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

Author

David Joseph Hendy

Affiliation

Independent Researcher

Correspondence

orcid@jhendy.co.uk

ORCID

https://orcid.org/0000-0002-1441-7603

Conflict of Interest

None

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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

David Joseph Hendy[1]

[1] Independent Researcher | orcid@jhendy.co.uk | https://orcid.org/0000-0002-1441-7603

Abstract

Reliable estimates of when global mean temperature will exceed the Paris Agreement's 2°C threshold[1] are generally derived from emissions scenarios and climate models rather than from the observed temperature record itself. This study investigates whether the observed warming trajectory alone can provide a stable empirical estimate of the crossing date. Least-squares exponential, quadratic and linear curves were fitted to monthly global temperature anomalies from the HadCRUT5, NASA GISS v4 and NOAA v6.1 datasets over fitting spans ranging from 20 to 150 years for the HadCRUT5 and NOAA datasets and from 20 to 120 years for the NASA dataset. In total, 1,089 combinations of dataset, curve type and fitting span were evaluated. For each combination, predicted 1.5°C and 2°C crossing dates were recalculated as the fitted record was progressively truncated by one month at a time from 2026. Standard deviations of the 2°C crossing dates were then calculated after truncation had reached each final year between 2020 and 2000. Exponential fits using the HadCRUT5 dataset using fitting spans of approximately 148 and 96 years accounted for most of the lowest-standard-deviation solutions. Assuming (a) these fitted trajectories adequately represent the underlying warming trend, (b) the temperature datasets accurately reflect global mean temperature, and (c) recent warming behaviour continues, the analysis projects a 2°C crossing around 2041 for the longer span and 2035 for the shorter 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 methodologically contested. This means 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. 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), NOAAGlobalTemp 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]

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 produces a set of crossing-date estimates for that combination, and their standard deviation serves as a measure of stability: a smaller spread means a more stable, more reliable projection.

This entire process was repeated for 21 different starting end dates, ranging from 2000 to 2020. Because earlier end dates leave more room to shorten the data before running out, they generate more crossing-date estimates (up to 27, for the 2000 end date) than later end dates (as few as 7, for 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 available at Reference 11. Each combination was ranked by the standard deviation of its predicted 2°C crossing date, producing a ranked table for every one of the 21 end dates. Reference 12 shows the top 10 rankings for each of these 21 dates.

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 Reference 13. Actual datasets containing observed temperatures read by this code to generate these results can be downloaded from References 14, 15 and 16.

Observations

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. Figure 1e 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 1e. Together, they suggest that an exponential curve better approximates the true shape of the observed warming trend than a quadratic curve does, at least when the fit extends back to 1850. [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 is 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 1b, using a 148-year span) rather than excluding it (as in Fig 2b, 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 1e, 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 less constrained and can straighten out - this pushes the projected 2°C crossing later. But that same lack of constraint lets the 96-year curve fit more closely to the extreme temperatures of the 2020s.[10] This effect dominates: the 96-year span actually produces an earlier projected crossing, centered around 2035, compared to 2041 for the 148-year span, for end dates extending back to 2006.

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 119 years. The best long-span fits, approaching 150 years, come from the HadCRUT5 dataset assembled by the Met Office. This suggests that, over the period these long spans cover - extending back to before 1900 - an exponential function represents the trajectory of the HadCRUT5 temperature record more closely than either a quadratic or linear function.

Three conditions underlie the projections that follow: (a) the fitted curve accurately represents the true underlying trend in observed global temperatures, (b) the observed datasets faithfully reflect actual global temperatures, and (c) the physical drivers of warming continue behaving as they have over the past two decades. 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 play a decisive role in producing the later, 2041 estimate for spans approaching 150 years. Which of the two estimates proves more accurate will depend on which fitted curve better represents the actual temperature trajectory between now and whichever crossing date occurs.

Data Availability

This study uses fixed historical snapshots of the HadCRUT5, NASA GISTEMP v4, and NOAA GlobalTemp v6.1 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
- 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
- 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

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.

References

1. UNFCCC (2015). Paris Agreement. United Nations Treaty Series, Treaty No. A-54113. No DOI is assigned by the depositary; the authoritative text is held at the URL below. This is the founding policy instrument that defines the 1.5°C and 2°C thresholds being extrapolated toward in this manuscript, included separately from the scientific assessment literature because it is the legal text setting the targets rather than a scientific assessment of when they will be crossed. https://unfccc.int/process-and-meetings/the-paris-agreement
2. IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Read Chapter 4 (Future Global Climate: Scenario-Based Projections and Near-Term Information) to see the most authoritative assessment of how emissions-scenario-driven projections, rather than the observed temperature signal alone, are used to estimate future warming. https://doi.org/10.1017/9781009157896
3. Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J. and Taylor, K.E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937-1958. Read the Abstract to see how the complex Earth system models referenced in this manuscript's Introduction are coordinated and organised. https://doi.org/10.5194/gmd-9-1937-2016
4. Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C. et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153-168. Read the Abstract to see how the emissions scenarios referenced in this manuscript's Introduction are constructed and used to drive Earth system model projections. https://doi.org/10.1016/j.gloenvcha.2016.05.009
5. Morice, C.P., Kennedy, J.J., Rayner, N.A., Winn, J.P., Hogan, E., Killick, R.E., Dunn, R.J.H., Osborn, T.J., Jones, P.D. and Simpson, I.R. (2021). An updated assessment of near-surface temperature change from 1850: The HadCRUT5 data set. *Journal of Geophysical Research: Atmospheres*, 126(3), e2019JD032361. Read Figure 7 to see how HadCRUT5 compares by latitude band against NOAAGlobalTemp and GISTEMP, highlighting the differences between the three datasets used in this manuscript. https://doi.org/10.1029/2019JD032361
6. Noll, M. (2023). Exponential life-threatening rise of the global temperature. *EarthArXiv* preprint. Read Figure 3 to see this reputable independent work which similarly least squares fitted an exponential curve to observed global temperature anomalies, comparing it favourably against linear, quadratic and cubic fits, supporting the choice of curve-fitting approach used in this manuscript. https://doi.org/10.31223/x5t95v

7. Rath, S.S. et al. (2026). Evaluating the 1.5°C or 2°C climate thresholds: when could these thresholds be surpassed? *Environmental Research Letters*, 21, 094027. Read the Abstract to see this reputable work which tried 20-year and 30-year linear fits, a 55-year quadratic fit, and a LOESS-based sensitivity test on global temperature anomalies, and states that the quadratic method is preferred, supporting the approach in this manuscript of comparing different fitted span lengths across curve types. https://doi.org/10.1088/1748-9326/ae6461
8. Diffenbaugh, N.S. and Barnes, E.A. (2023). Data-driven predictions of the time remaining until critical global warming thresholds are reached. *Proceedings of the National Academy of Sciences*, 120(6), e2207183120. Read page 1 (Significance statement and Abstract) to see this independent machine-learning-based estimate of the 1.5°C and 2°C crossing dates, directly comparable to the crossing dates concluded in this manuscript. https://doi.org/10.1073/pnas.2207183120
9. Reschenhofer, E. (2025). The latest monthly highs suggest that the 1.5°C Paris Agreement threshold will probably be exceeded before 2028. *arXiv preprint*, arXiv:2503.12425. Read the Abstract and Figure 1 to see this independent statistical extrapolation of the HadCRUT5 monthly mean temperature record, which similarly brings forward the estimated 1.5°C crossing date, comparable to the shorter-span estimate concluded in this manuscript. https://doi.org/10.48550/arXiv.2503.12425
10. Goessling, H.F., Rackow, T. and Jung, T. (2025). Recent global temperature surge intensified by record-low planetary albedo. *Science*, 387(6729), 68-73. Read the Abstract to see this independent finding that record-low planetary albedo amplified the 2023/2024 temperature surge, supporting why the shorter fitted span gave more weight to those years and brought forward the crossing estimate discussed in this section. https://doi.org/10.1126/science.adq7280
11. Hendy, D. J. (2026). Least squares fitted global land sea temperature anomaly time series graphs. Zenodo. https://doi.org/10.5281/zenodo.20699641
12. Hendy, D. J. (2026). Standard deviations of 2°C crossing dates of fixed-span records for different last dates of the last record. Zenodo. https://doi.org/10.5281/zenodo.21130275
13. Hendy, D. J. (2026). Python code to least squares fit global land-ocean temperature anomalies. Zenodo. https://doi.org/10.5281/zenodo.21201587
14. HadCRUT5 analysis time series: ensemble means and uncertainties from 1850-01 to 2026-03 [Data set]. Met Office Hadley Centre. https://doi.org/10.5281/zenodo.20588286
15. NASA Goddard Institute for Space Studies (GISTEMP Team), Schmidt, G. A., Ruedy, R. A., Lenssen, N., Hendrickson, M., Jacobs, P., & Menne, M. (2026). NASA GISTEMP v4 - Global Mean Monthly Land-Ocean Temperature

Anomalies, 1880-01 to 2026-04 [Data set]. Goddard Institute for Space Studies. https://doi.org/10.5281/zenodo.20679028

16. NOAA National Centers for Environmental Information, Huang, B., Yin, X., Menne, M. J., & Vose, R. S. (2026). NOAA Global Land-Ocean Surface Temperature Time Series 90S.90N.v6.1.0.202605 from 1850-01 to 2026-05 [Data set]. NOAA National Centers for Environmental Information. https://doi.org/10.5281/zenodo.20682032

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

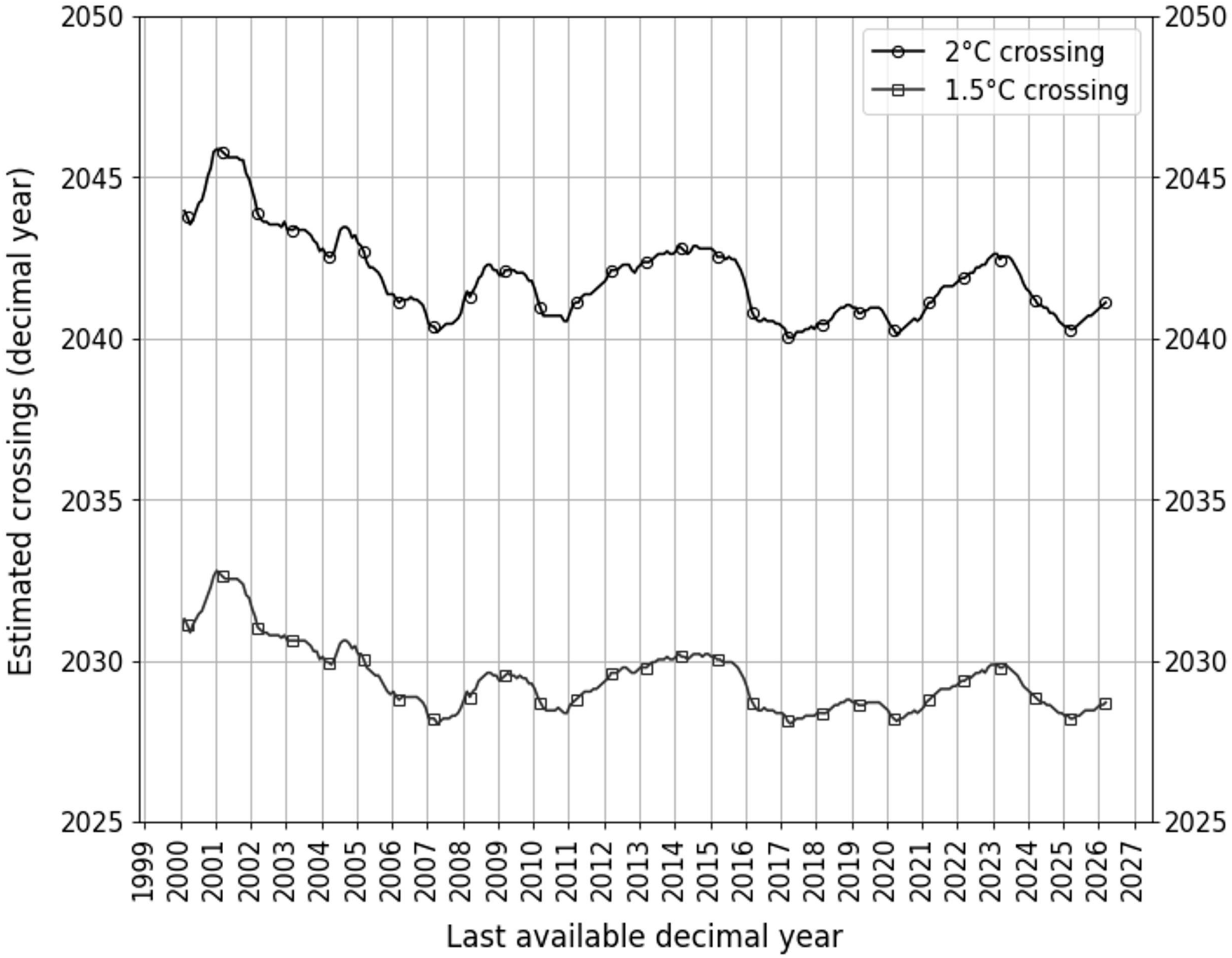

Fig 1a. Stability of 1.5°C and 2°C crossing dates
as Met Office HadCRUT5 Infilled data is progressively truncated.
Last 148 years are least-squares fitted with an exponential where
Temperature (°C) $= A + Be^{C(y-\bar{y})}$ where y = decimal year.

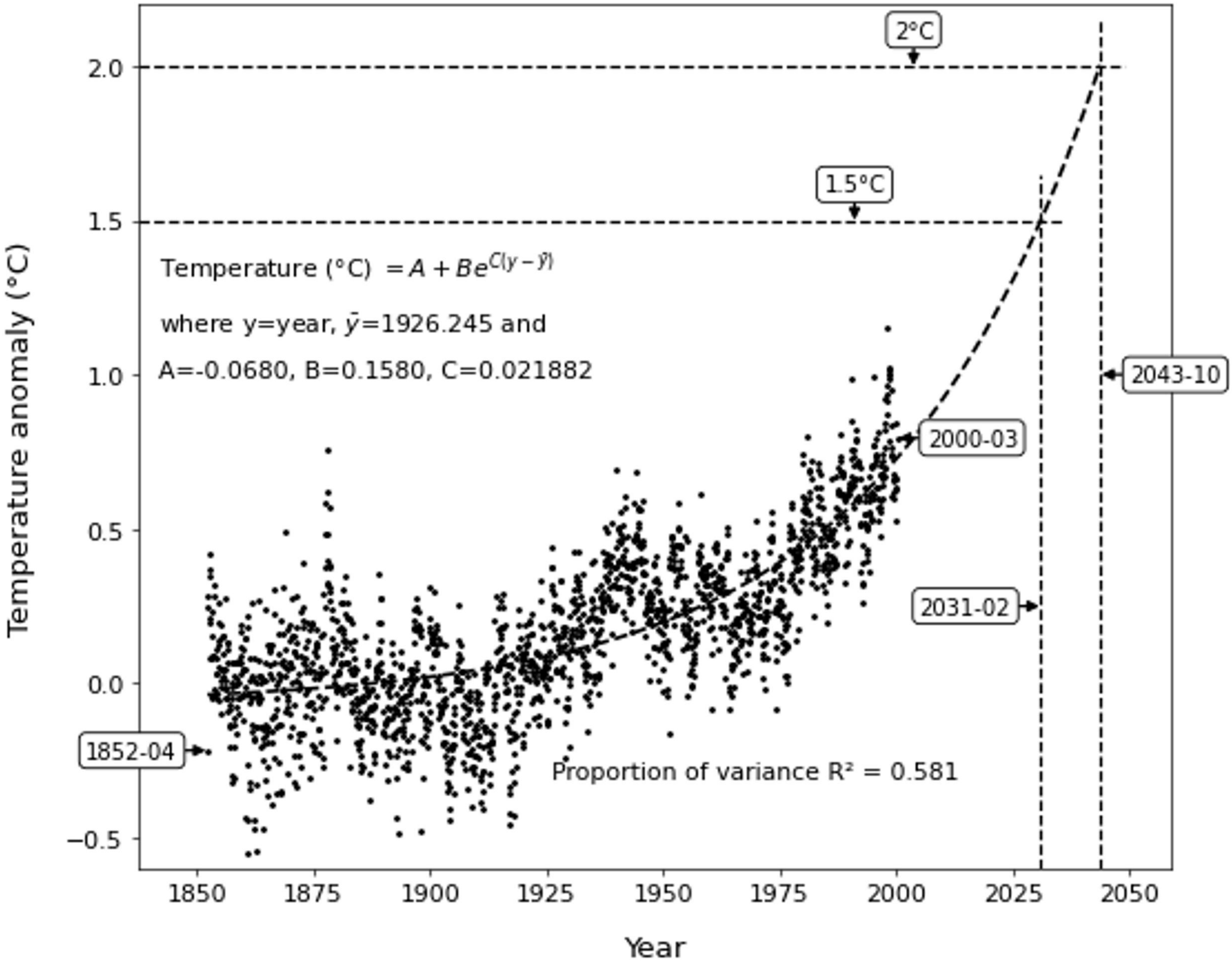

Fig 1b. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies
For Land and Sea relative to the 1850-01 to 1900-12 mean
extrapolated to 1.5°C and 2°C using a least squares exponential fit
from 1852-04 to 2000-03 (148 years)

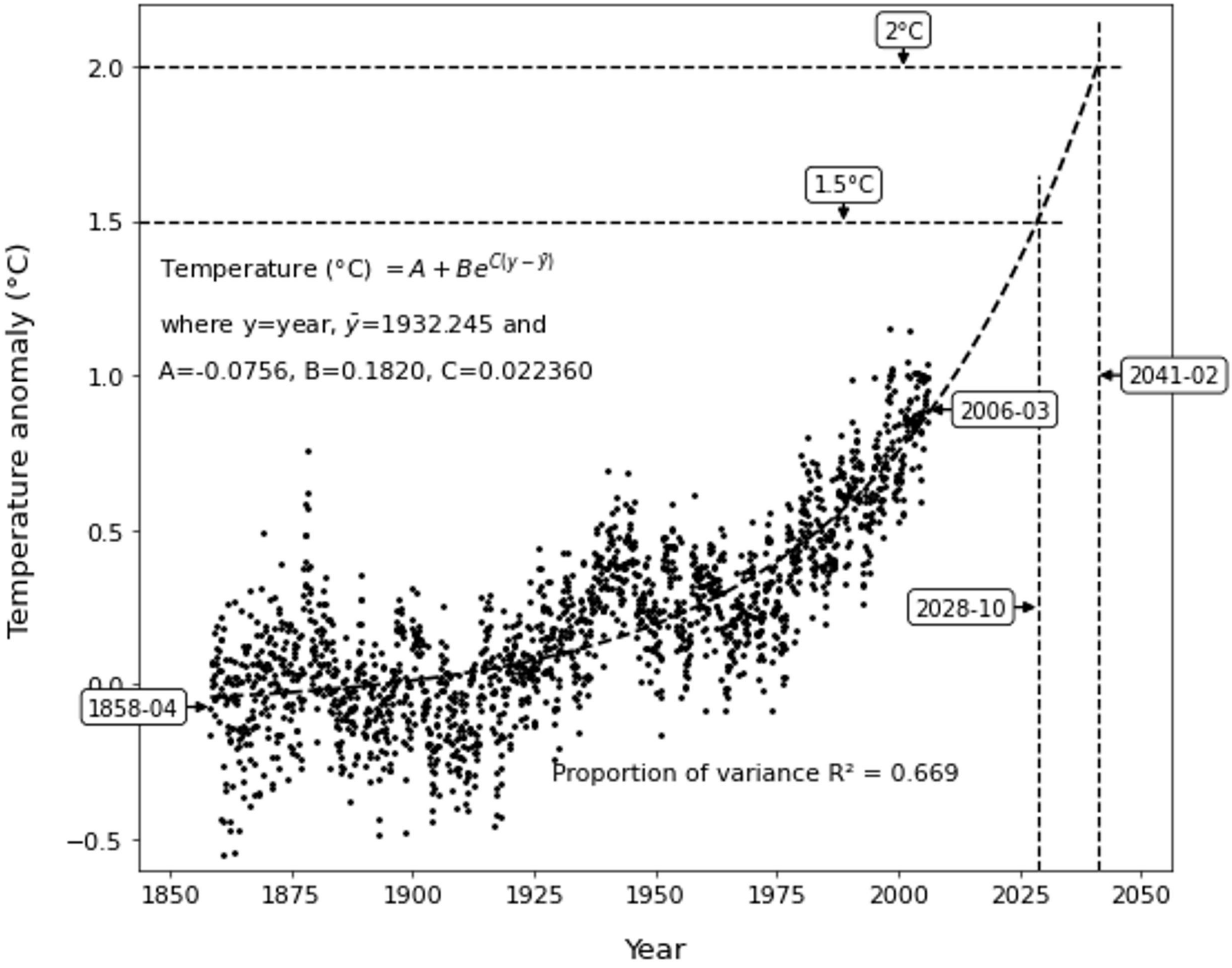

Fig 1c. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1858-04 to 2006-03 (148 years)

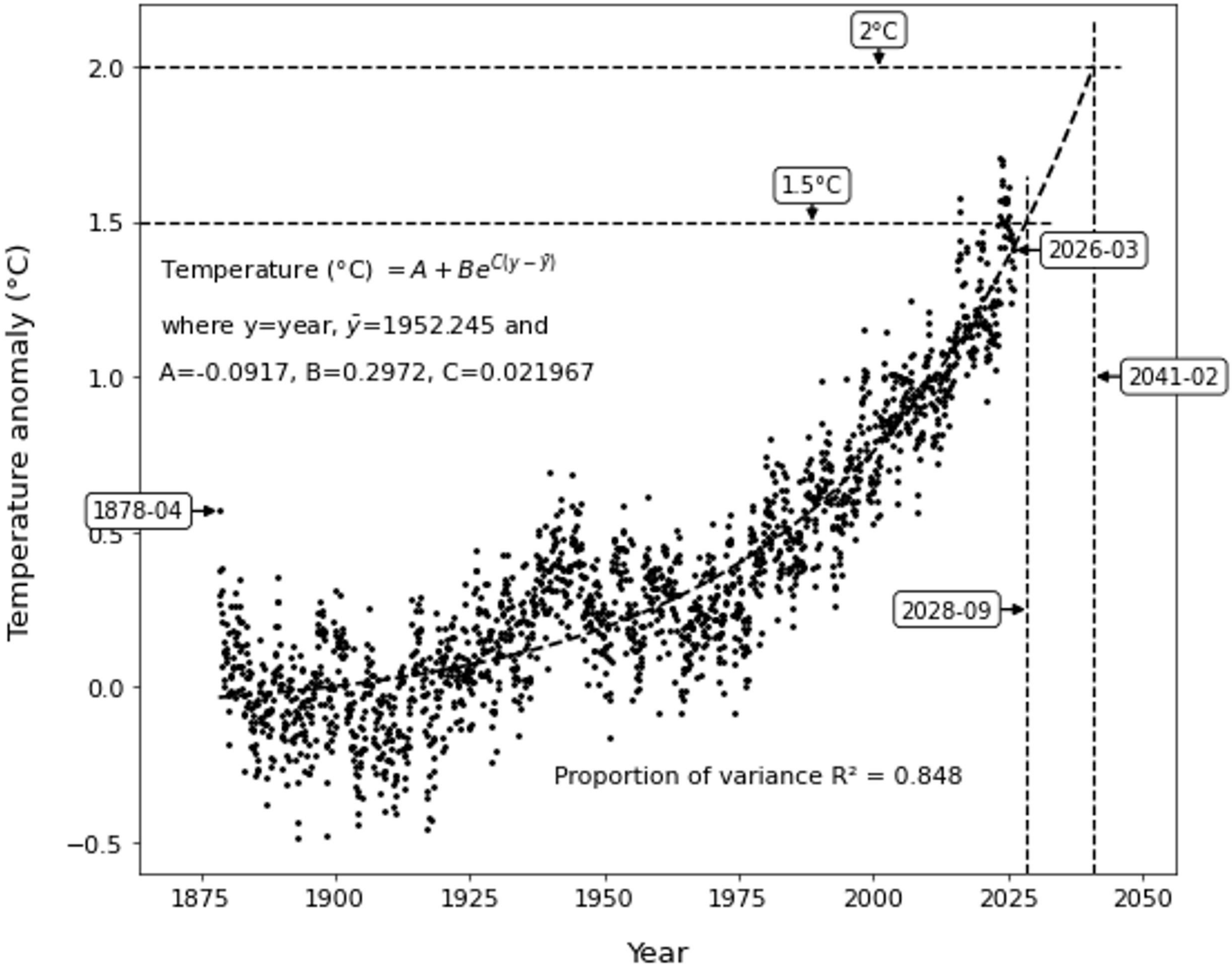

Fig 1d. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies
For Land and Sea relative to the 1850-01 to 1900-12 mean
extrapolated to 1.5°C and 2°C using a least squares exponential fit
from 1878-04 to 2026-03 (148 years)

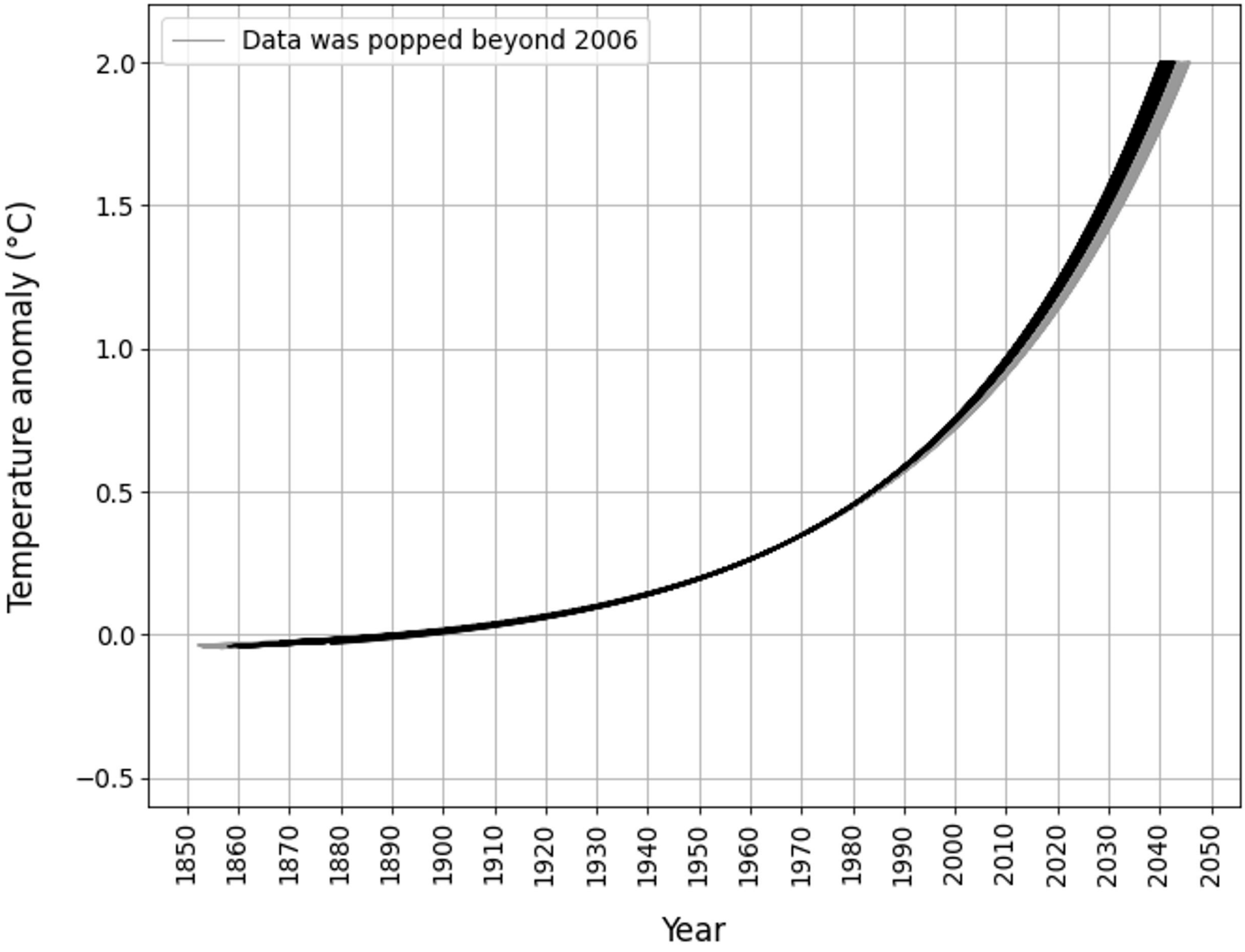

Fig 1e. Met Office HadCRUT5 Infilled fitted lines using an exponential from the last 148 years corresponding to a last available date of 2000-02 to 2026-03.

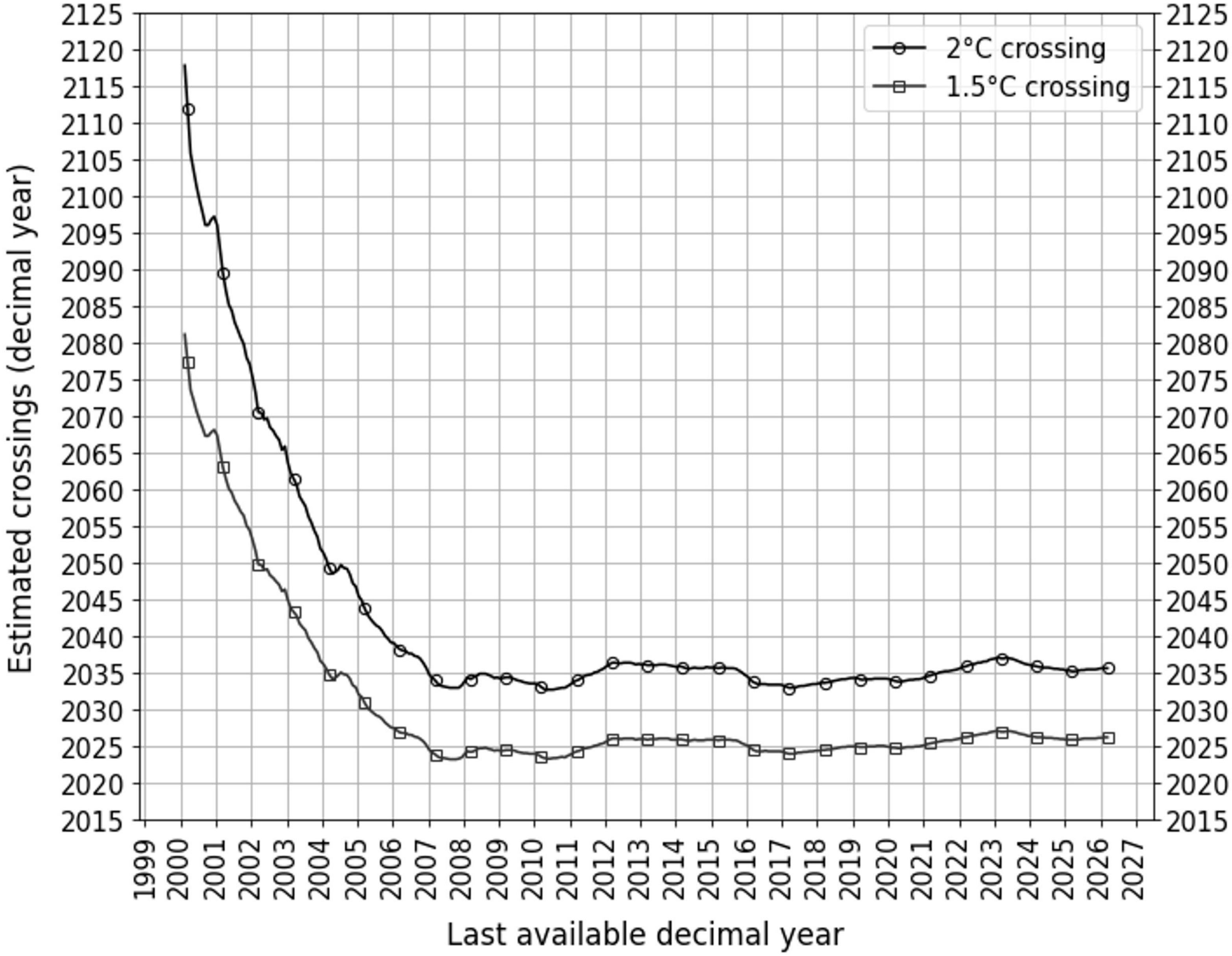

Fig 2a. Stability of 1.5°C and 2°C crossing dates

as Met Office HadCRUT5 Infilled data is progressively truncated.

Last 96 years are least-squares fitted with an exponential where

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

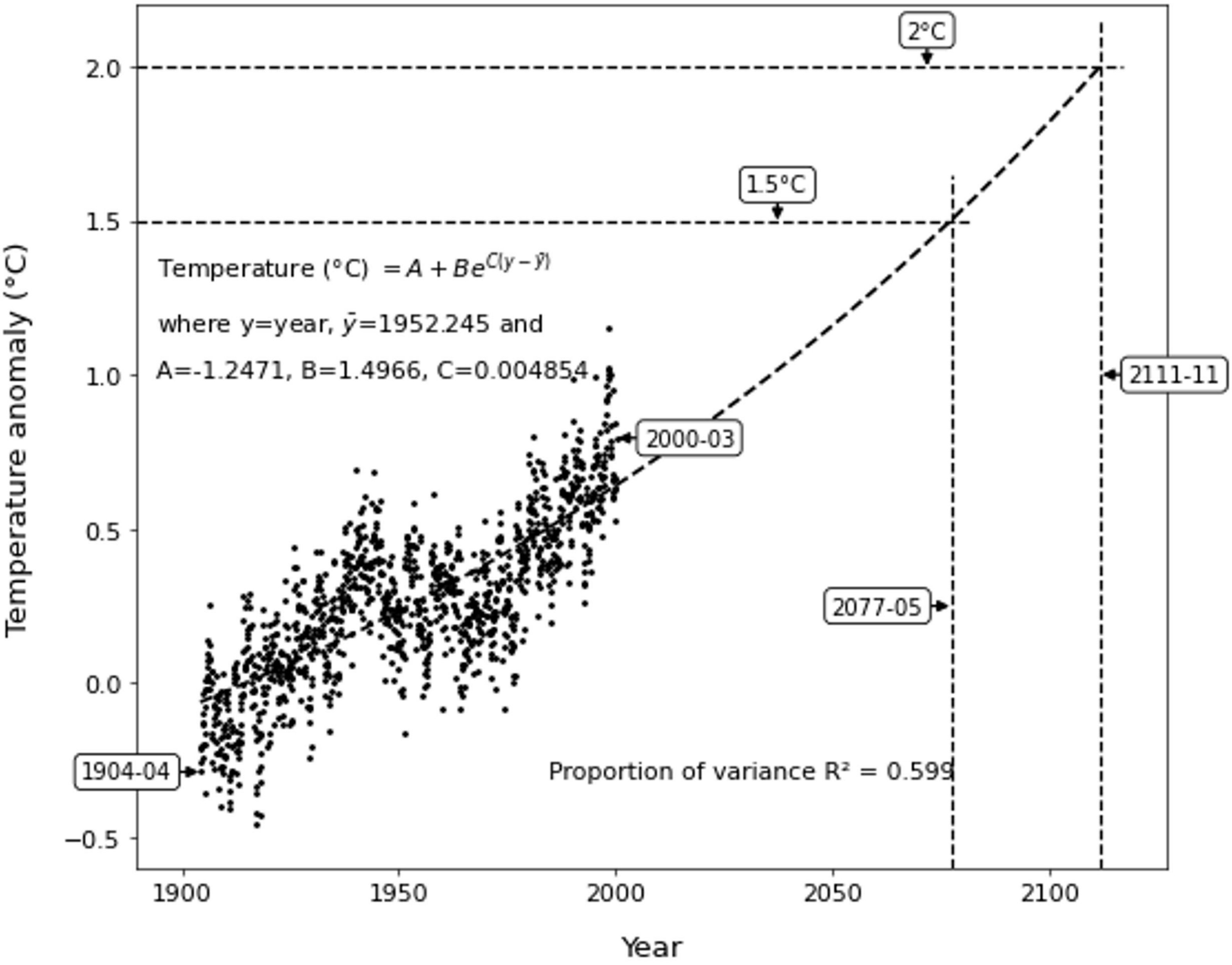

Fig 2b. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies
For Land and Sea relative to the 1850-01 to 1900-12 mean
extrapolated to 1.5°C and 2°C using a least squares exponential fit
from 1904-04 to 2000-03 (96 years)

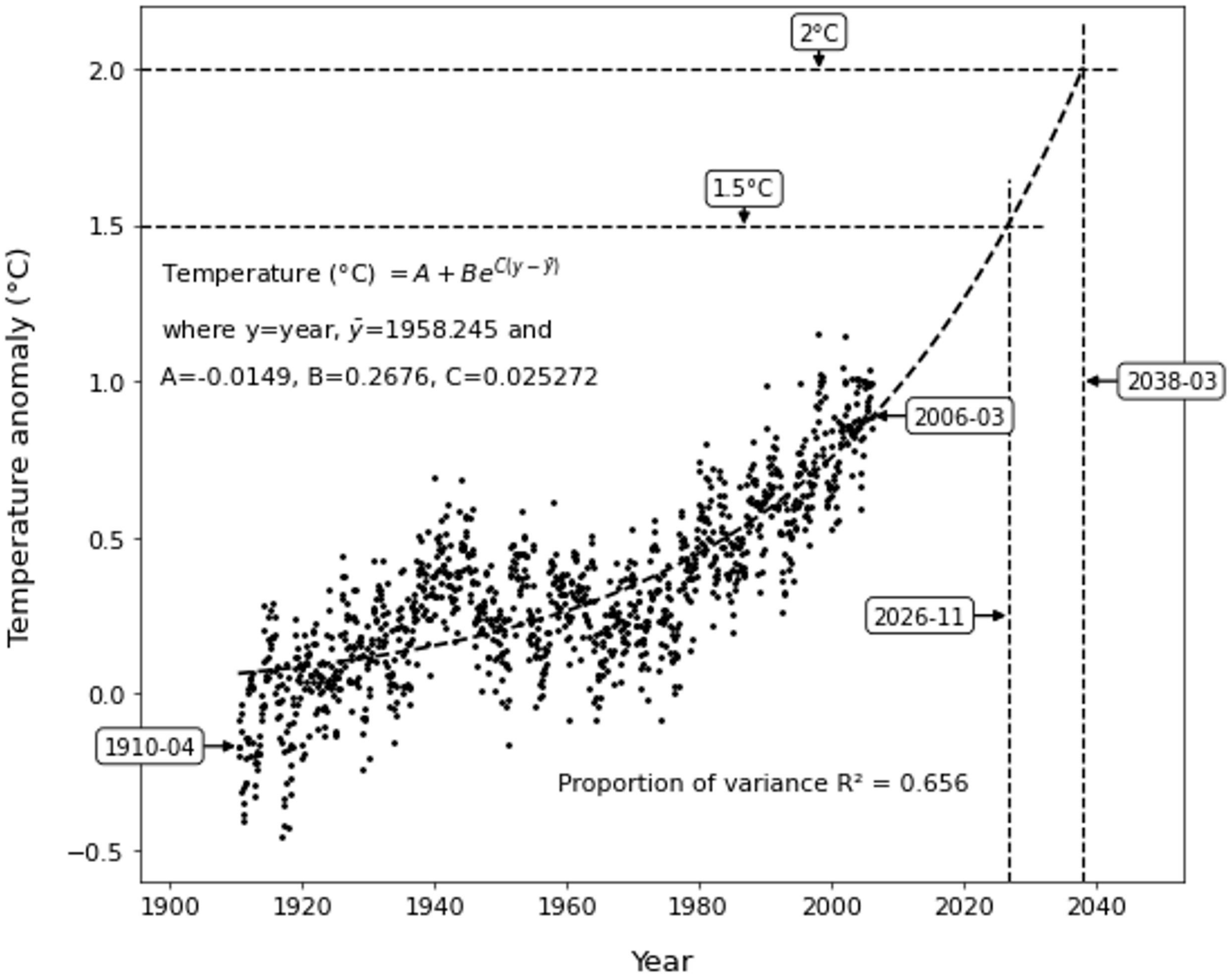

Fig 2c. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies For Land and Sea relative to the 1850-01 to 1900-12 mean extrapolated to 1.5°C and 2°C using a least squares exponential fit from 1910-04 to 2006-03 (96 years)

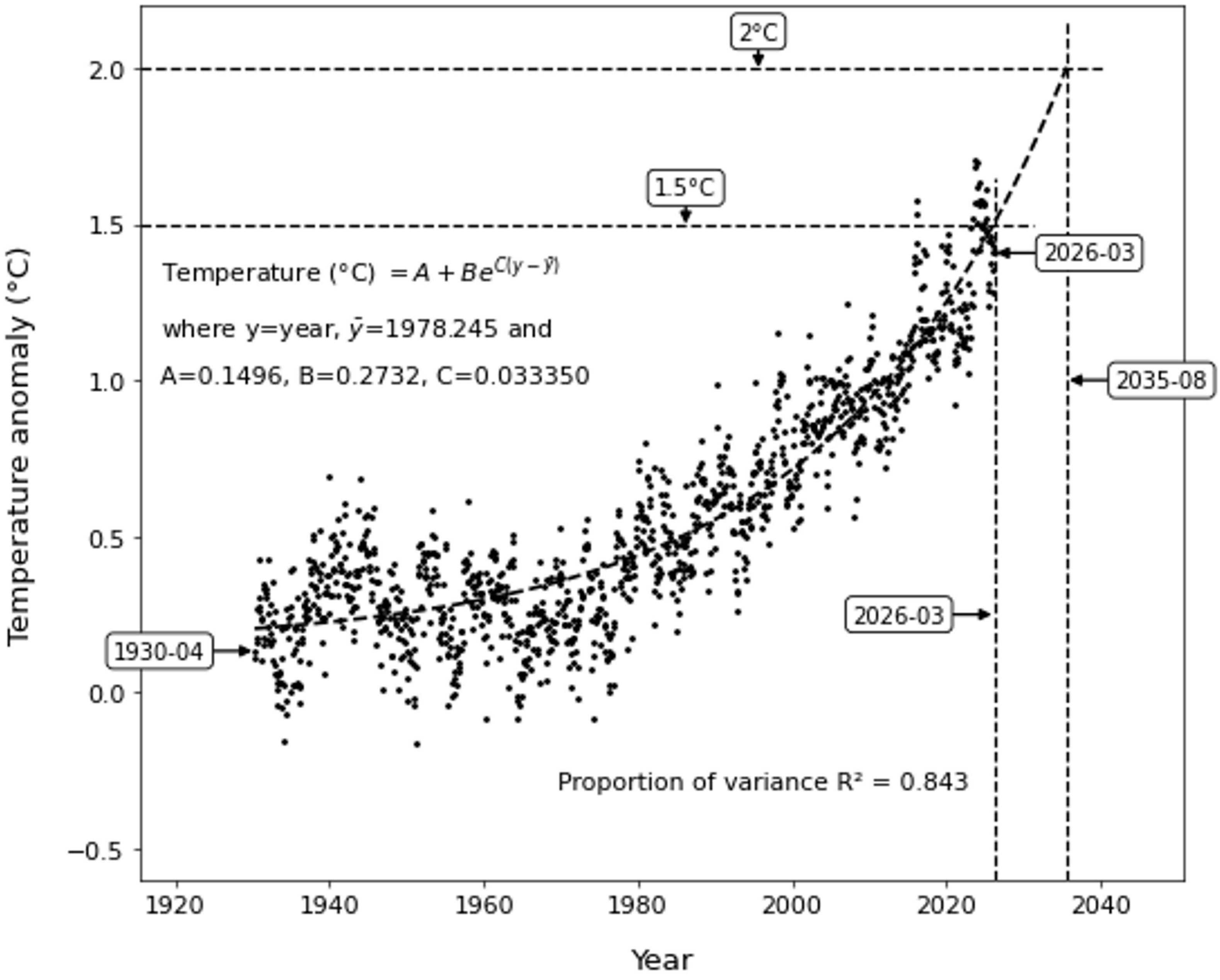

Fig 2d. Met Office HadCRUT5 Infilled Global Monthly Temperature Anomalies
For Land and Sea relative to the 1850-01 to 1900-12 mean
extrapolated to 1.5°C and 2°C using a least squares exponential fit
from 1930-04 to 2026-03 (96 years)

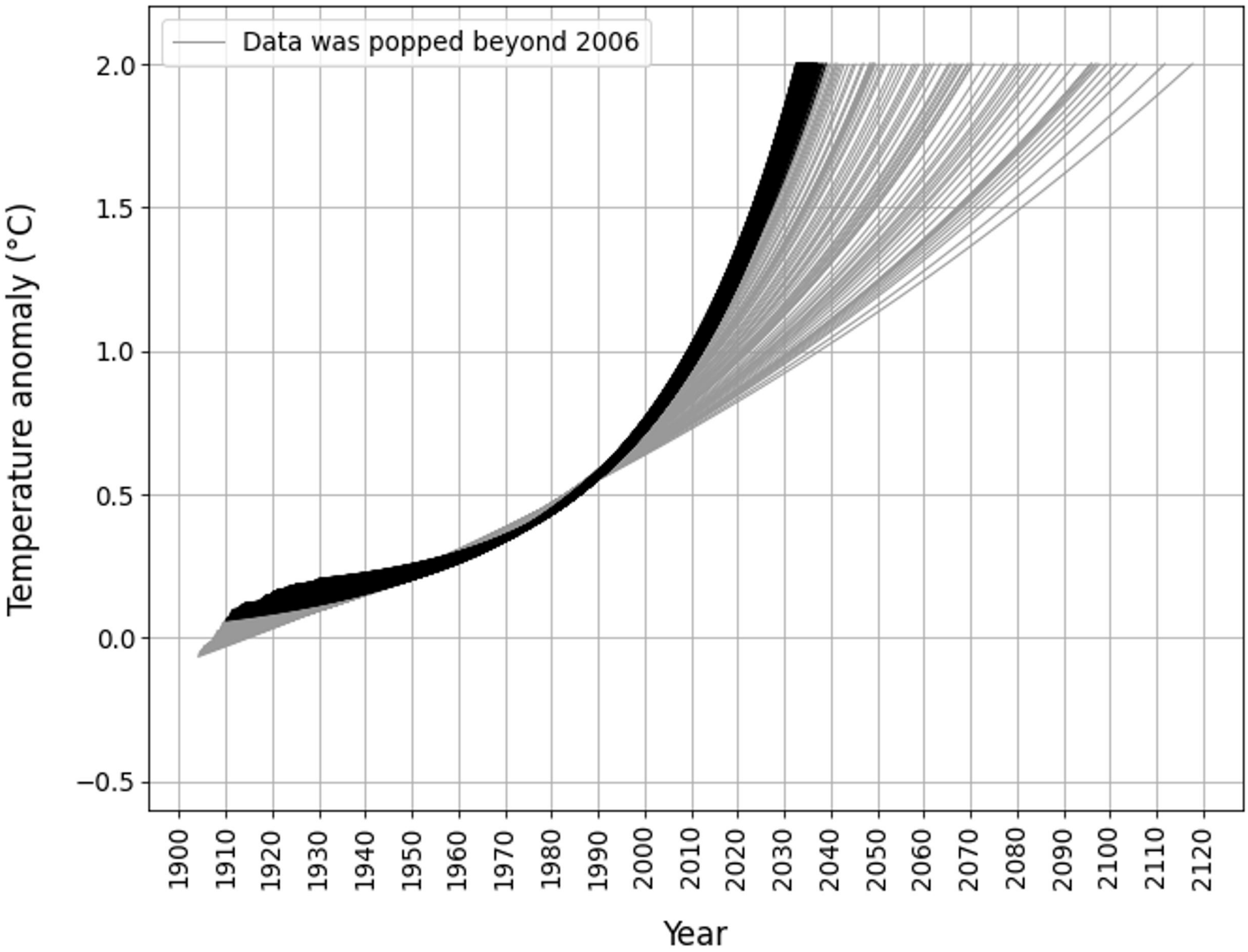

Fig 2e. Met Office HadCRUT5 Infilled fitted lines using an exponential from the last 96 years corresponding to a last available date of 2000-02 to 2026-03.