Getting it right matters – temperature goal interpretations in geoscience research

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Key Points:

- The Paris Agreement long-term temperature goal refers to changes in long-term global climatological averages, excluding natural variability
- Interpretations of this goal that include natural variability are not consistent with UNFCCC, IPCC and WMO definitions and practice
- Deviating interpretations that include natural variability significantly distort key policy-relevant insights, like carbon budget estimates

The adoption of the 1.5°C long-term warming limit in the Paris Agreement made 1.5°C a 'hot topic' in the scientific community, with researchers eager to address this issue [*Rogelj and Knutti*, 2016]. Long-term warming limits have a decades-long history in international policy [*Randalls*, 2010]. To effectively inform the climate policy debate, geoscience research hence needs a core understanding of their legal and policy context. Here, we describe this context in detail, and illustrate its importance by showing the impact it can have on global carbon budget estimates. We show that definitional clarity is essential on this important matter.

Scientific assessments of warming levels of 1.5°C and 2°C global mean temperature (GMT) increase above pre-industrial levels have risen to prominence through the inclusion of these levels in the long-term temperature goal (LTTG) of the Paris Agreement. The goal itself is inscribed in Article 2.1(a) of the Paris Agreement and reads: „Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" [*UNFCCC*, 2015a]. (Note that Article 2.1(a) in its entirety is referred to as the Paris long-term temperature goal [*Schleussner et al.*, 2016], and that this goal includes reference to temperature levels of 'well below 2°C' and 1.5°C.) The Paris Agreement does not provide a precise definition of what holding 'well-below 2°C' or limit to '1.5°C' increase above pre-industrial levels means. When considered in isolation, such references to warming levels thus allow for a wide range of interpretations, not all of which are consistent with their definition in climate policy and practice.

A wide variety of interpretations have indeed already been applied throughout the geoscience literature. For example, temperature targets have been compared to annual global mean temperature evolutions that include natural variability, either generically by using unsmoothed annual mean model output [*Chen and Zhou*, 2016; *Joshi et al.*, 2011] or explicitly by showing how the Inter-decadal Pacific Oscillation influences the year in which the 1.5°C Paris temperature limit could be breached [*Henley and King*, 2017]. Other studies have analyzed 1.5°C or 2°C worlds based on decadal-averages around these temperature levels [*King et al.*, 2017], or suggest to use averaging windows which are at least a few decades in width [*James et al.*, 2017]. Studies have furthermore interpreted global mean temperature targets to apply to increases in regional temperatures [*Chen and Zhou*, 2016; *Joshi et al.*, 2011] or to temperatures over land only [*Huntingford and Mercado*, 2016]. Finally, studies have also interpreted the temperature levels referred to in the Paris Agreement's long-term temperature goal as long-term climatological global means [*Lehner et al.*, 2017; *Sanderson et al.*, 2016; *Sanderson et al.*, 2017].

These widely different interpretations lead to quite different insights, and definitional clarity is hence necessary to ensure effective, policy relevant communication and discussions in and outside the geoscience community on this politically sensitive matter. What would be an appropriate interpretation of the temperature limit included in the Paris Agreement? The answer lies in rigorous analysis of the available information and examination of the context – in this case the legal framework of the United Nations Framework Convention on Climate Change (UNFCCC).

The 1992 Climate Convention and successive IPCC reports provide a clear guidance here. The Climate Convention (UNFCCC), to which the Paris agreement is a subsidiary legal instrument, contains the definition of climate change in its Article 1 [*UNFCCC*, 1992]. This definition makes clear that for the purpose of the UNFCCC and any related legal instrument, climate change "means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". In addition, the most recent IPCC Assessment (AR5) provides further clarity by defining 'climate' as the statistical description in terms of the mean and variability of relevant quantities over a period of time, with a classical period for averaging being 30 years, also commonly used by the World Meteorological Organization (WMO). It further goes on to define 'climate change', from any cause, as a statistically identifiable change in 'climate' statistics that 'persists for an extended period, typically decades or longer' [*IPCC*, 2013a].

In the Paris Agreement context, the UNFCCC definitions apply and IPCC Assessment Reports, particularly the Fifth, played a predominant role defining and underpinning the scientific components of the agreement. The formulation that references holding warming 'well below 2°C' and further limiting increases to '1.5°C' reflects a high-level conclusion by decision makers, which was informed by their constituencies and their interpretations of the overall scientific literature with respect to an acceptable level of level of human induced 'climate change' relative to a pre-industrial reference period. Indeed, when the scientific literature relates risks and impacts to global-mean temperature increases, it typically uses GMT increase averaged over periods of 20 to 30 years as a reference, including in the latest reports of IPCC Working Groups I and II [*IPCC*, 2013b; 2014]. At the same time, such assessments include the effects and risks posed by climate variability relative to a long-term GMT. When, in the period 2013 to 2015, the UNFCCC carried out a review of its 2°C long-term global goal to consider strengthening it to 1.5°C, global long-term climatological averages relative to a 1850-1900 reference period were used to discuss the different temperature levels considered [*UNFCCC*, 2015b], in line with their use in the IPCC's Reasons for Concern (RFC) [*O'Neill et al.*, 2017].

Besides its use in impact studies, long-term GMT limits are also used in climate change mitigation studies, which here provide a further supporting perspective. The Paris Agreement indicates that to achieve its long-term temperature goal, greenhouse gas emissions need to be rapidly reduced in order to achieve *"a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century".* This is equivalent to achieving global zero greenhouse gas emissions [*Schleussner et al.*, 2016] and linked to scientific findings on emission pathways characteristics in line with interpreting the UNFCCC temperature limits as global long-term climatological averages [*Clarke et al.*, 2014; *Rogelj et al.*, 2015], thus providing another line of evidence.

As a consequence, it is clear that the temperature references in the Paris Agreement can only be understood as changes in climatological averages attributed to human activity excluding natural variability. Warming levels in the Paris Agreement hence do not refer to temperature modulations that are the result of chaotic patterns of natural variability on time scales of single years, months or days, or of temperature events in one particular geographical location. However, even when interpreting temperature levels embedded within the long-term temperature goal as climatological averages, some important sources of uncertainty remain, for example, related to the precise fraction of GMT increase to date that can be attributed to human activities [*Bindoff et al.*, 2013]. As this uncertainty is carried forward into the future, decision makers have to take it into account by pursuing global emission pathways that limit GMT increase to a given level with a given probability, for example 66 per cent [*Clarke et al.*, 2014].

Why is the question of interpretation so important? Long-term temperature targets provide guidance for short, mid and long-term global mitigation action, and can be translated into specific carbon budgets over different time periods that can inform mitigation requirements [*Clarke et al.*, 2014; *Collins et al.*, 2013]. This translation from temperature targets to carbon budgets requires specific choices about (i) the nature of the budgets, (ii) the probability and time horizon of achieving a given goal (for example, limiting warming to 1.5°C by 2100 with 50 per cent probability), and (iii) has to account for the geophysical uncertainty in the response of the climate system [*Collins et al.*, 2013; *Rogelj et al.*, 2016]. Adopting a different interpretation of the Paris long-term temperature goal will thus also alter carbon budget estimates.

To illustrate this point, we here analyze how temperature target interpretations affect carbon budget estimates and in particular what the effect of including natural variability on an annual basis would be. We derive annual deviations of global mean surface air temperature from the centered 21-year running mean over the period 1900-2090 from 24 CMIP5 coupled climate models (GCMs) and the combined historical and RCP2.6 scenarios. The estimates of natural variability obtained in this way are still an approximation only, as low-frequency variability over multiple decades is not captured by this method. Averaged over all models, we find the 66% range of GMT deviations due to internal variability to be normally distributed and of the order of +/-0.1°C (Figure 1, and Figure S1 for individual GCMs). This value is robust over time in RCP2.6 (Figure S2) and over different RCP scenarios (not shown).

Natural variability results in stochastic fluctuations around the long-term climatological GMT. For instance, in a world with long-term GMT rise stabilized at 1.5°C, annual GMT is expected to *exceed* 1.5°C in half of all years due to internal variability. We now assess changes to the carbon budget for worlds in which we allow annual GMT to exceed 1.5°C in only one in 5, 10 or 20 years or, alternatively, never. To this end, we derive the estimated annual warming anomaly for each of these return periods with respect to the long-term mean. Subsequently, to avoid annual warming with a given return period, we lower the long-term GMT target by the estimated maximum annual warming anomaly due to internal variability for each respective return period. We then derive the reduction in carbon budgets for each of these cases by means of the transient temperature response to cumulative emissions of carbon (TCRE, see Table 1).

For the sake of this illustration, internal variability and the inferred anomalies are assumed to be independent from GMT warming (an assumption supported by CMIP5 model data, see Figure S2). This implies that the estimated carbon budget adjustments can also be used with higher temperature levels, like 2°C or 2.5°C.

The adoption of annual mean warming targets instead of long-term temperature averages strongly influences the available carbon budget estimated to be compatible with '1.5°C'. In case the annual GMT would only be allowed to exceed the 1.5°C temperature limit once every 20 years, the carbon budget would be reduced by about 420 Gt CO_2, nearly 20% of the originally estimated budget since 1870. If the 1.5°C limit should not be breached in any given year, the budget since 1870 is roughly halved, and already overspent today. In other words, there are substantial real-world policy differences involved in re-interpretations of the Paris Agreement's long-term temperature goal. Policymakers in Paris adopted the long-term temperature goal based upon the assessments supplied by the IPCC along with carbon budgets consistent with the goal.

A thorough understanding of how the long-term temperature goal is interpreted in the UNFCCC is thus indispensable for scientific studies to provide policy relevant information and analysis to on-going national, regional and international policy discussions and negotiations implementing the Paris Agreement. It is important that scientists examining this topic are fully aware of the full legal and scientific characteristics of the Paris Agreement LTTG. By contextualising and communicating their insights, researchers can support decision makers in their efforts to pursue science-based policies in a forum that is already overloaded by unsubstantiated noise.

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Tables and figures

Exceedance of 1.5°C annual mean warming	1 in 2 years	1 in 5 years	1 in 10 years	1 in 20 years	Never
Equivalent long-term global-mean warming [°C]	1.5	1.41	1.36	1.31	~1
Implied reduction in long-term global-mean warming [°C]	0	0.09	0.14	0.19	0.5
Implied reduction in carbon budget [Gt CO_2]	0	200	311	422	1110

Table 1: Implications of annual warming targets for equivalent long-term global-mean warming and respective carbon budgets, based on a TCRE of 1.65 °C / 1000 PgC, the arithmetic mean of the IPCC AR5's likely 0.8 to 2.5 °C / 1000 PgC range [Collins et al., 2013]. Note that the cumulative carbon budget for limiting warming to 1.5°C relative to 1861-1880 in 50% of the model simulations was reported to be of the order of 2300 Gt CO_2, since 1870. This estimate assumes invariable non-CO_2 contributions.

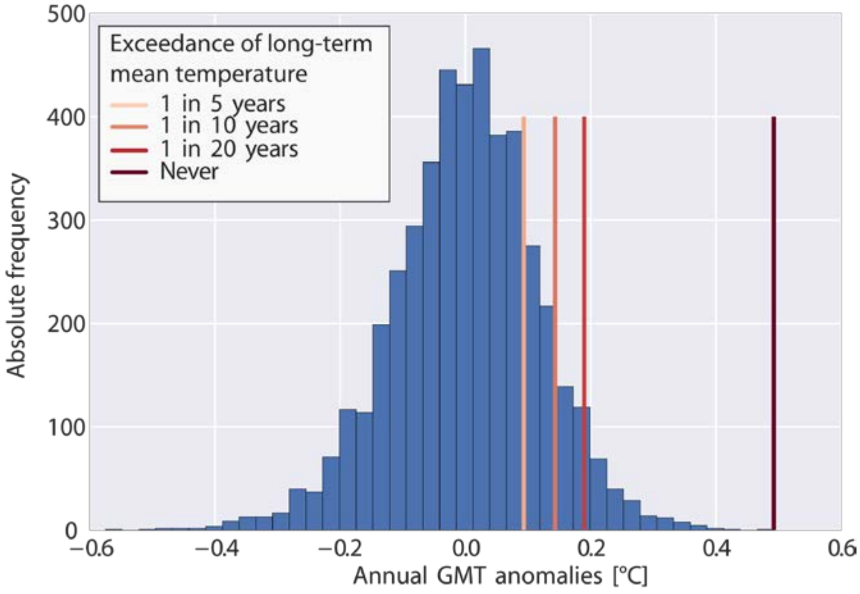

Figure 1: Annual GMT anomalies from running 21-year average for 24 CMIP5 models and the 1900-2090 period (combined historical and RCP2.6 scenario). Levels of annual GMT anomalies for different return times are marked by vertical lines.

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