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Global mean temperature indicators linked to warming levels avoiding climate risks

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CORRIGENDUM

Corrigendum: global mean temperature indicators linked to warming levels avoiding climate risks (2018 *Environ. Res. Lett.* 13 064015)

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Updated results for hot extremes

The computation of the land-fraction affected by daily temperature extremes (TXx) erroneously also included ocean cells. To resolve this error, the data underlying figure 2(a) was recomputed, leading to higher changes in TXx. In the results section the sentence describing the figure should thus read:

‘At 1.68 °C GMT_{AR5} warming, 74% of the land area experiences an increase in the annual maximum daily temperature of 1 °C relative to 1986–2005, while at 1.5 °C GMT_{AR5} warming only 62% of the land area would experience this increase.’

Absolute changes in TXx are not core to the argument presented in the paper, and the discussion section thus needs no update.

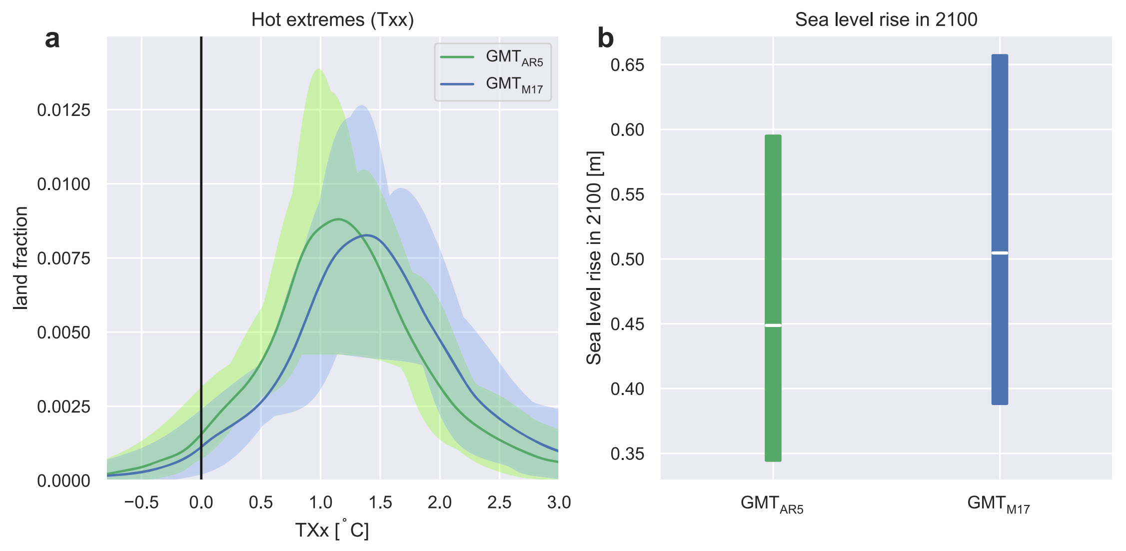

Figure 2.

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Global mean temperature indicators linked to warming levels avoiding climate risks

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Abstract

International climate policy uses global mean temperature rise limits as proxies for societally acceptable levels of climate change. These limits are informed by risk assessments which draw upon projections of climate impacts under various levels of warming. Here we illustrate that indicators used to define limits of warming and those used to track the evolution of the Earth System under climate change are not directly comparable. Depending on the methodological approach, differences can be time-variant and up to 0.2 °C for a warming of 1.5 °C above pre-industrial levels. This might lead to carbon budget overestimates of about 10 years of continued year-2015 emissions, and about a 10% increase in estimated 2100 sea-level rise. Awareness of this definitional mismatch is needed for a more effective communication between scientists and decision makers, as well as between the impact and physical climate science communities.

Introduction

Many climate change impacts relevant for societies scale with global mean surface air temperature (GMT) rise (Seneviratne *et al* 2016, UNFCCC 2015b), making it an adequate proxy for the assessment of global climate change risks (Knutti *et al* 2015). International climate policy has adopted levels of global mean temperature increase to guide global climate action. The most prominent example of such temperature rise levels is the long-term temperature goal of the UN Paris Agreement of '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, Schleussner *et al* 2016b). The second part of the goal provides highly relevant context as it explicitly links the temperature levels referenced in the Paris Agreement to the assessment of climate risks and impacts.

The adoption of global average temperature levels to avoid climate risks have been informed by a multi-year science-policy process (UNFCCC 2015b), which was predominantly based on the findings of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014). Its products, such as the 'reasons of concern' (O'Neill *et al* 2017) link various climate risks to levels of GMT increase. The warming levels at which these risks emerge depend on the method that underlies the global average temperature estimation, which ties them to the methods used in the scientific basis of the underlying risk assessment, the AR5. This context is key for scientists to understand how to interpret the Paris long-term temperature goals (Rogelj *et al* 2017).

With the Paris Agreement in place, international policy has shifted focus from defining its goals to implementing and tracking progress towards their achievement. Monitoring GMT rise has thus become a key component of assessments of whether climate mitigation actions are on track to achieve the Paris temperature goal, for example in terms of carbon budgets (IPCC 2014, Rogelj *et al* 2016). Clarity on how global mean temperature is assessed is essential for this process. However, there is no single established and agreed-upon method to assess GMT change. In particular, substantial differences emerge between observational-based and model-based GMT products (Richardson *et al* 2016, Cowtan *et al* 2015). Here we will assess the implications of discrepancies between different GMT products for our ability to track progress towards the Paris Agreement temperature goal. To this end, we evaluate different methodological approaches to GMT that have been used for policy-relevant statements, carbon budget estimates or for resulting climate impacts.

The IPCC AR5 determines global mean temperature change (hereinafter referred to as GMT_{AR5}) relative to the 1986–2005 period. Past warming since the 1850–1900 preindustrial reference period is 0.61 °C based on the HadCRUT4 observational dataset (Morice *et al* 2012). Future warming relative to preindustrial is defined as the sum of past warming and the CMIP5 climate model ensemble mean relative to the 1986–2005 baseline (IPCC 2014). For carbon budget estimates the IPCC AR5 Working Group 1 uses the model-based global mean surface air temperature increase (hereafter GMT_{SAT}) since the 1861–1880 period from the Coupled Model Intercomparison Project (CMIP5) (IPCC 2013). Note that carbon budgets have been assessed slightly differently in different working groups and subsequent publications (see Rogelj *et al* (2016) for an overview).

The HadCRUT4 observational GMT product is only based on regions for which observational data exists. Parts of the rapidly warming Arctic, for example, are undersampled (Cowtan *et al* 2015). Furthermore, surface air temperatures over land and sea ice are blended with sea surface temperatures over the open ocean. In contrast, CMIP5-model-based global mean temperature is derived with global coverage and based on surface air temperatures (SAT) alone. The differences between observational-based and model-based GMT have been shown to introduce considerable differences (Richardson *et al* 2016, Cowtan *et al* 2015) and to be partly responsible for discrepancies of the observational record and model projections over the recent decade (Medhaug *et al* 2017). Correcting for discrepancies between the HadCRUT4 and infilled datasets also affects the warming level of the 1850–1900 period (Richardson *et al* 2016, Cowtan *et al* 2015). In the following we will investigate the implications of using non-AR5 GMT products for tracking progress against Paris Agreement warming levels for carbon budgets as well as climate impact indicators.

Methods

Based on the method by (Richardson *et al* 2016, Cowtan *et al* 2015) we have derived a model-based GMT estimate that has been corrected for masking and blending as in the HadCRUT4 observational record ($GMT_{blend-mask}$). We use an ensemble of 32 CMIP5 models forced with the RCP8.5 scenario (see table S1 available at stacks.iop.org/ERL/13/064015/mmedia). For each GCM all runs are averaged to one global mean temperature time series.

This GMT product can be considered a proxy for future observations if the HadCRUT4 approach to derive GMT is continued. Assessments of future GMT could also be rebased to the observational warming record since 1986–2005. This has e.g. been done recently by Millar *et al* (2017), using human-induced warming until 2015 determined as 0.93 °C based on HadCRUT4 ($GMT_{M17,}$ Millar *et al* 2017). The future warming difference for rebased products like GMT_{M17} solely depends on the offset to GMT_{SAT} over the rebase period. An overview of the different GMT products is given in table 1. As other observational datasets project higher warming than HadCRUT4 over this period (Rohde *et al* 2013, Cowtan and Way 2014, Hansen *et al* 2010) we also included two sensitivity cases assuming an attributable warming of 1 °C and 1.1 °C until 2015 (Haustein *et al* 2017) (table S4). Conversions between different GMT products are based on the 20 year running mean values from the CMIP5 models which are closest to 1.5 °C in the source GMT product.

The intensity of hot extremes is measured as the annual maximum value of daily maximum temperature (TXx). Following Fischer and Knutti (2014), we derive grid-cell based time averaged differences between the 1986–2005 reference period and model specific 21 year periods with a mean warming above 1986–2005 of 0.89 °C for GMT_{AR5} and 1.07 °C for GMT_{M17}. The mid-years of the 21 year periods are listed in table S5. These differences are aggregated in a spatial probability density function (PDF) over the global land mass and all models area-weighting each grid-cell. The smoothed PDFs are estimated using a weighted Gaussian kernel density estimation method with a bandwidth estimated following 'Silverman's rule'. Sea level rise projections for different warming levels are derived using a component-based approach (Mengel *et al* 2018) with an updated Antarctic ice sheet contribution (Nauels *et al* 2017). The updated method emulates a recently proposed and more sensitive Antarctic response to future warming (Deconto and Pollard 2016).

Results

The discrepancies between the different GMT products and the GMT_{AR5} are displayed in figure 1. Deviations

Table 1. Overview of the different GMT computation methods.

$\mathbf{GMT_{SAT}}$	Global mean surface air temperature icrease in CMIP5 models relative to 1861–1880.
$\mathbf{GMT_{AR5}}$	IPCC AR5 method: global mean temperatures relative to preindustrial levels are obtained by adding model-based GMT_{SAT} anomalies to the 1986–2005 reference period and observed warming up to this period from the HadCRUT4 dataset relative to 1850–1900 (0.61 °C).
$\mathbf{GMT_{M17}}$	Analogue methodological approach to GMT_{AR5}, but updates the observed warming to the 2010–2019 period as in Millar *et al* (2017). Past warming until that period is set to the observed attributable warming until 2015 based on HadCRUT4 (0.93 °C).
$\mathbf{GMT_{Obs\_1\,°C}}$	Analogue methodological approach to GMT_{M17}, but assumes a past attributable warming until 2015 of 1 °C.
$\mathbf{GMT_{Obs\_1.1\,°C}}$	Analogue methodological approach to GMT_{M17}, but assumes a past attributable warming until 2015 of 1.1 °C.
$\mathbf{GMT_{blend-mask}}$	Following methodological approach of Cowtan *et al* (2015): This method includes regridding the CMIP5 model output to a 5° × 5° grid, blending surface air temperatures (tas) and surface ocean temperatures (tos) in grid points partly covered by sea ice and masking the model output to the observational coverage of HadCRUT4. For this method, observational coverage is required. We assume that future observation coverage stays similar to the coverage of the years 1986–2016 For each month, we treat a grid cell as covered by observations if in 20 out of the 30 years of 1986–2015 observations were available for the given month. Observational coverage was taken from CRUTEM4 and HadSST3 datasets.
$\mathbf{GMT_{blend}}$	Analogue methodological approach to $\mathbf{GMT_{blend-mask}}$, but using global coverage and regridding model output to a 1° × 1° grid.

are smallest for GMT_{SAT}, as modelled CMIP5 1986–2005 warming since 1861–1880 matches well with the HadCRUT4 reconstruction. This is remarkable, as considerable differences exceeding 0.1 °C between blended-masked GMT and surface air temperature-only products are already apparent for this period (Richardson *et al* 2016). This–coincidental—close match might be one of the reasons why the methodological difference between observed and modelled GMT products has not risen to larger prominence before. As a result, deviations that result from the mix of products for the AR5 impact appraisals and the AR5 carbon budget estimates are small.

Deviations for the $GMT_{blend-mask}$ and the GMT_{M17} products are more pronounced. A 1.5 °C global mean temperature rise in GMT_{AR5} corresponds to a warming of just 1.31 °C in the $GMT_{blend-mask}$ product (full ensemble range: 0.85 °C–1.77 °C, compare figure 1(*a*)) and table 2). The difference between $GMT_{blend-mask}$ and GMT_{AR5} is not constant in time (Richardson *et al* 2016) and increases with increasing warming (figure 1(*b*)). It is largely introduced by undersampling of fast warming Arctic regions and sea-ice loss. As a result, the future strength of this effect will depend on the emission scenario and will be less pronounced under stringent mitigation scenarios (Richardson *et al* 2018). A substantial discrepancy between model-based GMT_{SAT} and $GMT_{blend-mask}$ is already apparent over the observational record and particularly pronounced in recent decades. Rebasing the reference period as in GMT_{M17} introduces a time-invariant offset. In this case, a GMT_{AR5} 1.5 °C warming corresponds to 1.32 °C (1.06 °C–1.53 °C) increase in GMT_{M17}.

Differences between GMT products are sensitive to the choice of method. The difference between GMT products with recent reference periods (GMT_{AR5} and GMT_{M17}) and GMT products referenced against a preindustrial period ($GMT_{blend-mask}$ and GMT_{SAT}) depends on the choice of the preindustrial period (Hawkins *et al* 2017). Setting the preindustrial period to 1850–1900, for example, slightly reduces the difference between $GMT_{blend-mask}$ and GMT_{AR5} (see figure S3). Furthermore, differences depend on the method used to convert between GMT products. For example, basing the conversion into GMT_{AR5} on annual mean temperatures within a range of 1.5 °C ± 0.05 °C in the source GMT product (instead of analysing 20 year running mean values close to 1.5 °C) yields slightly lower differences between GMT_{AR5} and GMT_{M17} and $GMT_{blend-mask}$, (see figure S5). Finally, these results depend on the understanding of the 'multi-model mean' (see figure S2). If all available model runs are weighted equally instead of weighting contributions per model, GMT_{M17} and $GMT_{blend-mask}$ would both reach +1.7 °C at the time when GMT_{AR5} reaches +1.5 °C (see figure S4). All conversions between GMT products and choices in the method are listed in tables S2 and S3.

The choice of GMT indicators for expressing current and future warming can influence how much carbon emissions are perceived to remain for limiting warming to internationally agreed levels such as 1.5 °C (see table 2). As indicated earlier, international temperature goals have been underpinned by climate risk assessments pegged to GMT_{AR5} levels of global mean warming. Warming in the real world, however, is expressed in observation-based indicators. Our $GMT_{blend-mask}$ time series aims to mimic the limitations of one commonly used indicator (HadCRUT4 (Morice *et al* 2012)). Consistent with (Schurer *et al* 2018, Richardson *et al* 2018) we estimate a mismatch between GMT_{AR5} and $GMT_{blend-mask}$ at the time GMT_{AR5} reaches 1.5 °C of about 0.2 °C ($GMT_{blend-mask}$ is cooler, see table 2). At the moment GMT_{AR5} reaches 1.5 °C, the remaining carbon budget for avoiding the assessed impacts of 1.5 °C warming should be effectively zero. However, because of the mismatch between $GMT_{blend-mask}$ and GMT_{AR5}, a

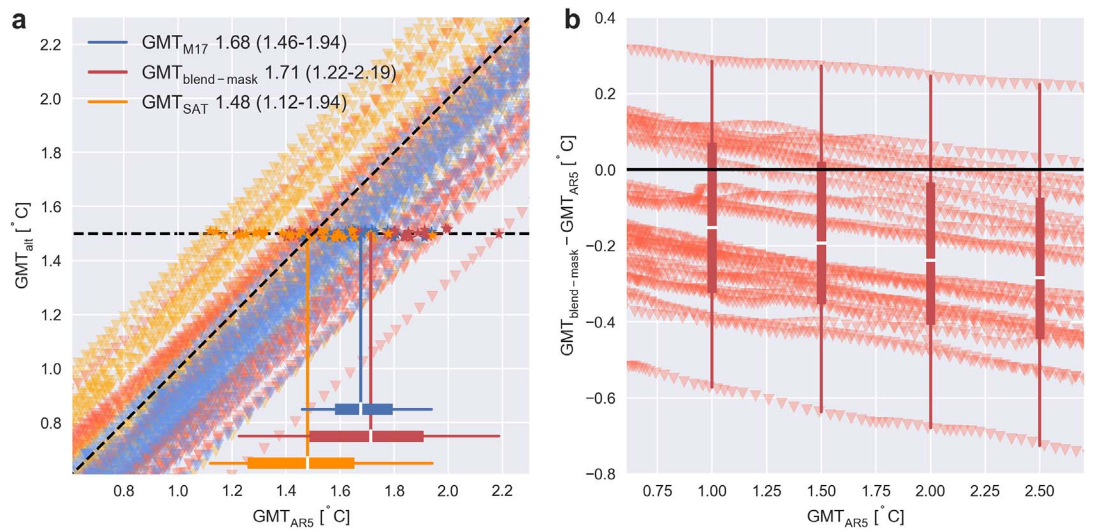

Figure 1. Mismatch between global mean temperature products. (*a*) Warming in alternative products (GMT_{alt}, *y*-axis) as compared to GMT_{AR5} (*x*-axis) for 32 CMIP5 models. Triangles show 20 year running mean warming from individual CMIP5 models in the respective products. The warming ranges in GMT_{AR5} are derived from a distribution of GMT_{AR5} values of the years in which each model's GMT_{alt} is closest to 1.5 °C (highlighted by stars). Boxplots show the full model spread (whiskers), the 66% range (boxes) and the multi-model mean (white bar). In the legend the multi-model mean and the full ensemble range are indicated. (*b*) Warming-dependent differences between $GMT_{blend-mask}$ and GMT_{AR5}. As in panel (*a*), boxplots represent the model spread at selected warming levels in GMT_{AR5} (+1 °C, +1.5 °C, +2 °C and +2.5 °C).

Table 2. Conversions between 1.5 °C warming levels in different GMT products and carbon budget implications. Temperatures are given in °C since preindustrial (see table 1). Multi-model mean and the full ensemble ranges in brackets are derived as in figure 1 for the 20 year running mean values closest to 1.5 °C in the respective GMT product. Carbon budget estimates are 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) and assume invariable non-CO_2 contributions. Positive values indicate an increasing budget in the alternative GMT product compared to GMT_{AR5}.

	GMT_{SAT}	GMT_{M17}	$GMT_{blend-mask}$
Warming of 1.5 °C in alternative GMT products expressed in GMT_{AR5} [°C]	1.48 (1.12−1.94)	1.68 (1.46−1.94)	1.71 (1.22−2.19)
Warming expressed in alternative GMT products corresponding to a GMT_{AR5} warming of 1.5 °C [°C]	1.52 (1.05−1.88)	1.32 (1.06−1.53)	1.31 (0.85−1.77)
Estimate of implied remaining carbon budget for 1.5 °C in alternative GMT products at time of reaching 1.5 °C of GMT_{AR5} warming [in Gt CO_2]	−44 [1000, −845]	400 [978, 67]	422 [1445, −600]

$GMT_{blend-mask}$ indicator would continue to suggest a remaining available budget of about 422 Gt CO_2 at that point in time (using an average transient climate response to cumulative emissions of carbon of 1.65×10^{-3} °C/Gt C). This amounts to a carbon budget overestimate the size of about 10 years of continued year-2015 emissions. An adjustment of similar size would be required to make recently published carbon budget estimates (GMT_{M17}, calculated as in Millar *et al* (2017)) consistent with the assessed warming levels for avoiding global warming risks (table 2).

Reaching 1.5 °C in GMT_{M17}, or $GMT_{blend-mask}$ (here considered a proxy for expected observational warming) would correspond to climate risks at higher temperature levels when following the AR5 method. These levels are 1.68 °C for GMT_{M17} and 1.71 °C for $GMT_{blend-mask}$ (see table 2). Several highly vulnerable systems such as tropical coral reefs (Schleussner *et al* 2016a) or Arctic sea-ice (Screen and Williamson 2017) are very sensitive to small warming increments. Also extreme weather indicators have been found to robustly increase with increasing GMT_{SAT} (Seneviratne *et al* 2016) and threshold based indices even in a non-linear fashion (Fischer and Knutti 2015). Figure 2 illustrates how the different GMT products (GMT_{AR5} and GMT_{M17}) lead to different projected changes in global extreme hot day temperatures (TXx, figure 2(*a*)) and 2100 sea-level rise (figure 2(*b*)).

The intensification of extreme hot days is stronger for 1.68 °C GMT_{AR5} warming when 1.5 °C is reached in GMT_{M17} than for 1.5 °C GMT_{AR5} warming. At 1.68 °C GMT_{AR5} warming, 40% of the land area experiences an increase in the annual maximum daily temperature of 1 °C relative to 1986–2005, while at 1.5 °C GMT_{AR5} warming only 30% of the land area would experience this increase. Similarly, the difference between 1.68 °C and 1.5 °C GMT_{AR5} warming could lead to an additional sea level rise of 5 cm in the median for the end of the century, about 10% of the projected median rise for 1.5 °C relative to the 1986–2005 period. Note that future sea level rise exhibits a considerable dependency on the temperature

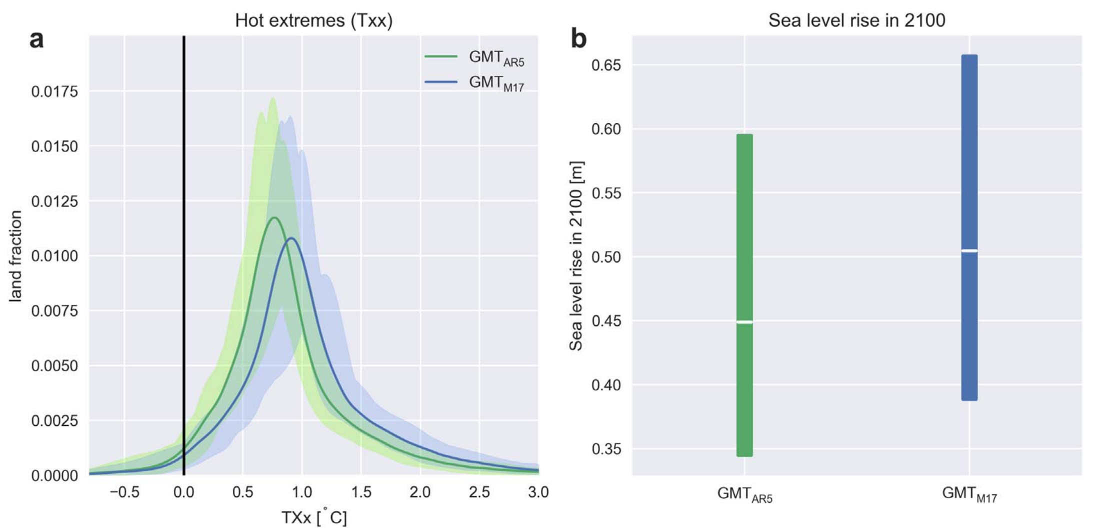

Figure 2. Differences in climate hazards at 1.5 °C in different GMT products. (*a*) Changes in hot extremes (TXx) on global land area at 1.5 °C relative to the 1986–2005 reference period based on Fischer and Knutti (2014). Probability density functions show the globally aggregated land fraction that experienced a certain change in TXx for GMT_{AR5} (green) and GMT_{M17} corresponding to 1.68 °C warming in GMT_{AR5} (blue). The shaded areas show the range of land fraction PDF's of the individual models. (*b*) Sea level rise in 2100 relative to 1986–2005 with uncertainty, based on Mengel *et al* (2018). Boxes indicate the 66% range, the white bar the median. Projections are given for 1.5 °C warming in the GMT_{AR5} (green) and GMT_{M17} product (blue).

trajectory and projections for Paris Agreement compatible pathways would therefore divert slightly from the stylised estimates presented here (Mengel *et al* 2018).

Discussion

Our analysis outlines important differences between different GMT products and illustrates their implications for climate risks assessment. We have shown that by using GMT products other than those used in the IPCC AR5, risks identified for a certain level of global warming in this report would occur at other levels. The quantified discrepancies between observationally derived GMT products and climate change risk levels as expressed in international agreements have important consequences for on-going discussions in the climate policy arena. Climate action is guided by the desire to *avoid* impacts, not by reaching an imaginary GMT number. If the impacts policy makers aim to avoid (as indicated in the Paris Agreement) will occur at a lower levels in other GMT products, then science needs to communicate this clearly and ideally provide adequate adjustments. In order to limit potential confusion this requires understanding of both, the identified discrepancies between GMT products and the nature of the Paris Agreement temperature goal (Rogelj *et al* 2017). Indeed, the discrepancy between observed GMT products and the GMT_{AR5} will not be easy to reconcile and communicate.

It is important to clarify that our argumentation is not rooted in a scientific reasoning in favour of the IPCC AR5 method that is not without shortcomings and ambiguities. The 1986–2005 reference period, for example, is not free of influences of natural variability (like volcanic eruptions). Climate models used for projecting future warming are not systematically evaluated and may already exhibit substantial deviations compared to observed present-day warming (see figure 1). Furthermore, the effect of different definitions of the 'pre-industrial level' needs to be considered (Hawkins *et al* 2017). At the same time, scientists will continue to use observed GMT products to assess the state of the climate system. Approaches to assess GMT will be, and should be, updated as our scientific understanding progresses. To ensure the policy relevance of future products in relation to the Paris Agreement and to maintain the agreement's integrity, it is therefore of key importance that different (updated) GMT metrics can be converted into the GMT_{AR5} values used at the time, and that full transparency is provided about methods, as we have attempted here. This also relates to other methodological choices in the IPCC AR5 such as the use of multi-model means instead of medians or the 'one-model-one-vote' principle (Flato *et al* 2013). Diverting from this approach by averaging over all available model runs yields slightly different estimates for the biases between the GMT products (compare figure S4). Under the UNFCCC, climate policy now progresses in quinquennial cycles which include a stocktaking phase and a phase in which governments put forward new proposed actions to limit climate change. If, during the stocktaking phase, current progress and the current state of the Earth system is not assessed with metrics comparable and consistent with the metrics used to define the Paris Agreement long-term temperature goal, the assessment of progress will be imprecise, and, as we have shown, the risk of hitting instead of avoiding some particularly sensitive climate impacts would be increased. In the context of the 1.5 °C and 2 °C global average temperature limits, our results show that following practices based on observational products (Millar *et al* 2018) would consistently lead to an underestimation of the urgency of emissions reductions (Schurer *et al* 2018, Richardson *et al* 2018).

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