming benchmark chosen by a recent study³⁸ is also within the range 1.63–1.83 °C. Accounting for rounding and the strictly-less-than condition on the 66% (likely) threshold, existing interpretations of the LTTG ‘well below 2 °C’ limit converge on a Paris-consistent peak warming in the 1.65–1.8 °C range. This benchmark of Paris compliance guards against ambition backsliding relative to interpretations of the LTTG prevalent around the adoption of the Paris Agreement.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-026-02685-y>.

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Methods

Investigating scenarios shows that exceedance probabilities and peak temperatures generally relate to each other via a logistic function with an offset. This is essentially a one-term logistic regression model. Uncertainties in the trade-offs between the warming impacts of different types of emissions mean this relationship is not precise and has a minor dependence on the exact emissions pathway, but the shape of this logistic fit is surprisingly consistent across hundreds of scenarios and several climate models, as seen in Extended Data Fig. 1. Here previous scenario temperature assessments are taken from the AR6 database³⁹ and the SRI.5 database⁴⁰. An inverse logistic relationship is fitted between the median peak temperature (T) and the probability of exceeding 2 °C (p), following the expression

$$T = T_0 - \frac{1}{k \log\left(\frac{L}{p-p_0} - 1\right)} \quad (1)$$

for arbitrary constants T_0 , k , L and p_0 , for each climate emulator (MAGICC or FaIR) run on each database. The values of T at the probabilities of interest are then calculated from the fitted expression, shown by the lines in Extended Data Fig. 1. The codebase for carrying out these calculations is available⁴¹.

Data availability

The AR6 data required for running this analysis³⁹ are available from <https://data.ece.iiasa.ac.at/ar6/> and <https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/>.

Code availability

The code to complete this logistic regression analysis and generate all figures is available via GitHub at <https://github.com/Rlamboll/HowBelowsWellBelow> and via Zenodo at <https://doi.org/10.5281/zenodo.20289530> (ref. 41).

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Author contributions

R.D.L. conceived the paper and carried out the analysis. R.D.L. and J.R. co-wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

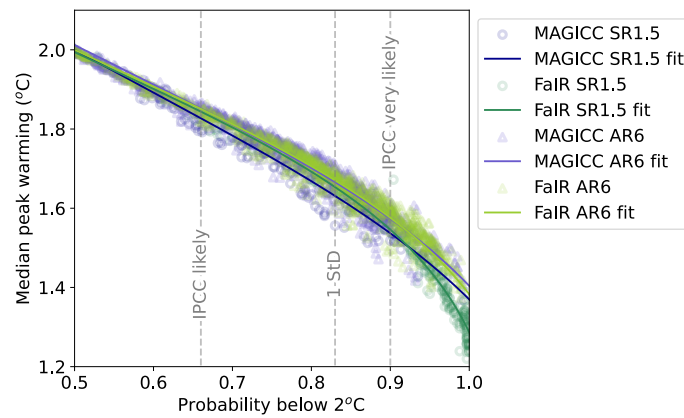
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Extended Data Fig. 1 | Relationship between probability of global warming remaining below 2 °C and median peak warming. Features marked with SR1.5 refer to results calculated with the climate model calibrations and emission scenarios available at the time of the IPCC Special Report on Global Warming of 1.5 °C (SR1.5), which are calibrated to the state of scientific uncertainty as assessed by the IPCC Fifth Assessment (AR5) that informed the Paris Agreement.

Features marked with AR6 reflect the simple climate models and emission scenarios at the time the IPCC Sixth Assessment. Probabilities of global warming projections are expressed starting from observed values in 2015. Dashed coloured lines are inverse logistic functions with offsets, fitted to the appropriate points. Dashed grey vertical lines indicate probabilities where the Paris Agreement target has previously been interpreted.