Assessing internal variability of global mean surface temperature from observational data and implications for reaching key thresholds

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Key Points:

- Observed interannual variability of global mean surface temperature is less than simulated in large model ensembles
- Observed variability can be used alongside wrecent data to estimate the probability that key temperature thresholds have been crossed

Abstract

Observed global mean surface temperature (GMST) combines a forced response with internal variability, and quantifying internal variability is important in assessing the reaching of key thresholds, such as the 1.5 °C warming threshold in the Paris Agreement. This paper uses observational data to estimate internal variability. Since the current period of warming began in the 1970s, the 10-year mean of GMST has been very close to the 30-year mean for the period it is centred in and can therefore be considered as a robust indicator of the recent state of the climate. The range between the 5th and 95th percentile of annual residuals of observed GMST is 0.319 °C, substantially less than the corresponding range in large model ensembles, implying that the first individual year above 1.5 °C may occur later than indicated by climate models. The largest annual residuals are mostly associated with large-amplitude El Niño-Southern Oscillation (ENSO) events or major volcanic eruptions, with the relationship between cool years and La Niña more consistent than that between warm years and El Niño. The relationship between multi-year GMST means for differing periods indicates that the probability that the 1.5 °C threshold has been crossed (using the IPCC definition of the midpoint of the first 20-year period above the threshold) exceeds 50% once the most recent observed 11-year mean reaches 1.43 °C.

Plain Language Summary

An increase in temperature of 1.5 °C from pre-industrial times is widely seen as a critical point in climate change, but how do we know when warming of 1.5 °C has occurred? “Crossing” of 1.5 °C is formally defined using 20-year averages, but since we don’t want to wait many years to know whether we’ve crossed 1.5 °C or not, how can we make use of the data we have now? This paper shows how to use existing observations to determine how likely it is that 1.5 °C has been crossed. It also shows how much global temperatures vary from year to year, and when we might expect to start seeing individual years above 1.5 °C (which many people will interpret as meaning that there has been a sustained crossing of 1.5 °C). Global temperatures do not vary as much from year to year in observations as they do in models, which suggests that the first years above 1.5 °C may happen a little later than forecasts based on models say they will.

1 Introduction

Global mean surface temperature (GMST) is a key indicator used in the assessment of climate change. The Paris Agreement has an objective of limiting the increase in global temperature to well below 2 °C above pre-industrial levels, while pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.

The centrality of the 1.5 °C temperature threshold to the Paris Agreement, and climate policy more generally, means that there is great public and policy interest in determining when it (and other key thresholds) has been reached. This requires a metric which has a sufficient level of stability not to be unduly influenced by short-term variability, whilst still being available in a reasonably timely manner. It is expected that individual years above 1.5 °C, which are likely to be widely (if inaccurately) perceived as indicating a sustained breaching of the 1.5 °C threshold, will occur before longer-term metrics reach that level. (Individual months more than 1.5 °C above the 1850-1900 baseline have already occurred in all data sets used in this paper, in late 2015 and/or early 2016 at the peak of the 2015-2016 El Niño). The World Meteorological Organization (WMO) Annual to Decadal Climate Outlook issued in May 2021 (WMO, 2021) stated a 40% probability that an individual year exceeding 1.5 °C would occur at some point in the period between 2021 and 2025, whilst projections reported (Arias et al., 2021; Lee et al., 2021) in the IPCC Sixth Assessment Report (AR6) indicate that for most emissions scenarios, the central estimate of the first 20-year period with a mean exceeding 1.5 °C has a midpoint in the early 2030s, with the probability of any individual year exceeding 1.5 °C reaching 40 to 60% by 2030 under most scenarios.

The volatility of short-term trends in global surface temperature has been well documented, particularly in the context of the relatively slow rate of global temperature increase between 1998 and 2012 (IPCC AR6 WGI Cross-Chapter Box 3.1; Eyring et al., 2021). Analysis using various observational data sets by Liebmann et al. (2010), Risbey et al. (2014) and Marotzke and Forster (2015) all found that the difference between the most positive and most negative 15-year trends in the observational record was in the range of 0.4 °C to 0.5 °C per decade. Less attention, however, has been given to the variability of multi-year means and their stability as an indicator of the current state of the climate.

2 Data and definitions

GMST is defined as the combination of air temperature at a nominal elevation of 2 m over land, and sea surface temperature over ocean. This is distinct from global surface air temperature (GSAT) which is defined as air temperature at a nominal elevation of 2 m over both land and ocean. The relationship between GMST and GSAT is discussed in Cross-Chapter Box 2.1 of the Working Group I IPCC Sixth Assessment Report (Gulev et al., 2021). “Global surface temperature” is used as a generic term which covers both GMST and GSAT.

The GMST assessment in AR6 (Gulev et al., 2021) draws on four GMST data sets: HadCRUT5 (Morice et al., 2021), Berkeley Earth (Rohde and Hausfather, 2020), NOAAGlobalTemp-Interim (Vose et al., 2021) and Kadow et al (Kadow et al., 2020). These data sets meet the criteria of having data in at least 80% of the years between 1850 and 1900, data for at least 90% of global gridpoints in each year from 1960 onwards, and use the most recent generation of SST data sets (HadSST4 (Kennedy et al., 2019) or ERSSTv5 (Huang et al., 2017)) for their SST data. They can thus be considered to be globally quasi-complete since 1960 (addressing biases arising from limited coverage of data-sparse areas at high latitudes in earlier generations of data sets), and to have sufficient temporal coverage to allow the calculation of a pre-industrial baseline. Annual and monthly mean temperature anomalies in each of the four data sets are calculated directly from the gridded data, with the global mean taken as the mean of the northern hemisphere and southern hemisphere means. This may differ from anomalies reported by the data providers themselves.

The primary metric used in AR6 for the assessment of observed changes in GMST is the difference in mean GMST between 1850-1900 (taken as an observational approximation of the pre-industrial period, which is not formally defined in the Paris Agreement) and the mean of the most recent 10-year period (2011-2020). This difference is calculated independently for each of the four component data sets and then averaged across the four data sets. Results are also reported for changes over a number of other time periods (e.g. from 1850-1900 to 1995-2014, which is the modern reference period used in CMIP6 model assessment). Linear trends are still reported in AR6 for a number of time periods but are no longer the primary metric for GMST assessment, as they had been in the Fifth Assessment Report and earlier IPCC reports. An annual (Figure 1) and monthly time series of anomalies from the 1850-1900 reference period is also calculated by calculating anomalies for the four individual data sets and then averaging these. These show sustained warming from about 1970 onwards; the period from 1970 to the present is defined as the "current period of warming" in this paper.

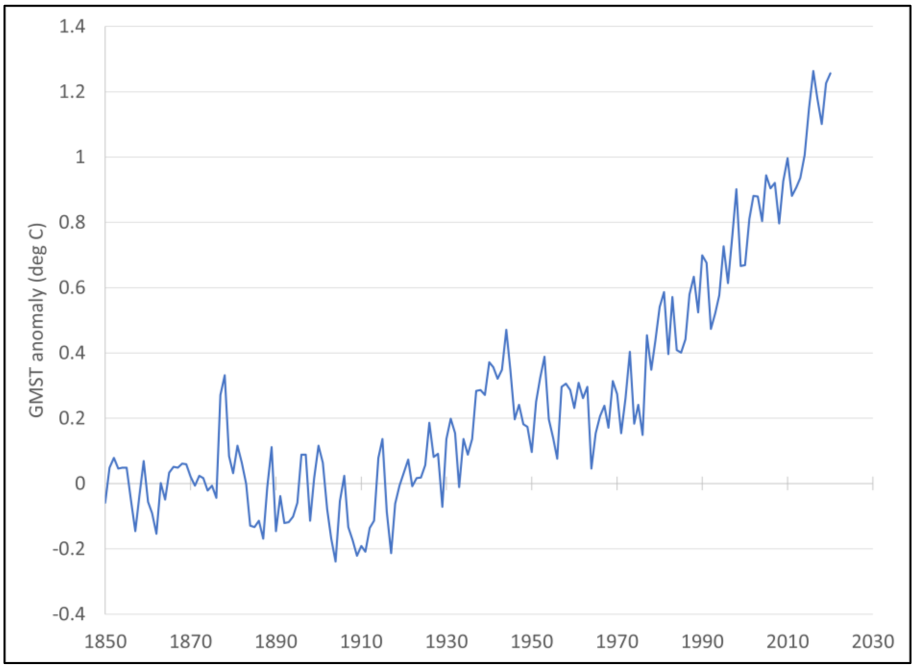

Figure 1. GMST anomalies (1850-1900 baseline) from a mean of four data sets as described in the text.

The crossing time of a given global temperature threshold is defined in AR6 as the midpoint of the first 20-year period in which the global surface temperature exceeds that threshold (Arias et al., 2021). This is a different approach to that used in the IPCC Special Report on Global Warming of 1.5 °C (SR1.5) (Allen et al., 2018), which defines the global warming level at a given point of time as being the mean of the 30-year period centred on that time, extrapolating any secular trend into the future if necessary.

3 What length of averaging period is required to be a robust indicator of the state of the climate?

In a changing climate, the choice of an averaging period to represent the recent climate is a balance between, on the one hand, having a period which is sufficiently long to capture major modes of internal variability in the global climate, and on the other hand, having a period which excludes older data which are no longer representative of recent climate.

The question of optimal averaging periods for station data has been extensively considered in the literature (e.g. Angel et al. (1993), Huang et al. (1996), Srivastava et al. (2003)), with WMO (2007) considering the question in a climate change context. 30 years has traditionally been considered a standard averaging period, and is the period used by WMO to define a climatological standard normal. WMO (2007) found, however, that for most variables (including temperature), the predictive accuracy of multi-year averages for periods from about 10-15 years upwards was not appreciably different from that of a 30-year average, suggesting that at the station level, a 10-15 year average is sufficient to capture most forms of internal variability.

One method of assessing the internal variability of *n*-year means relative to a 30-year mean (taken here as a baseline) is to consider the variability of the residuals of the *n*-year means when compared with the 30-year period with the same midpoint as the *n*-year period.

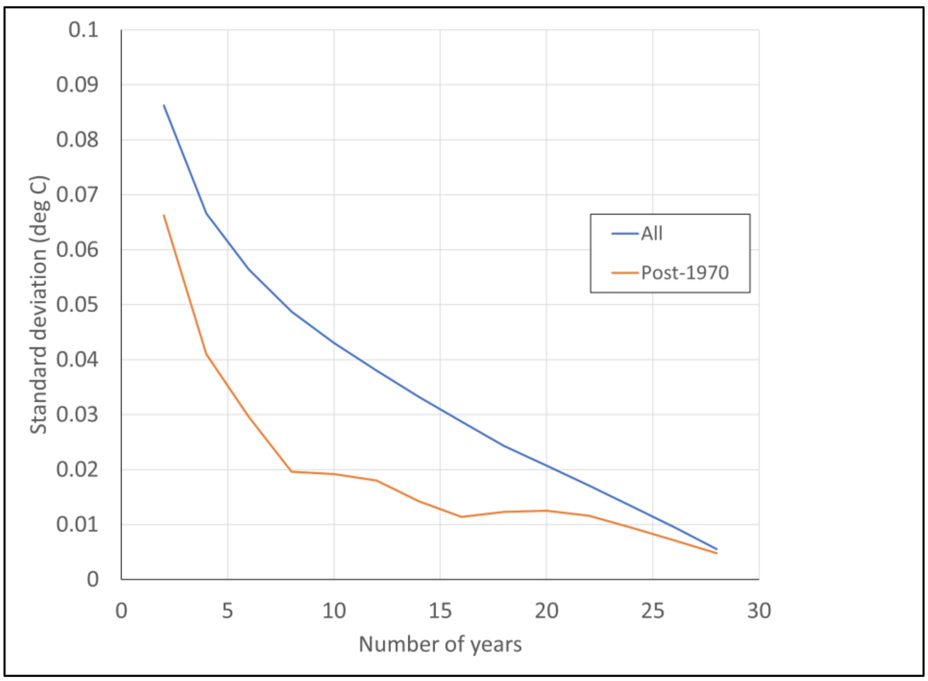

Figure 2. The standard deviation of the difference between global mean surface temperatures averaged over *n* years and the mean of the 30-year period that *n*-year period is entered in. The blue line shows the full record, and the red line the post-1970 period (using 30-year reference periods of 1971-2000 and later).

The results of this are shown in Figure 2, considering both the full GMST record and the period since the current sustained warming trend began in the 1970s. This indicates that, as expected, the standard deviation of the residuals decreases as the period over which the means are taken increases. Over the full instrumental record, this is a steady decrease. However, from the 1970s onwards, the standard deviation of the residuals falls sharply, with increasing average period up to 8 years, but then much more slowly from 8 years thereafter.

Considering in particular the 10-year averaging period used as part of the IPCC assessment of observed changes in global temperature, since 1970, the standard deviation of the residual is 0.019 °C (this compares with 0.013 °C for a 20-year period). The largest post-1970 difference between a 10-year mean and the 30-year mean it is centred in was for 1991-2000, where the 1991-2000 mean was 0.031 °C cooler than the 1981-2010 mean, in part reflecting the fact that post-1991 cooling due to the Pinatubo eruption had a larger influence on a mean taken over a shorter period. (The largest difference at any point in the record is 0.117 °C between the 1937-1946 and 1927-1956 means, reflecting the temporary reversal of global temperature trends around that time). This indicates that, unless there is a substantial change in the secular warming trend, the 10-year average is sufficiently stable to be a relatively robust indicator of the current state of the underlying climate.

4 Internal variability in global surface temperature at the annual timescale

An estimate of internal variability in mean annual global temperatures is made by calculating the residual for each annual value (T_y for year *y*) from the mean of the 11-year period centred on year *y* but excluding year *y* (i.e. $T_{y-5},\ldots,T_{y-1}$, $T_{y+1},\ldots,T_{y+5}$). The 11-year period is chosen to match as closely as possible the 10-year period used for IPCC temperature assessments whilst allowing a period which is symmetric about the candidate year.

Figure 3 shows the residuals in each individual year and the frequency distribution of the residuals, while Table 1 shows the 5-95% percentile range in the residuals (corresponding to the IPCC 'very likely' range), both for the combined time series and for the four individual component data sets. The annual residuals are weakly but not significantly autocorrelated (r = +0.234).

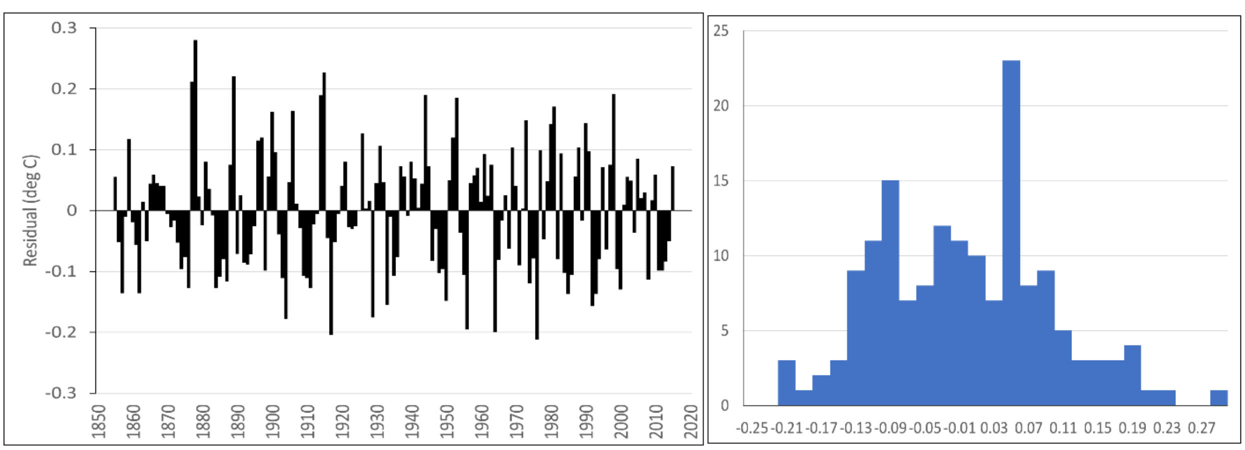

Figure 3. (Left) Time series of the annual global temperature residuals for the combined time series. (Right) Frequency distribution of these residuals (labels show the midpoint of alternate 0.02 °C intervals).

Table 1

Standard deviation and 5-95 percentile range of annual residuals (°C)

Data set	Standard deviation	5^{th} percentile	95^{th} percentile	$(95^{th} – 5^{th})$ percentile
HadCRUT5	0.102	−0.157	0.180	0.337
Kadow	0.099	−0.148	0.170	0.318
NOAA	0.093	−0.140	0.164	0.304
Berkeley Earth	0.108	−0.163	0.190	0.353
Combined	0.099	−0.146	0.173	0.319

This shows that the width of the 'very likely' (5-95%) range for the combined data set is 0.319 °C. There is little difference between the value for the combined data set and that in the four individual component data sets (which range from 0.304 °C to 0.353 °C), indicating that the process of averaging the four data sets does not substantially smooth interannual variability. By way of comparison, the width of the 5-95% range in various large CMIP6 model ensembles reported in AR6 (Lee et al., 2021) is between 0.4 °C and 0.6 °C, indicating that these models are simulating more interannual variability than is occurring in observational data sets. This is also consistent with the results which Bengtsson and Hodges (2019) obtained using the HadCRUT4 data set (an earlier generation than the HadCRUT5 data set used in this analysis).

The largest individual positive residuals are associated with strong El Niño events, in 1878 (+0.280 °C), 1915 (+0.227 °C) and 1889 (+0.220 °C), consistent with the known relationship between the El Niño-Southern Oscillation (ENSO) and global surface temperatures (e.g. Trenberth et al. (2002), Thompson et al. (2009)). Recent reassessments of the 1877-1878 El Niño event (Huang et al. (2020), Vaccaro et al. (2021)) indicate that in terms of Pacific SST anomalies, it was of comparable intensity to the well-known extreme El Niño events of 1982-1983, 1997-1998 and 2015-2016. 1998 had the largest annual mean temperature residual (+0.191 °C) of the post-1915 period. The temperature signal of the 1982-1983 El Niño was largely offset by the 1982 eruption of El Chichón. (A final residual for 2016 cannot yet be calculated using this methodology but data available to date indicate that it is likely to be in the order of 0.16 °C to 0.17 °C).

The largest negative residuals are associated either with strong La Niña events (1976 (−0.212 °C), 1917 (−0.205 °C), 1956 (−0.196 °C)) or major volcanic eruptions (1964 (−0.200 °C), 1904 (−0.178 °C)). Although the 1991 Pinatubo eruption had the largest negative radiative forcing of any post-1900 eruption (Luo (2018), Gulev et al. (2021)), El Niño conditions existed for much of the 1991-95 period, partly offsetting the volcanic signal, and hence the negative residuals in this data associated with Pinatubo are smaller than those associated with Mount Agung (1963) or the 1902 eruptions, with a lowest value of −0.157 °C in 1992. Although uncertainties in individual annual values are substantially greater pre-1900 as a result of sparser observations, there is little evidence of any signal in the observed interannual variability, with the standard deviation of the residuals over the full period of record (0.099 °C) similar to that for the post-1900 period (0.100 °C).

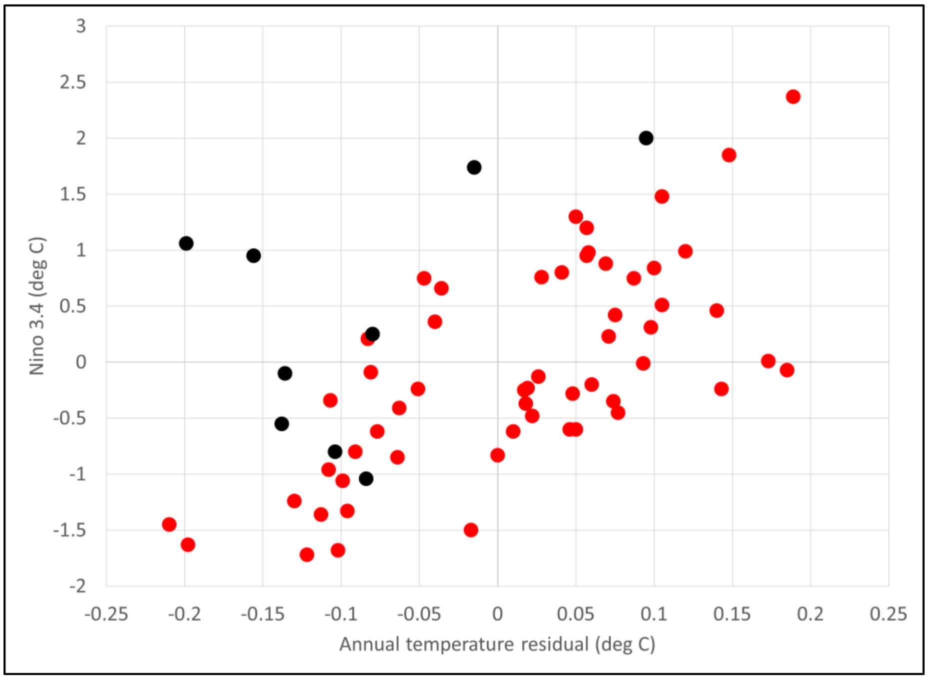

Figure 4. Annual residuals of global mean surface temperature and values of the Niño 3.4 index (ERSSTv5, detrended, mean of September-November in the preceding year). The three years following each of the eruptions of Mount Agung (1963), El Chichón (1982) and Pinatubo (1991) are shown in black. Data shown are from 1950-51 to 2014-15.

The ENSO influence on global temperatures is further illustrated in Figure 4, which shows GMST residuals as a function of the value of the Niño 3.4 index in September-November of the preceding year, from 1950 when reliable values of the index commenced. The relationship is especially consistent in La Niña years; excluding years affected by volcanic eruptions, 9 of the 10 years with the coolest GMST residuals make up 9 of the 10 years with the largest negative values of the Niño 3.4 index. The relationship between El Niño and warmth is less consistent; while the three strongest non-volcanic El Niño years all have GMST residuals exceeding +0.1 °C, anomalously warm years have also occurred under neutral ENSO conditions, with 1953 and 1980 both exceeding +0.15 °C.

To explore the relationship further, residuals were recalculated using GMST for 12-month periods starting in each of the 12 calendar months, rather than just the calendar year. The correlation of these with the September-November Niño 3.4 values is shown in Figure 5, and shows that the ENSO influence on 12-month means of GMST manifests most strongly for 12-month means beginning in months between August and November, and most weakly for 12-month means beginning in March and April. However, this has little impact on the overall variability of 12-month mean temperatures, with the standard deviation of 12-month residuals ranging between 0.097 °C and 0.103 °C regardless of the start month.

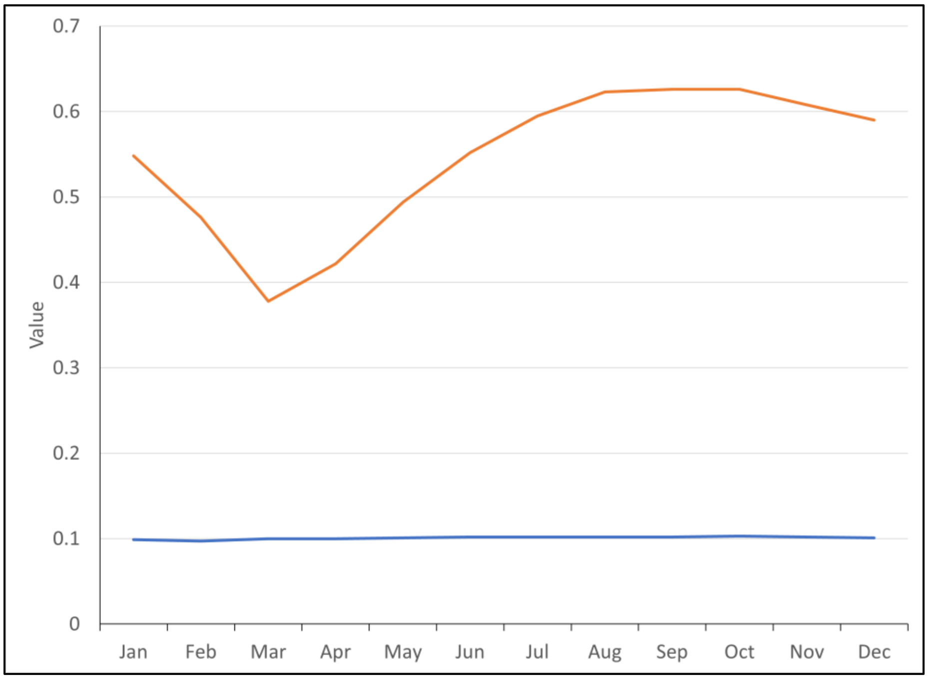

Figure 5. (Red) Correlation between 12-month mean GMST for periods starting in the stated month, and the Niño 3.4 index (as per Figure 4, using Niño 3.4 for the preceding year for GMST 12-month periods starting in January to March). (Blue) Standard deviation (°C) of residuals of the 12-month mean GMST for 12-month periods starting in the stated month.

5 Probability of individual years above thresholds

Table 2 shows the crossing times of thresholds which have already been crossed, along with the first individual year above the threshold. Since the present phase of consistent warming began in the 1970s, the first year above a threshold has generally occurred between 1 and 6 years before the midpoint of the crossing period for that threshold. The exception is the 0.9 °C threshold, which was reached (with 0.901 °C) in 1998, 8.5 years before the midpoint of the 1997-2016 crossing period, indicating the sensitivity of such an analysis to the specific thresholds used, as the next year above 0.9 °C did not occur until 2005. (Conversely, 2010 reached 0.996 °C, four years before the 1.0 °C threshold was reached for the first time).

Table 2

Crossing periods for particular temperature thresholds and the first individual year in which those thresholds were reached

Threshold (°C)	Crossing period	First year above threshold	Difference with midpoint of crossing period (years)
0.3	1964-1983	1878	96.5

0.4	1971-1990	1944	36.5
0.5	1976-1995	1980	5.5
0.6	1982-2001	1988	3.5
0.7	1987-2006	1995	1.5
0.8	1993-2012	1998	4.5
0.9	1997-2016	1998	8.5
1.0	Not yet occurred	2014	
1.1	Not yet occurred	2015	
1.2	Not yet occurred	2016	

The probability of an annual residual above +0.12 °C in the observed data is approximately 10% (Figure 6). The central estimates of crossing times projected in AR6 imply warming rates for the period from 2001-2020 to the date of reaching the 1.5 °C threshold which range from 0.021 °C/year (SSP1-1.9) to 0.030 °C (SSP5-8.5) (Table 3). Assuming that this rate of secular warming is constant over that period, this implies crossing of a 1.38 °C threshold, and hence a probability of an individual year exceeding 1.5 °C reaching 10%, at a point 4 to 6 years before the midpoint of the crossing period, and thus around 2025 for SSP5-8.5 and 2029 for SSP1-1.9. This is broadly consistent with the observations reported in Table 2 for lower thresholds. It can also be compared with the WMO outlook for 2021-2025 issued in May 2021, which assessed a 40% probability of an individual year exceeding 1.5 °C in that period (which, assuming a constant secular warming trend over that period, equates roughly to a 10% probability in the midpoint year, 2023).

Table 3
Central estimate of IPCC AR6 1.5 °C crossing period, implied warming rate and implied crossing of 1.38 °C threshold

Scenario	Central estimate of 1.5 °C crossing period[a]	Implied warming rate from 2001-2020 (°C per year)	Projected crossing of 1.38 °C threshold
SSP1-1.9	2025-2044	0.021	2029
SSP1-2.6	2023-2042	0.023	2027
SSP2-4.5	2021-2040	0.025	2026
SSP3-7.0	2021-2040	0.025	2026
SSP5-8.5	2018-2037	0.030	2025

Note: Implied warming rate is from 2001-2020 to the stated 1.5 °C crossing period. Projected crossing of 1.38 °C assumes a constant warming rate from 2001-2020 to 1.5 °C crossing.
[a] Arias et al. (2021)

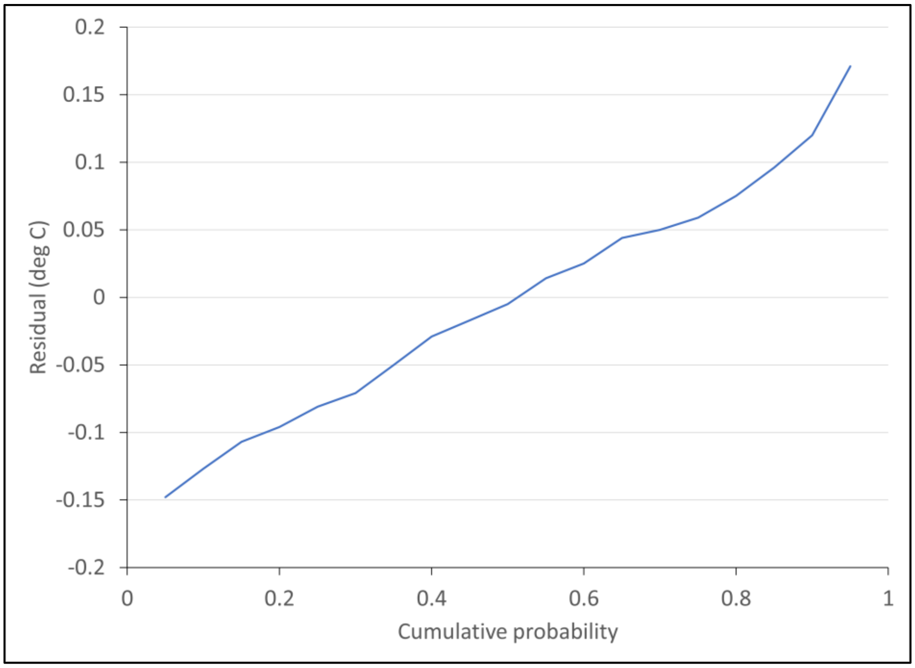

Figure 6. Cumulative probability distribution of residuals of annual GMST.

6 Assessing the likelihood that a threshold has been crossed from observational data

Using the 20-year period used for the crossing time definition in AR6, it can only be determined definitively that a threshold has been crossed 10 years after the event. However, in a consistently warming climate, well before that period is completed the probability that the threshold has been crossed will be very close to 1. To give one example, as of the end of 2020, there had not yet been a 20-year period with mean temperatures more than 1.0 °C above those of 1850-1900 (the 2001-2020 mean anomaly was +0.99 °C), and hence a definitive crossing date for the 1.0 °C cannot yet be determined; however, for crossing to have occurred before 2020, a sufficient condition is for the 2010-2029 mean to be above 1.0 °C, which would require a 2021-2029 mean above 0.9 °C. As this value is 0.19 °C below the 2011-2020 mean, and lower than any individual year from 2012 onwards, it was extremely likely as of the end of 2020 that crossing of the 1.0 °C threshold had occurred before 2020.

The purpose of this section is to establish an objective method of assessing the probability that crossing has occurred by a certain year, as a function of the available observational data and historical probability distributions. Figure 7 shows indicators of the distribution of the difference between 20-year means of GMST commencing in year *y*, and *n*-year means of GMST commencing in year *y*, since the current warming phase began in the 1970s. This allows the probability that a 20-year period projecting into the future will have GMST exceeding a certain threshold to be estimated, as a function of an *n*-year observed mean ending in the most recent year.

Of particular interest here is the case of $n = 11$, since if the 20-year mean for the period extending from year (yy – 10) to (yy + 9) exceeds a threshold, that means that threshold has been crossed on or before year *yy*. For $n = 11$, the 10th percentile of the differences is 0.060 °C, the 50th percentile is 0.079 °C, and the 90th percentile is 0.101 °C. This indicates that, providing there is no major change in the underlying warming rate, the probability that 1.5 °C has been crossed on or before the current year exceeds 50% once the observed mean for the most recent 11 years reaches 1.43 °C. The probability is about 90% once the 11-year mean reaches 1.44 °C, while crossing is unlikely to have occurred if the observed 11-year mean is below 1.40 °C. There is no instance in the post-1970 observed data of a difference of less than 0.05 °C between the 11- and 20-year means (Figure 7, right).

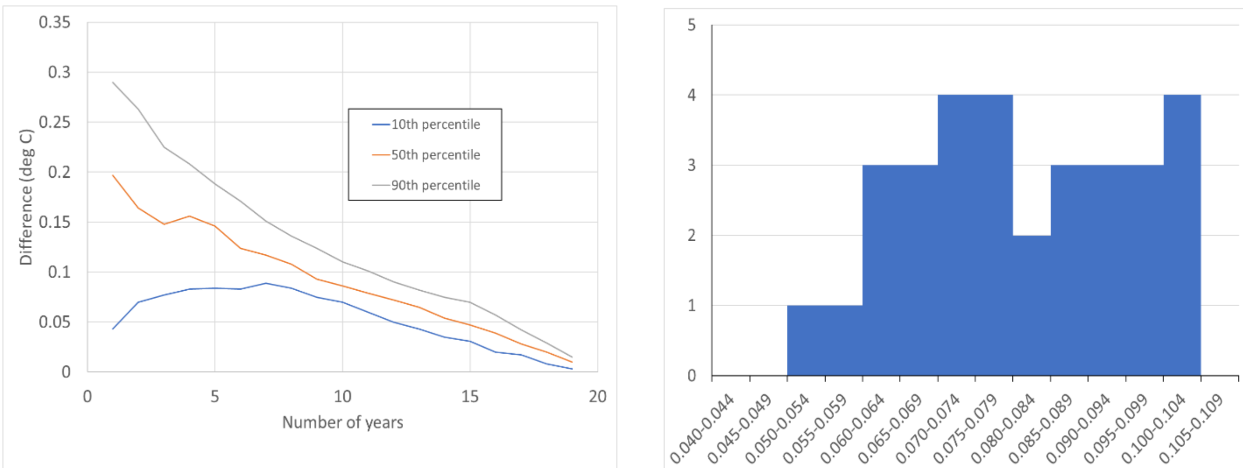

Figure 7. (Left) Differences in observed data (1971-2020) between the 20-year mean of GMST starting in year *y* and the *n*-year mean starting in year *y*. (Right) Frequency distribution of the differences (°C) between the 20- and 11-year means.

7 Discussion

The results obtained indicate that interannual variability in observed GMST is lower than that generally observed in model ensembles, which may indicate that models are overestimating global temperature variability, that observational data are not capturing the full range of variability which occurs, or a combination of the two. A possible scenario for observational data under-representing variability is that the methods used to interpolate GMST data sets over data-sparse areas fails to fully capture interannual variability in those areas; however, Bengtsson and Hodges (2019)'s finding that interannual variability was lower in observations than models still held when they masked models to the areas with available data in the HadCRUT4 data set, which is not interpolated and treats data voids as missing.

While a full consideration of why models might overestimate interannual variability of global surface temperature is beyond the scope of the paper, it has been found (Grose et al., 2020) that CMIP6 models tend to overestimate SST variability in most of the central and eastern equatorial Pacific (and hence overestimate ENSO amplitude), whilst they also tend to overestimate the duration of El Niño events (Figure 3.36, Eyring et al. 2021). As a substantial proportion of interannual GMST variability is attributable to ENSO, it would be expected that the capacity of a model to simulate ENSO amplitude, and the relationships between ENSO and GMST, would be important in determining its capacity to accurately simulate interannual variability of global surface temperature.

The results obtained here also indicate that, while trends of global surface temperature over short periods (10-15 years) are volatile, means of global temperature over a similar length of time are a relatively robust indicator of the recent state of the climate. This allows them to be used to assess the likelihood that key thresholds have been crossed with a relatively high level of confidence. This will become increasingly important as the world approaches 1.5 °C of warming since the pre-industrial period, which is likely to occur during the late 2020s or early 2030s under all emission scenarios.

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Open Research

The annual global mean surface temperature (GMST) time series used in this paper are available at https://doi.org/10.5281/zenodo.6321535. (Note for editor/reviewers: it is expected that by the time of publication, it will also be available in the IPCC AR6 data repository, in which case that reference will be added).

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