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Stable estimates of when global temperature thresholds will be crossed: least-squares fits as the end date of the fitted span is reduced

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Preprint Status

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Conflict of Interest

None

Keywords

HadCRUT5 · global warming · temperature anomaly · exponential fit · 1.5°C · 2°C · Paris Agreement · climate projections · least squares · temperature threshold

Stable estimates of when global temperature thresholds will be crossed: least-squares fits as the end date of the fitted span is reduced

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Abstract

Estimates of when global mean temperature will reach 2°C above the 1850–1900 mean are generally derived from emissions scenarios and climate models rather than from the observed temperature record itself. This study does the latter by progressively truncating observed temperature records at their most recent end and fitting different curve types to fixed-width spans. It examines both the coefficient of determination across the complete record from 1850 to 2026 and the standard deviation of the projected year in which the fitted curves cross 2°C. Exponential, quadratic and linear curves were fitted to monthly temperature anomalies from the HadCRUT5, NASA GISS v4 and NOAA v6.1 datasets. When looking at the crossing year, fitting spans ranged from 20 to 150 years for HadCRUT5 and NOAA, and from 20 to 120 years for NASA. In total, 1,089 combinations of dataset, curve type and fitting span were evaluated for truncation end years from 2020 to 2000. Of the three curves the exponential consistently gave the best fit and the HadCRUT5 dataset using an exponential gave the most stable 2°C crossing date. The projected crossing dates presented in this study depend on three conditions: first, that the observed temperatures accurately reflect actual temperatures; second, that the fitted trajectory adequately represents the observed trajectory; and third, that the temperature trajectory in the next 10 years continues to follow the temperature trajectory observed in the last 100 or so years. Provided these conditions are met, the most stable 2°C crossing estimates identified in this analysis are 2041 using a 148-year fitting span and 2035 using a 96-year fitting span.

Introduction

The trajectory of global mean surface temperature has been monitored continuously since the mid-nineteenth century. Yet converting this record into a reliable, data-driven estimate of when the 2°C Paris Agreement threshold will be crossed remains contested. Most projections rely on emissions scenarios and complex Earth system

models^{2,3,4} rather than the observed temperature signal itself. This paper takes a purely empirical approach, using observed temperatures to characterise the underlying warming trajectory and extrapolate a crossing date. It is deliberately agnostic to the mechanistic assumptions embedded in conventional climate modelling. It least-squares fits simple curve forms to long-term records of observed temperature and observes how far into the future the best-fitting curve type crosses 2°C in relation to the length of span fitted. Grounding the estimate in observed data rather than modelled futures complements scenario-based projections. Indeed, it produces a result that can be verified directly from the observed temperature record, independently of emissions scenarios or climate model projections.

Methods

Global monthly temperature anomaly data were used from three sources: HadCRUT5 (Met Office), NOAA GlobalTemp v6.1, and GISTEMP v4 (NASA).⁵ Each dataset was re-referenced to its own baseline: 1850-1900 for HadCRUT5 and NOAA, and 1880-1900 for NASA, since the NASA record only begins in 1880.

Three simple types of curves - exponential, quadratic, and linear - were fitted to each dataset using least squares.⁶ For each dataset and each curve, the fit was assessed by calculating a coefficient of determination.

To test how stable the projected crossing dates are, the fitting process was repeated while shortening the data. For a fixed span width (e.g., 96 years) and a chosen end date (e.g., 2020), a curve was fit using data up to that end date, then refit using data one month earlier, then two months earlier, and so on - each time recalculating the predicted 1.5°C and 2°C crossing dates. This produced a set of crossing-date estimates for that combination. The stability of these estimates as the record was truncated was assessed by ranking the standard deviation of the crossing dates at 2°C and studying how the curves collapsed for each ranking. This entire process was repeated for 21 different starting end dates, ranging from 2000 to 2020.

In total, spans ranging from 20 to 150 years were tested (20 to 120 years for NASA, given its shorter record), across all three datasets and three curve types, for a total of 1,089 combinations. The complete set of fitted graphs for all combinations is shown at [11] and the top 10 rankings for each end date are shown in the tables at [12].

Spans near 20 years never ranked among the most stable combinations and proved of little practical use. They also sometimes produced curves that pointed downward and never reached the temperature threshold at all. In those cases, the curve was constrained to avoid negative curvature - effectively flattening it into a straight line - so that a crossing date could still be calculated and plotted.

The Python code used to generate the results presented in this report is available at [13]. Actual datasets containing observed temperatures read by this code to generate

these results can be downloaded from [14-16].

Observations

Of the three curves the exponential gave the highest coefficient of determination when fitting the complete record as shown in Figs 1, 2 & 3. The quadratic's coefficient was only slightly less than that of the exponential. However, as years approached 1850, the quadratic curve started to rise, whereas the exponential curve stayed flat. In order to investigate which is more representative, the Central England Temperature monthly record was examined because this record goes all the way back to 1659. This record stayed flat beyond 1850 as shown in Fig 4, and hence followed the exponential rather than the quadratic.

Tables 1 and 2 rank the top 30 combinations by the stability (lowest standard deviation) of the projected 2°C crossing date, for end dates of 2000 and 2006 respectively. Every one of the top 30 entries in Table 1 uses an exponential fit with a span longer than 115 years - no quadratic or linear fit makes the list. The 148-year span is the only one that ranks in the top three for both end dates. Fig 5e overlays all the exponential curves produced using a 148-year span as the fitting window is repeatedly truncated back to 2000.

Two pieces of evidence point to the same conclusion: the complete absence of quadratic and linear fits among spans over 115 years, and the tight clustering of the overlaid exponential curves in Fig 5e. Together, they suggest that an exponential curve better approximates the true shape of the observed warming trend than a quadratic curve does when fitting data back to pre-industrial times.⁷

HadCRUT5 (the Met Office dataset) produces the best exponential fits overall. It accounts for the top 5 entries in Table 1, and 18 of the top 30.

As the data are truncated, the most stable crossing dates come from spans approaching 150 years. When a span reaches far enough back to include the 1850-1910 period (as in Fig 5b, using a 148-year span) rather than excluding it (as in Fig 6b, using a 96-year span), those early temperatures anchor the curve's shape, keeping it nearly unchanged as the fitting window slides forward from 2026 back to 2000. This stability is visible in Fig 5e, where the curves stay tightly bunched together. Since the HadCRUT5 record starts in 1850, a 150-year span is the longest possible when the end date is 2000.

A shorter, 96-year span excludes the 1850-1910 data, so the curve is not constrained by observed temperatures before 1910. This absence lets the 96-year curve fit more closely to temperatures in more recent years.¹⁰ This causes the 96-year span for end dates extending back to 2006 to project a crossing, centred around 2035, compared to 2041 for the 148-year span. If it is reasonable to assume that the fit to recent decades should be given greater importance than the fit to temperatures before

1910, the combined collapse of fitted curves, the close fit of each of those curves to observed temperatures and small deviation of the 2°C crossings from 2006 onwards in Fig 6 implies that the underlying trend in global temperature will breach the 2°C threshold in about 2035.

Conclusions

Exponential fits produce the most stable 2°C crossing-date estimates as the observed record is progressively truncated back to the year 2000, and this holds true across all fitting spans longer than 115 years. The HadCRUT5 dataset assembled by the Met Office gave crossing years with the lowest standard deviation.

The exponential curve outperformed the quadratic and linear curves in terms of both stable crossing date and quality of fit across the complete record.

Three conditions underlie the projections presented in this study. First, the fitted trajectories are assumed to adequately represent the underlying trend in observed global temperature. Second, the temperature datasets are assumed to accurately reflect global mean temperature. Third, the underlying temperature trajectory will continue to develop in the next 10 years as it has over the last 100 or so years. Given these conditions, the analysis projects a 2°C crossing around 2041 for spans of 148 years, and around 2035 for spans of 96 years.^{8,9} Temperatures observed before 1910 played a decisive role in delaying the crossing until 2041.

In summary, a simple exponential curve has been found to provide a close fit to observed temperatures in the long term and to cross the 2°C threshold in the short term. If it is reasonable to assume that the fit to recent decades should be given greater importance than the fit to temperatures before 1910, then the results support using the 96-year exponential estimate of about 2035 rather than the 2041 estimate obtained from the longer fitting span.

Data Availability

This study uses fixed historical snapshots of the HadCRUT5, NASA GISTEMP v4, NOAA GlobalTemp v6.1 and HadCET v2.1.1.0 datasets. Because these datasets are updated monthly and older versions are replaced, the exact versions used in this analysis have been archived on Zenodo to ensure long-term reproducibility.

- HadCRUT5 analysis time series: ensemble means and uncertainties from 1850-01 to 2026-03 Met Office Hadley Centre. Open Government Licence v3.0. DOI: [10.5281/zenodo.20588286](https://doi.org/10.5281/zenodo.20588286)
- NASA GISTEMP v4 – Global Mean Monthly Land-Ocean Temperature Anomalies, 1880-01 to 2026-04 NASA Goddard Institute for Space Studies. CC0 Public Domain. DOI: [10.5281/zenodo.20679028](https://doi.org/10.5281/zenodo.20679028)

- [NOAA Global Land-Ocean Surface Temperature Time Series 90S–90N v6.1.0.202605, 1850-01 to 2026-05](#) NOAA National Centers for Environmental Information. CC0 Public Domain. DOI: [10.5281/zenodo.20682032](#)
- [HadCET Monthly Mean Temperature v2.1.1.0, 1659-01 to 2026-06](#) Met Office Hadley Centre. Open Government Licence v2.0. DOI: [10.5281/zenodo.22936709](#)

The Python code used to generate fitted curves, crossing-date calculations, and figures is archived at:

- [Python code for least-squares fitting of global land-ocean temperature anomalies](#) DOI: [10.5281/zenodo.21201587](#)

Supplementary tables and graphs generated by the code are also archived:

- [Tables of crossing-date statistics](#) DOI: [10.5281/zenodo.21130275](#)
- [Least-squares fitted global temperature anomaly graphs](#) DOI: [10.5281/zenodo.20699641](#)

These archived datasets and materials provide reproducibility of the results reported in this manuscript, independent of future updates to the original temperature records.

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<https://doi.org/10.48550/arXiv.2503.12425>

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Table 1. Top 30 least squares fit statistics ranked by the standard deviation of the year for crossing 2°C when the temperature record of a fixed number of years was repeatedly truncated back by a year until the last year in the record was 2000.

Dataset Containing Observed Temperatures	Type Of Equation Used In Fit	Number Of Years Fitted	Rounded Crossing Year Mean	Rounded Crossing Year Standard Deviation
Met Office HadCRUT5 Infilled	exponential	150	2041	1.0
Met Office HadCRUT5 Infilled	exponential	149	2042	1.13
Met Office HadCRUT5 Infilled	exponential	148	2042	1.31
Met Office HadCRUT5 Infilled	exponential	147	2042	1.43
Met Office HadCRUT5 Infilled	exponential	146	2042	1.61
NASA GISTEMP v4	exponential	120	2043	1.75
Met Office HadCRUT5 Infilled	exponential	145	2042	1.77
NASA GISTEMP v4	exponential	119	2043	1.83
Met Office HadCRUT5 Infilled	exponential	144	2042	1.84
Met Office HadCRUT5 Infilled	exponential	137	2043	1.85
Met Office HadCRUT5 Infilled	exponential	143	2042	1.87
Met Office HadCRUT5 Infilled	exponential	138	2043	1.88
NASA GISTEMP v4	exponential	118	2043	1.92
Met Office HadCRUT5 Infilled	exponential	136	2043	1.93
Met Office HadCRUT5 Infilled	exponential	139	2043	1.95
Met Office HadCRUT5 Infilled	exponential	142	2042	1.96
Met Office HadCRUT5 Infilled	exponential	140	2042	2.02
Met Office HadCRUT5 Infilled	exponential	141	2042	2.04
Met Office HadCRUT5 Infilled	exponential	135	2043	2.04
NOAA v6.1.0.202604	exponential	124	2046	2.1
NASA GISTEMP v4	exponential	117	2044	2.14
NOAA v6.1.0.202604	exponential	123	2046	2.14
Met Office HadCRUT5 Infilled	exponential	134	2044	2.17
NOAA v6.1.0.202604	exponential	125	2045	2.21
NOAA v6.1.0.202604	exponential	122	2046	2.24
NOAA v6.1.0.202604	exponential	121	2046	2.27
NASA GISTEMP v4	exponential	116	2044	2.29
NOAA v6.1.0.202604	exponential	146	2040	2.29
NOAA v6.1.0.202604	exponential	147	2040	2.3
Met Office HadCRUT5 Infilled	exponential	133	2044	2.33

Table 2. Top 30 least squares fit statistics ranked by the standard deviation of the year for crossing 2°C when the temperature record of a fixed number of years was repeatedly truncated back by a year until the last year in the record was 2006.

Dataset Containing Observed Temperatures	Type Of Equation Used In Fit	Number Of Years Fitted	Rounded Crossing Year Mean	Rounded Crossing Year Standard Deviation
Met Office HadCRUT5 Infilled	exponential	147	2041	0.77
Met Office HadCRUT5 Infilled	exponential	146	2041	0.81
Met Office HadCRUT5 Infilled	exponential	148	2041	0.85
Met Office HadCRUT5 Infilled	exponential	149	2041	0.94
Met Office HadCRUT5 Infilled	exponential	150	2041	0.97
Met Office HadCRUT5 Infilled	exponential	145	2041	0.98
Met Office HadCRUT5 Infilled	exponential	144	2042	1.16
Met Office HadCRUT5 Infilled	exponential	96	2035	1.17
NASA GISTEMP v4	exponential	91	2037	1.18
NASA GISTEMP v4	exponential	92	2037	1.23
Met Office HadCRUT5 Infilled	exponential	97	2035	1.25
Met Office HadCRUT5 Infilled	exponential	95	2034	1.28
Met Office HadCRUT5 Infilled	exponential	143	2042	1.31
NOAA v6.1.0.202604	exponential	91	2038	1.36
NASA GISTEMP v4	exponential	90	2036	1.37
NOAA v6.1.0.202604	quadratic	76	2045	1.39
NASA GISTEMP v4	exponential	93	2037	1.42
Met Office HadCRUT5 Infilled	quadratic	78	2040	1.43
NOAA v6.1.0.202604	exponential	90	2037	1.43
Met Office HadCRUT5 Infilled	quadratic	79	2041	1.43
Met Office HadCRUT5 Infilled	exponential	142	2042	1.44
NOAA v6.1.0.202604	quadratic	77	2046	1.46
NASA GISTEMP v4	exponential	94	2038	1.47
NOAA v6.1.0.202604	quadratic	75	2045	1.49
NASA GISTEMP v4	exponential	89	2036	1.52
NASA GISTEMP v4	exponential	95	2038	1.53
Met Office HadCRUT5 Infilled	exponential	94	2034	1.53
Met Office HadCRUT5 Infilled	exponential	141	2042	1.54
Met Office HadCRUT5 Infilled	exponential	98	2036	1.55
NOAA v6.1.0.202604	exponential	92	2038	1.57

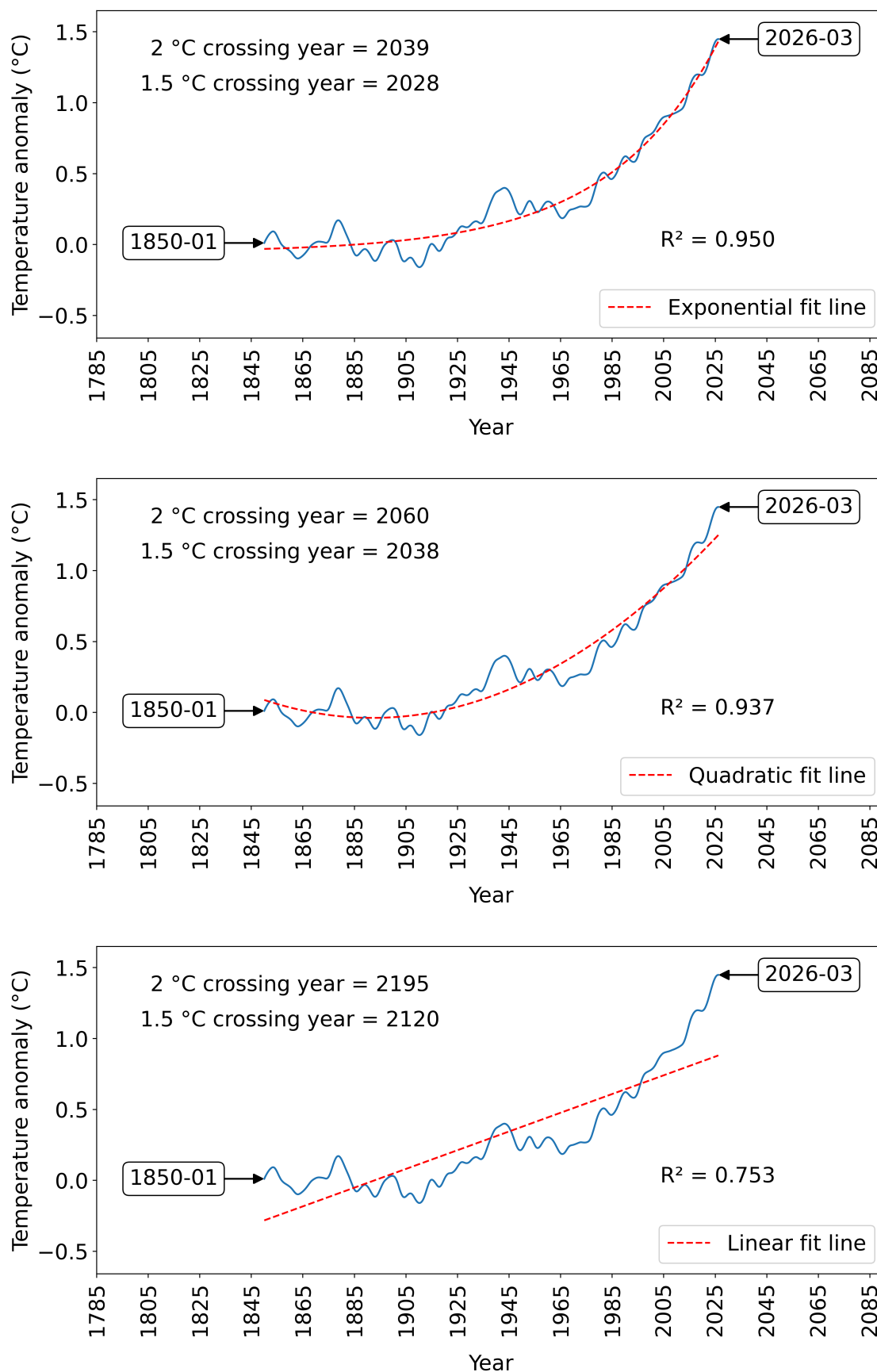


Fig 1. Global temperature given by MetOffice HadCRUT 5.1.0.0 data relative to 1850-1900 mean
 — monthly anomaly. Hann smoothed. (4-year half width)

R^2 = Coefficient of determination using smoothed data

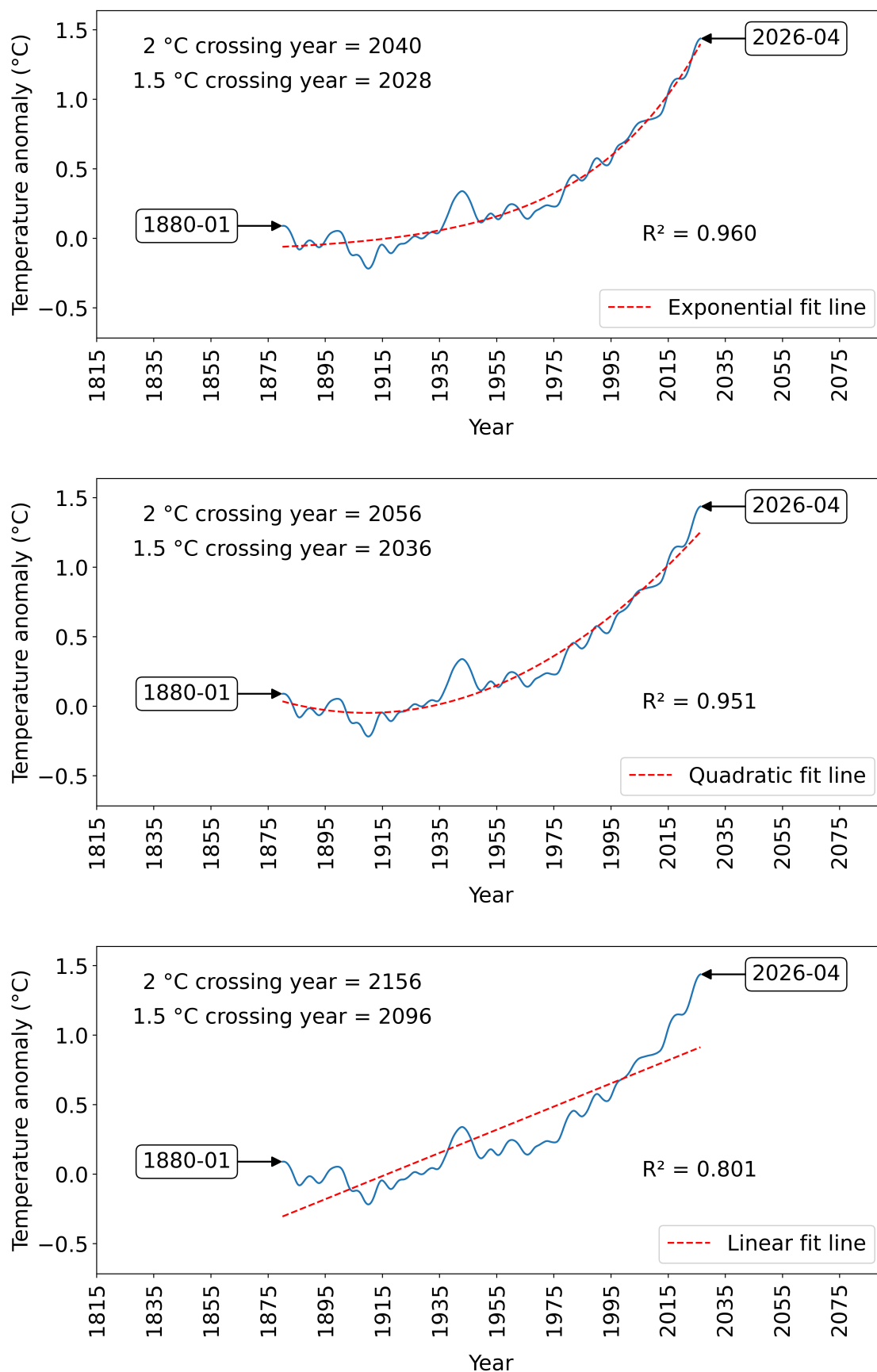


Fig 2. Global temperature given by NASA GISTEMP v4 data relative to 1880-1900 mean
— monthly anomaly. Hann smoothed. (4-year half width)

R^2 = Coefficient of determination using smoothed data

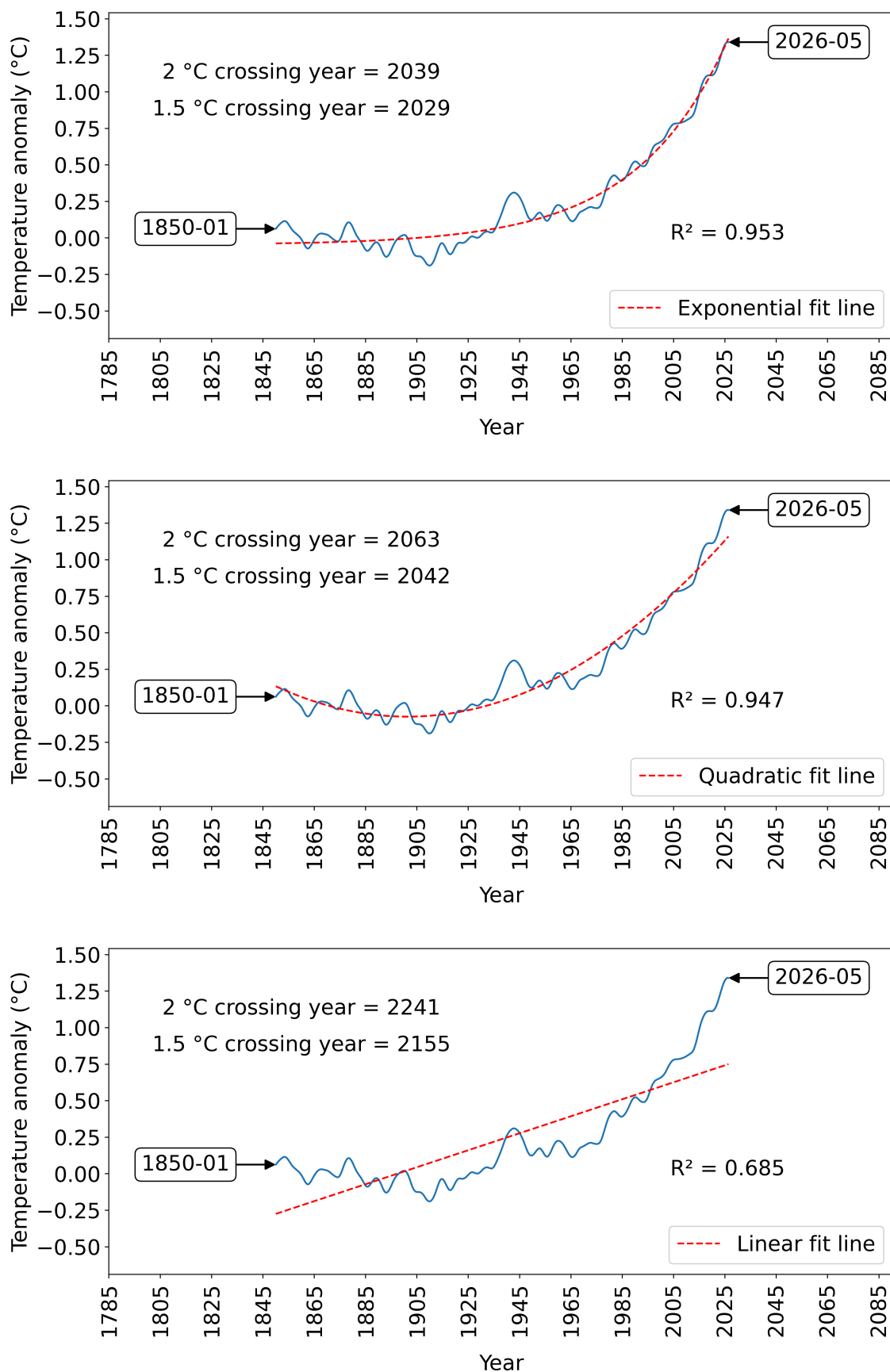


Fig 3. Global temperature given by NOAA 90S.90N.v6.1.0 data relative to 1850-1900 mean
— monthly anomaly. Hann smoothed. (4-year half width)

R^2 = Coefficient of determination using smoothed data

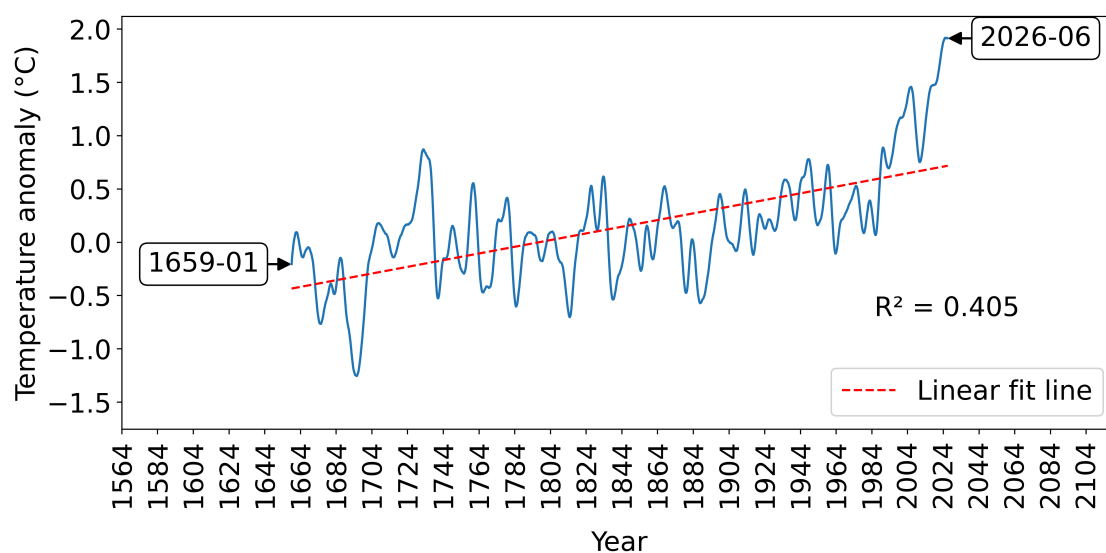
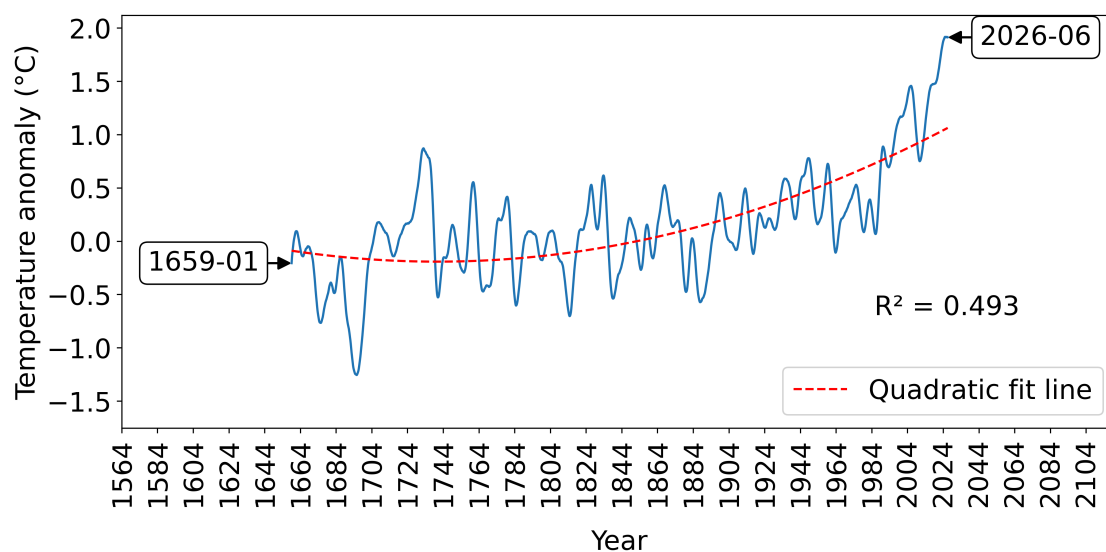
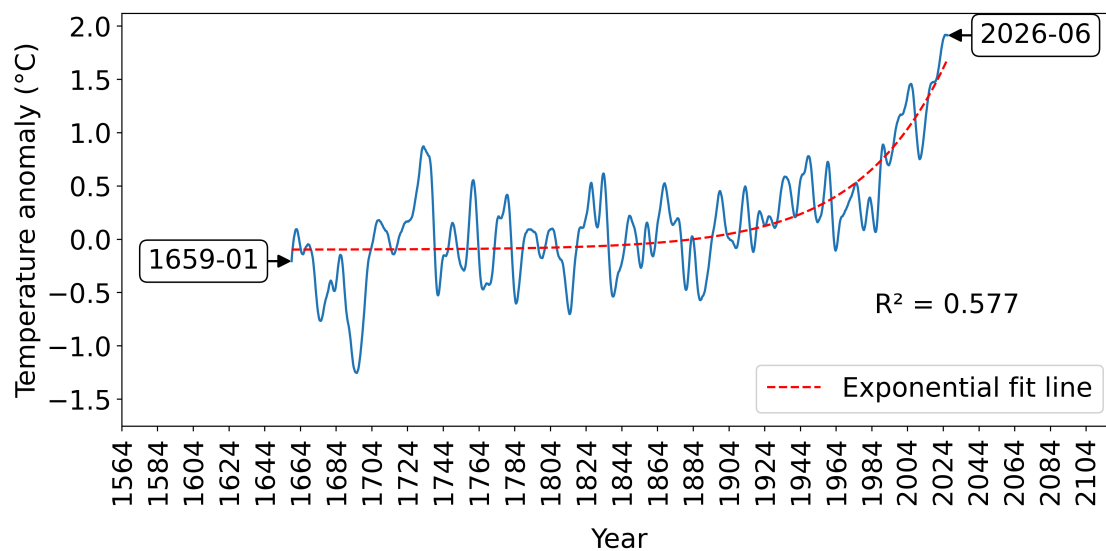


Fig 4. Central England Temperature (CET) relative to 1850-1900 mean

— monthly anomaly. Hann smoothed. (4-year half width)

R^2 = Coefficient of determination using smoothed data

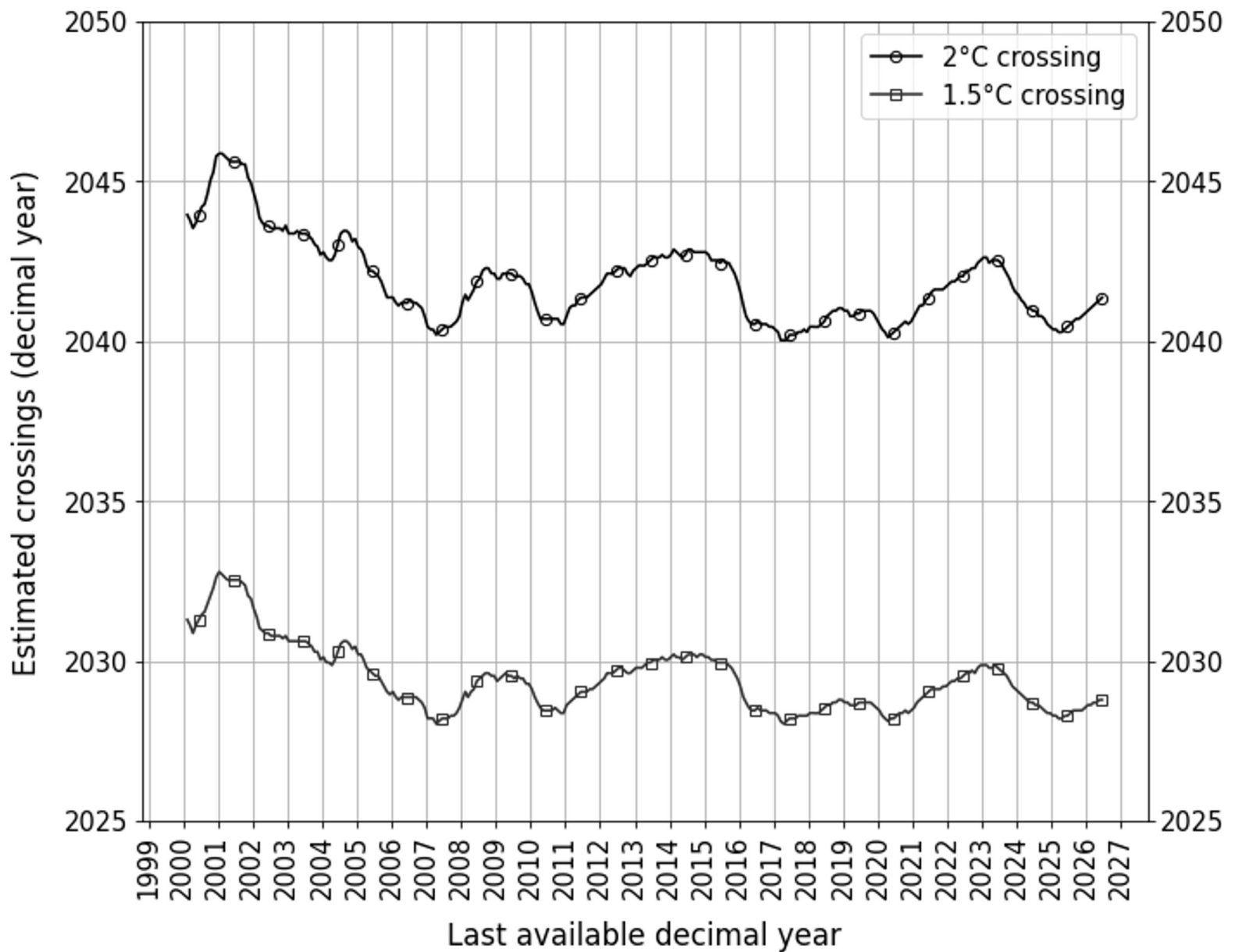


Fig 5a. Stability of 1.5°C and 2°C crossing dates as Met Office HadCRUT5 Infilled data is progressively truncated. Last 148 years are least-squares fitted with an exponential where

$$\text{Temperature (}^{\circ}\text{C)} = A + Be^{C(y - \bar{y})} \text{ where } y = \text{decimal year.}$$

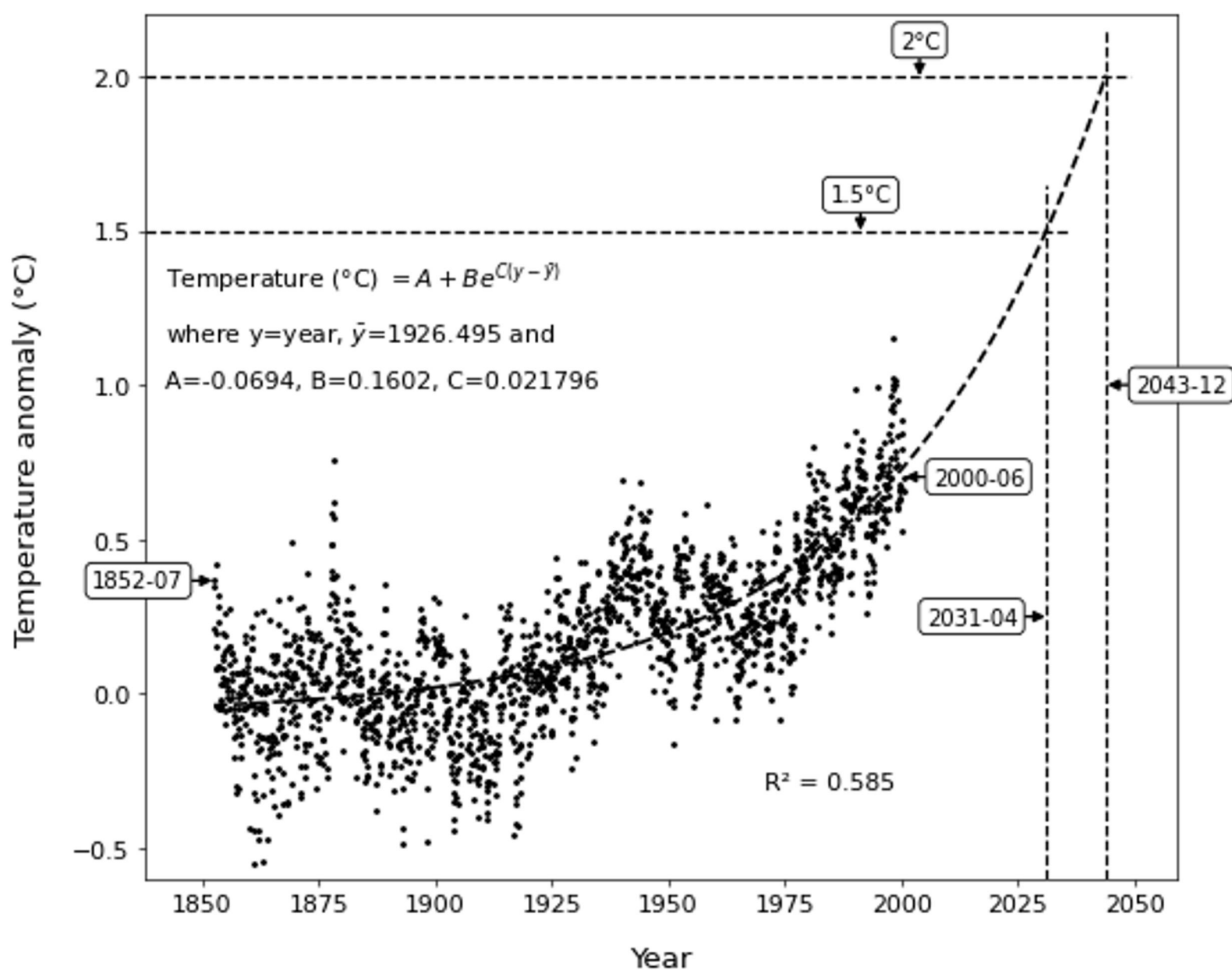


Fig 5b. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1852-07 to 2000-06 (148 years).

R^2 = Coefficient of determination using monthly data without any smoothing

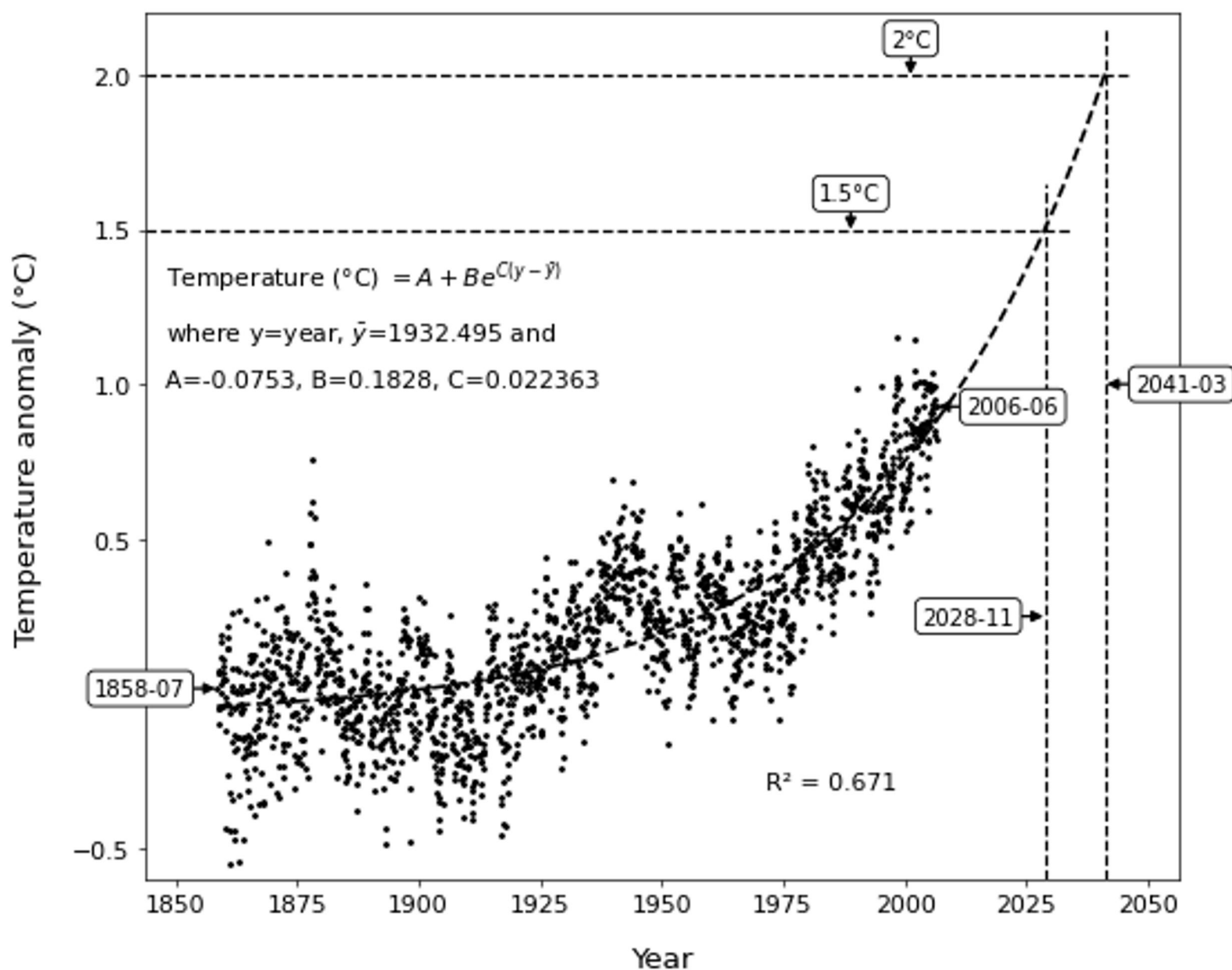


Fig 5c. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1858-07 to 2006-06 (148 years).

R^2 = Coefficient of determination using monthly data without any smoothing

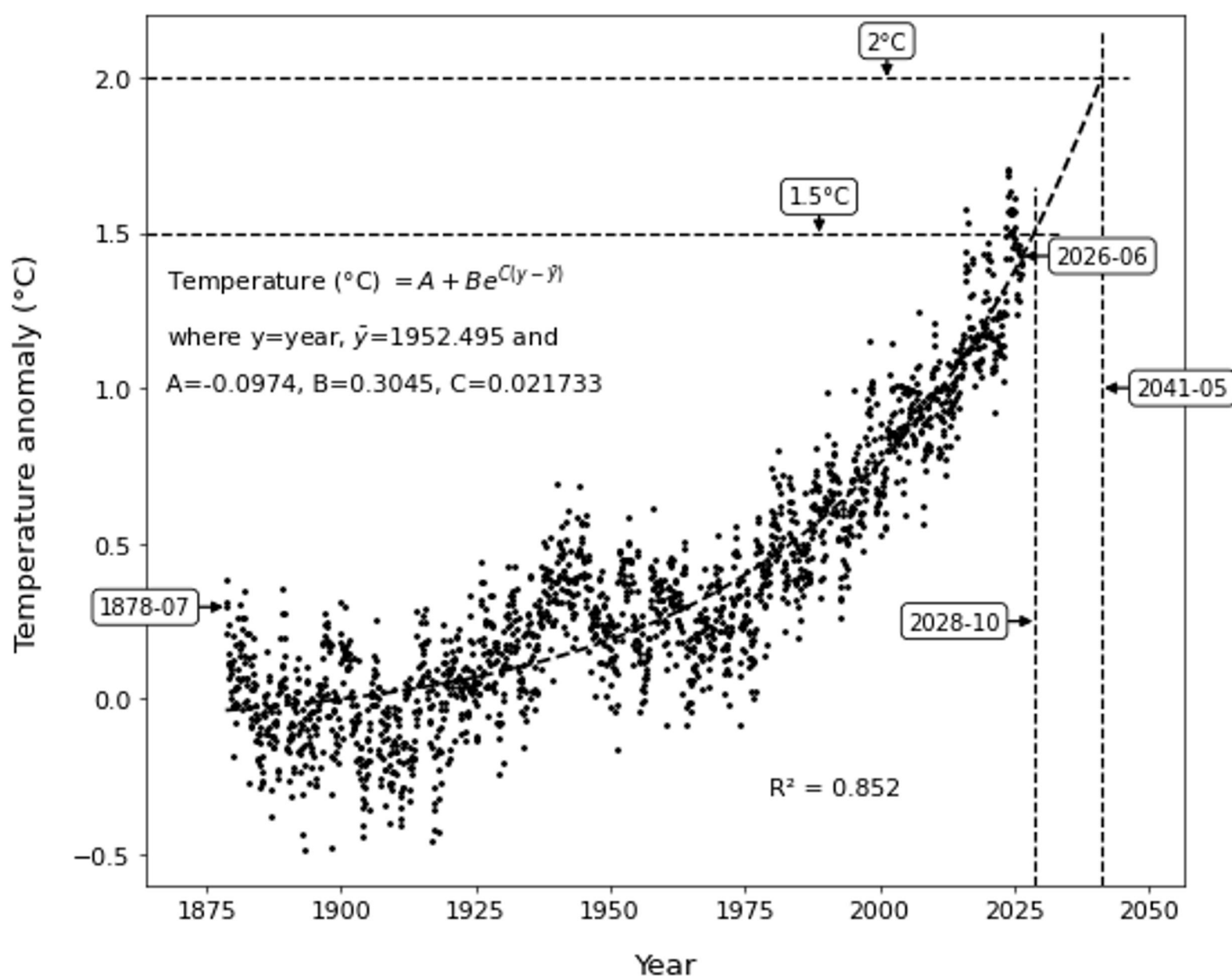


Fig 5d. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1878-07 to 2026-06 (148 years).

R^2 = Coefficient of determination using monthly data without any smoothing

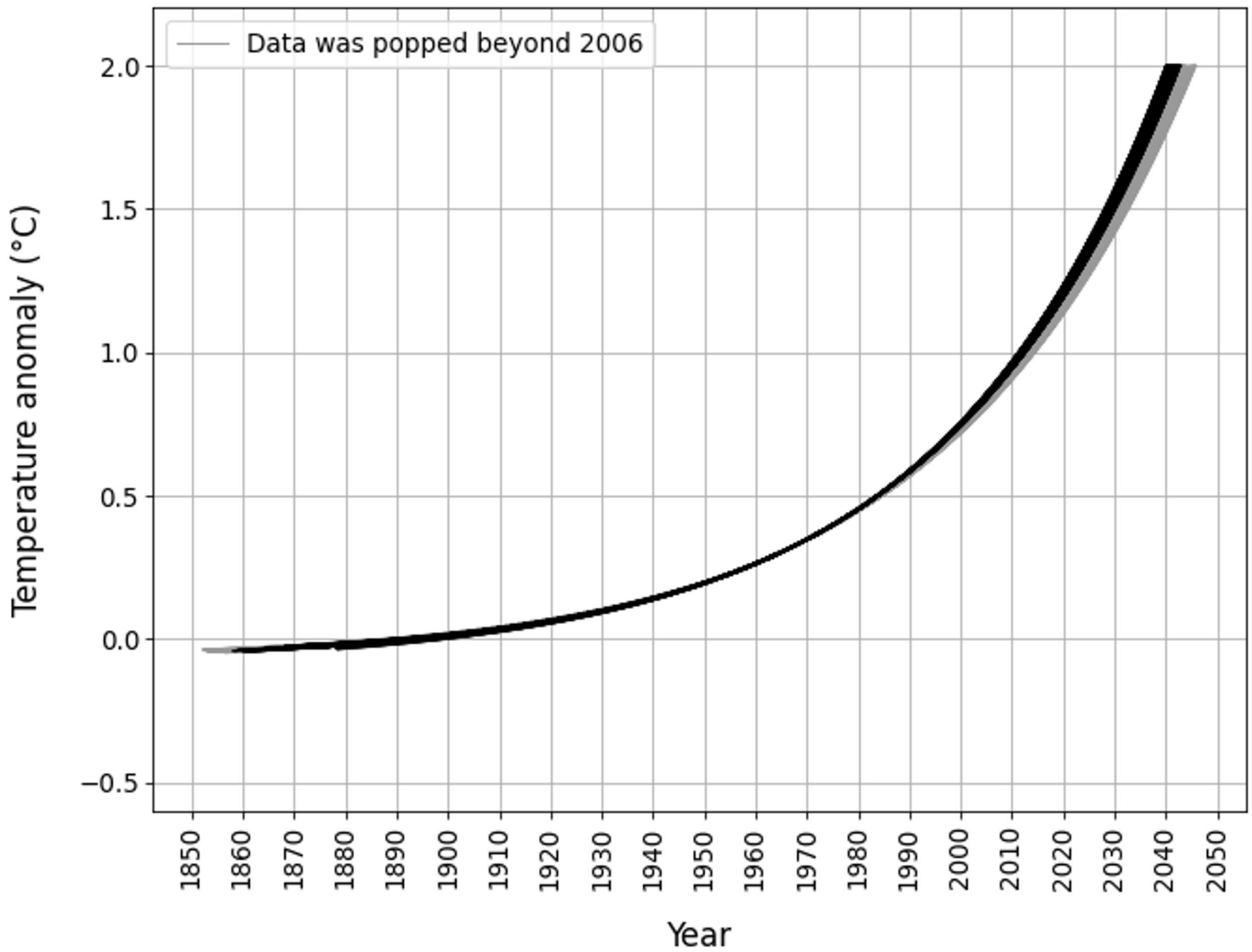


Fig 5e. Met Office HadCRUT5 Infilled fitted lines using an exponential from the last 148 years corresponding to a last available date of 2000-02 to 2026-06.

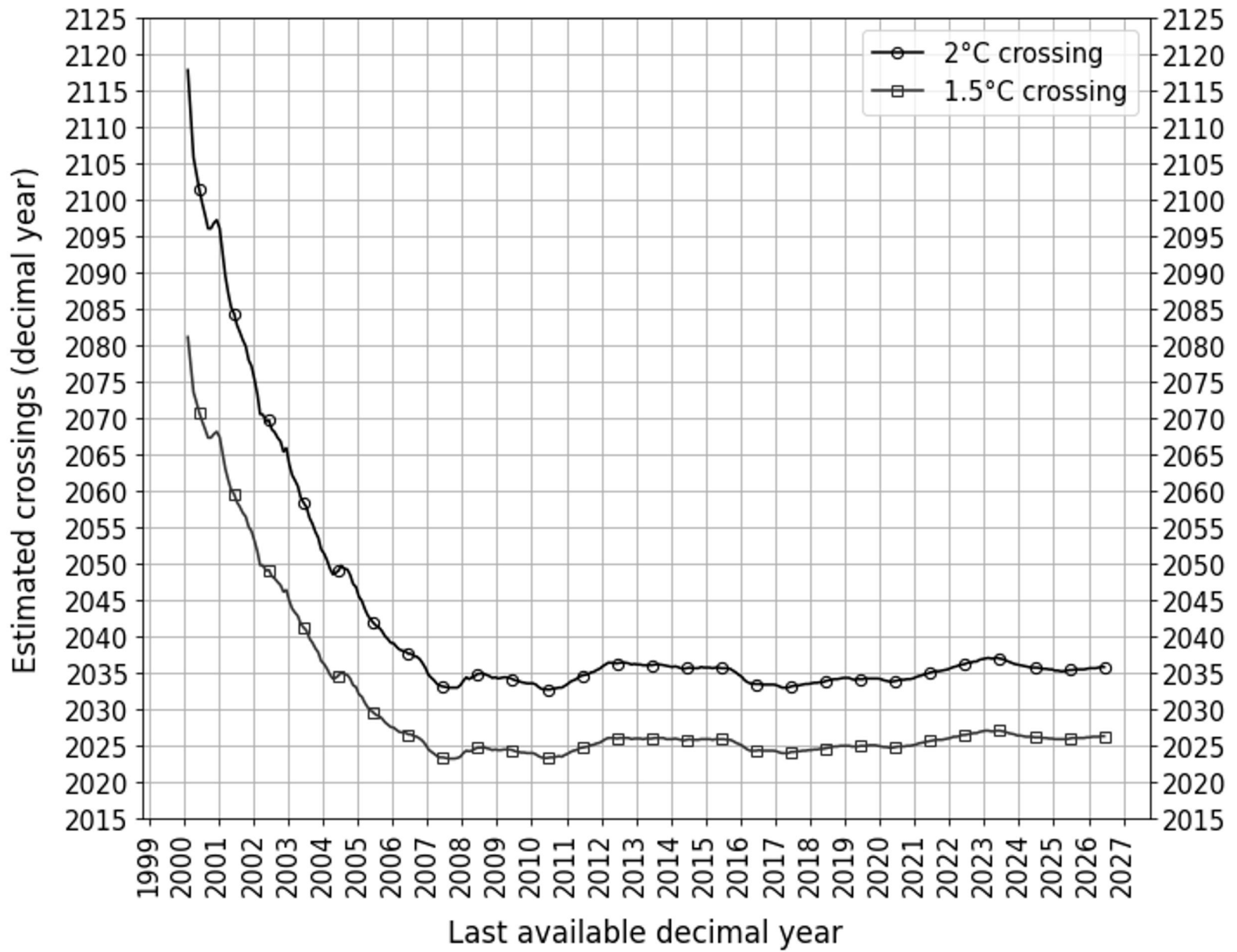


Fig 6a. Stability of 1.5°C and 2°C crossing dates as Met Office HadCRUT5 Infilled data is progressively truncated. Last 96 years are least-squares fitted with an exponential where

$$\text{Temperature (}^{\circ}\text{C)} = A + Be^{C(y - \bar{y})} \text{ where } y = \text{decimal year.}$$

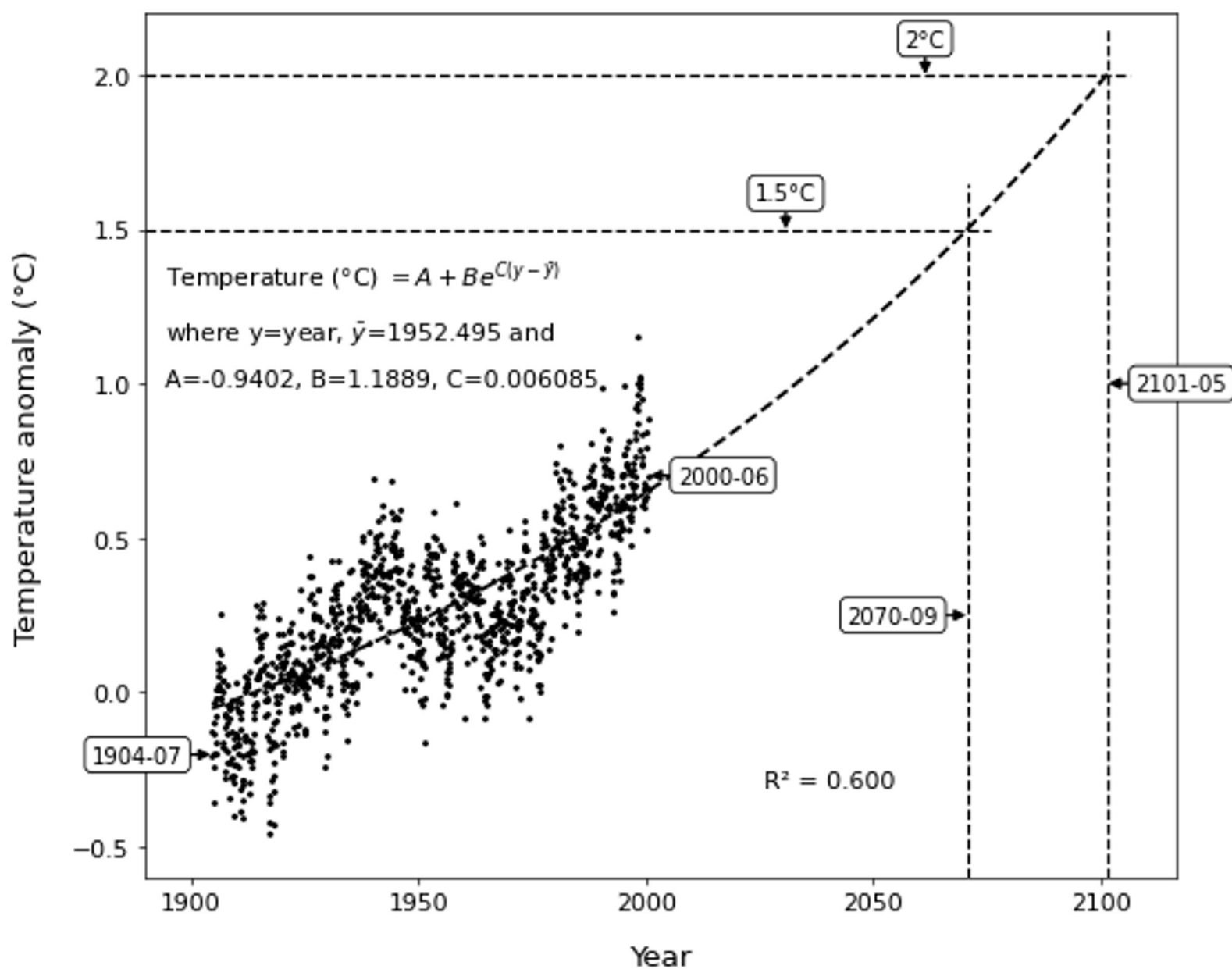


Fig 6b. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1904-07 to 2000-06 (96 years).

R^2 = Coefficient of determination using monthly data without any smoothing

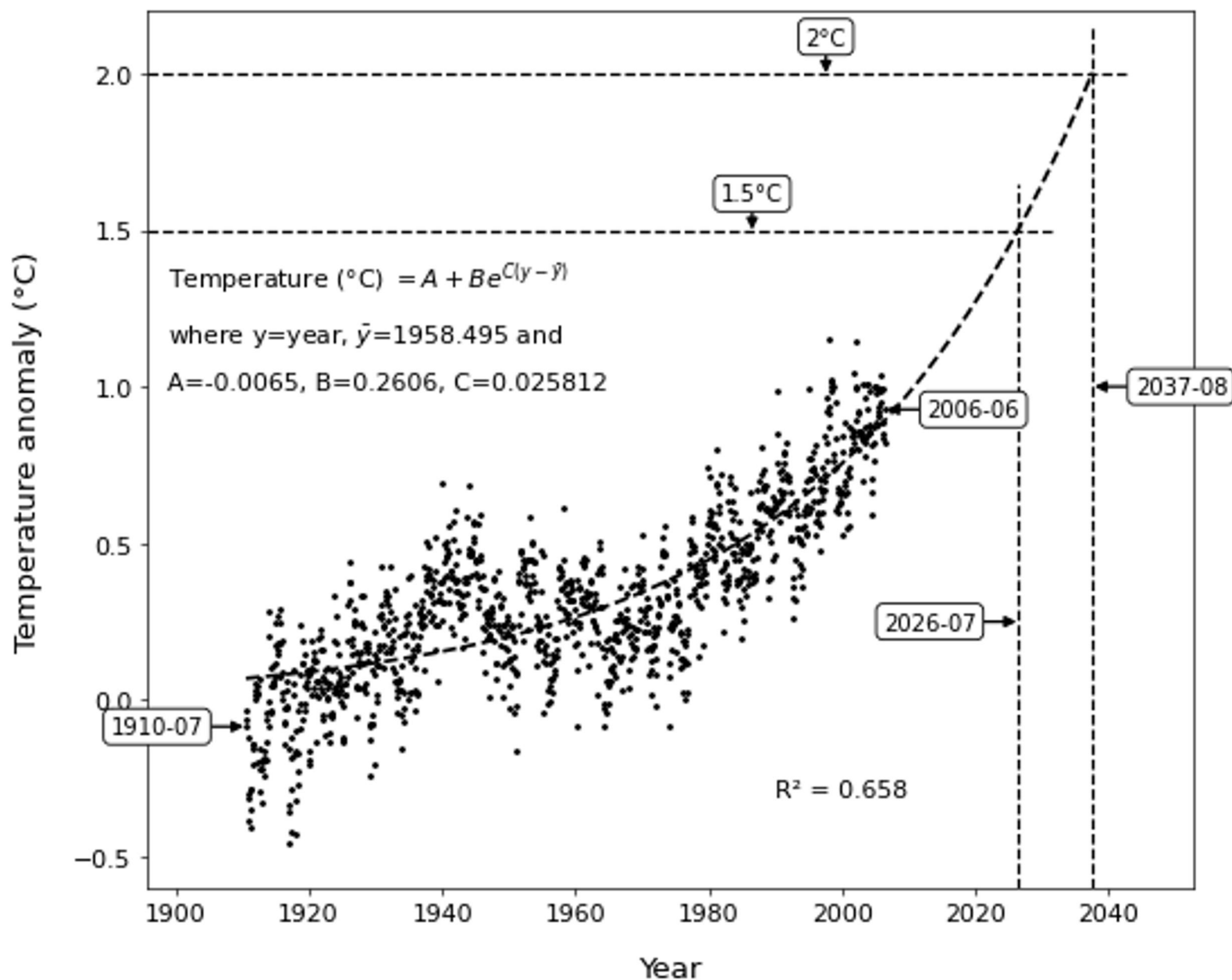


Fig 6c. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1910-07 to 2006-06 (96 years).

R^2 = Coefficient of determination using monthly data without any smoothing

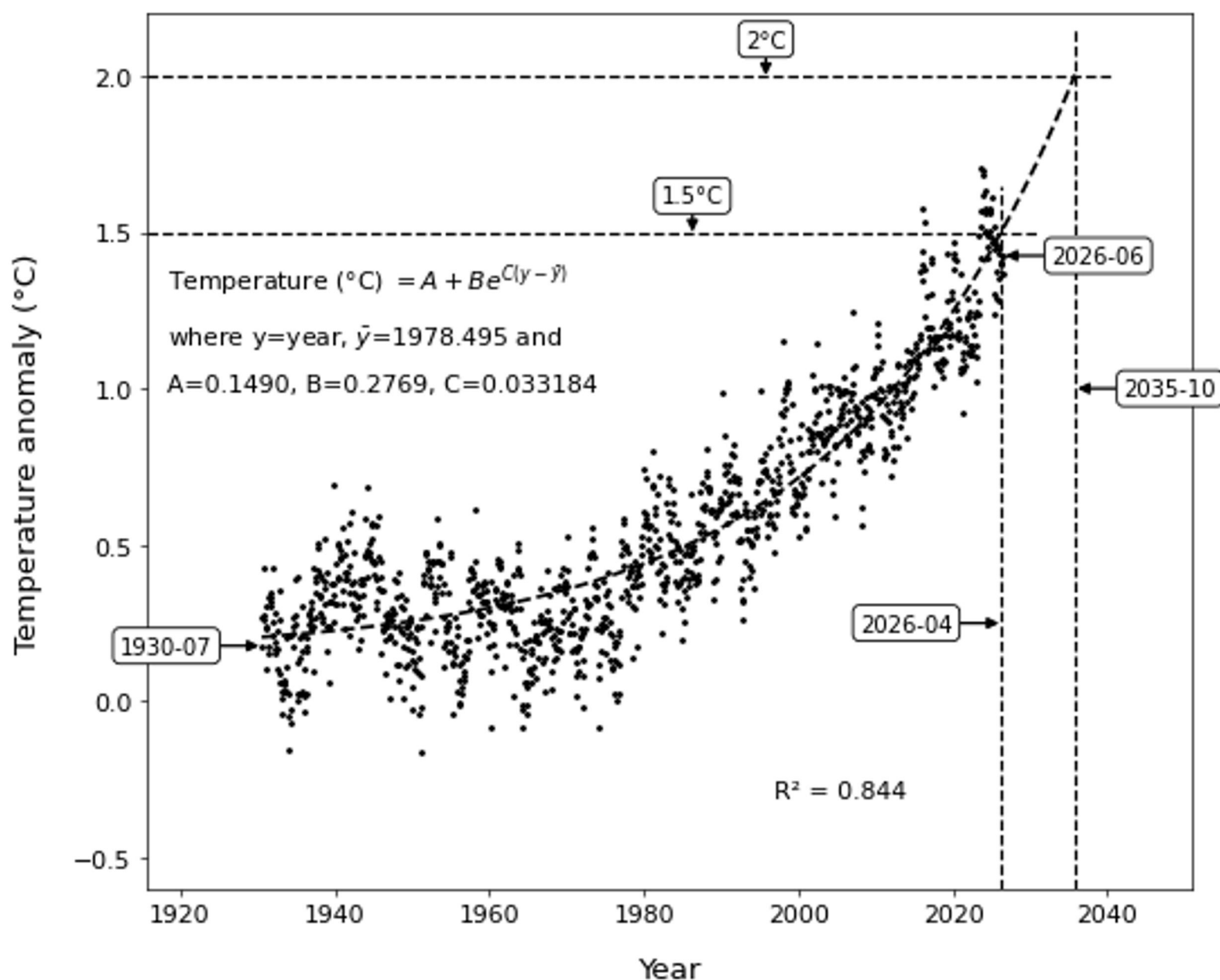


Fig 6d. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1930-07 to 2026-06 (96 years).

R^2 = Coefficient of determination using monthly data without any smoothing

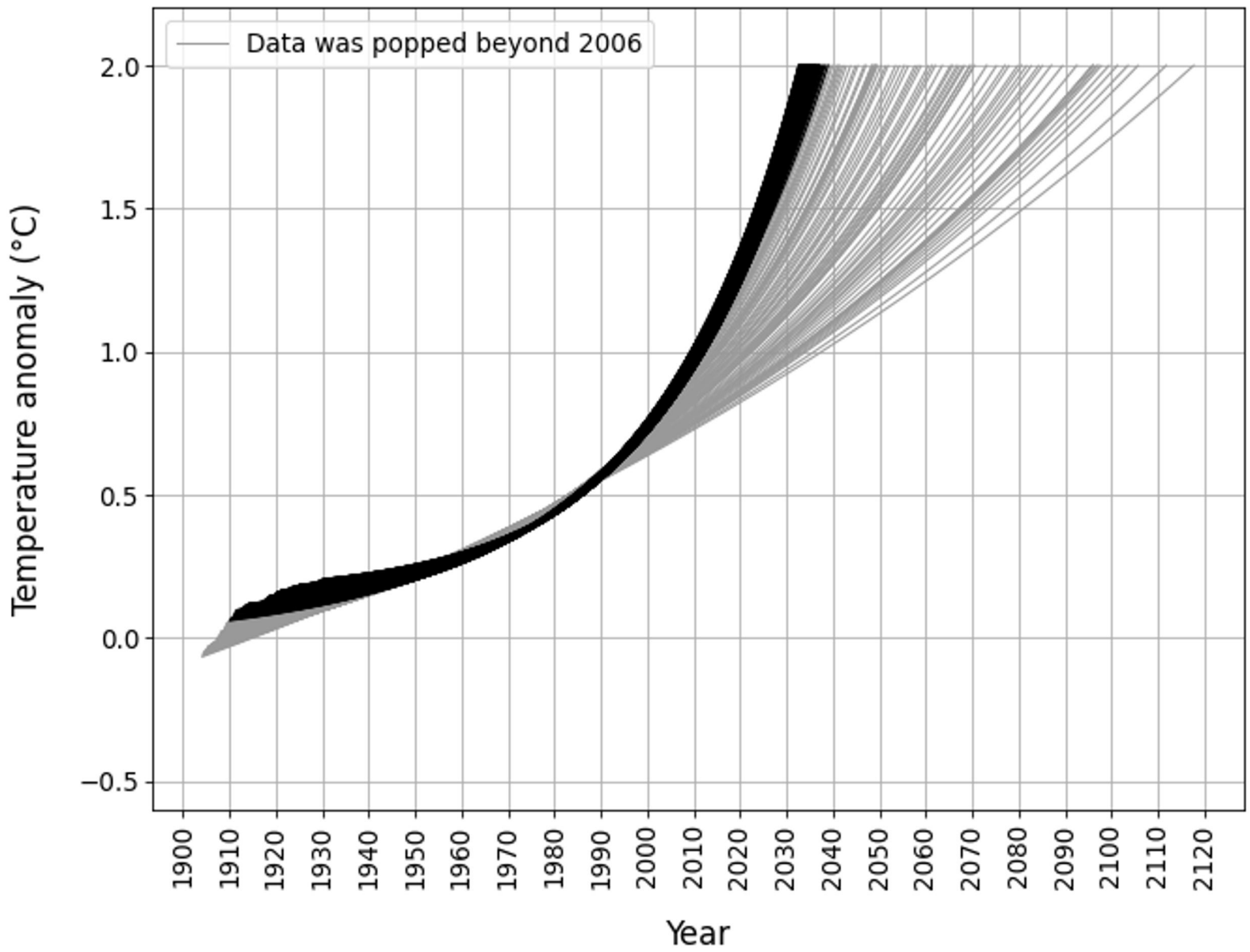


Fig 6e. Met Office HadCRUT5 Infilled fitted lines using an exponential from the last 96 years corresponding to a last available date of 2000-02 to 2026-06.