I thank referee-2 (RC2) for a thorough and thoughtful review of the manuscript. The report, together with RC1, has led to several significant changes to the analysis and produced a simpler model, which I describe first. All results below use this revised model, and all code and outputs are in the updated Zenodo package [https://doi.org/10.5281/zenodo.24016461]. Based on the reviews received, a revised manuscript has been prepared that is simpler, shorter, clearer, and more methodologically sound. The main conclusions have not qualitatively changed: a non-linear response of GSAT to anthropogenic ERF emerged in the observational record, from 1980–2025 GSAT is a non-linear function of anthropogenic ERF, and the simple partitioned ARDL model (P-ARDL) with observed ENSO performs better than FaIR over the observation period. The revised manuscript will be provided, if requested. The revised abstract follows:

"A time series of global surface air temperature anomalies (GSAT) and effective radiative forcing (ERF) was obtained from the IPCC Sixth Assessment Report (AR6) and its updates. $GSAT_{t-1}$, ERF, and the Relative Oceanic Niño Index (RONI) were used as independent variables in an autoregressive distributed lag (ARDL) model of GSAT. ERF was partitioned into anthropogenic ERF (AN) and solar/volcanic ERF (NAT) to account for sudden ERF reductions associated with large volcanic eruptions. The partitioned ARDL model (P-ARDL) was used to determine if a non-linear response of GSAT to AN emerged for start years 1951–1986 and for the primary analysis of the GSAT–AN relationship over 1980–2025. The AN exponent was ~1 ($\nu = 0.93$–1.07) for start years 1951–1968, increased for start years 1969–1978, and was >1 for start years 1979–1986 ($\nu = 1.54$–1.83). A linear response ($\nu = 1$) to anthropogenic ERF through 2025 was rejected for every start year from 1979 to 1986; a quadratic relationship could not be excluded. The P-ARDL model for 1980–2025 yields $GSAT_t = 0.27 + 0.28\ GSAT_{t-1} + 0.11\ AN_{t-1}^{1.75} + 0.19\ NAT_t + 0.12\ RONI_t$ ($R^2 = 0.968$). A linear response of GSAT to AN was rejected ($p = 0.004$). Based on this model, if ERF continues to rise by 0.7 W m^{-2} decade^{-1} and reaches 5.15 W m^{-2} in 2050, conditional on NAT at its 2015–2024 mean and RONI = 0, GSAT will likely be 2.9 °C (2.5–3.2 °C) by mid-century, against 2.4 °C (2.14–2.76 °C) for the calibrated constant-feedback Finite-amplitude Impulse Response (FaIR) climate model, 2.3 °C (1.86–2.89 °C) for the AR6 assessment and 2.2 °C (2.08–2.28 °C) for a linear response model. This analysis of AR6 data shows that the rate of increase in AN accelerated during the 1960s and 1970s, and a non-linear GSAT response to AN emerged in the late 1970s. Observations over the next 5–10 years are needed to determine if the 1980–2025 P-ARDL model can be prospectively validated and used as a simple observation-driven climate model for predicting future GSAT in a warming climate."

The revised model:

In the revised manuscript the model on which the conclusions rest is the partitioned model introduced in my reply to RC1 (AC1), with three changes: RONI replaces ONI (point 7), the exponent ν is estimated jointly with the other coefficients in a single step rather than fixed from the univariate analysis, and the primary analysis starts in 1980 (point 1). The model is

$$GSAT_t = a + \rho\ GSAT_{t-1} + \beta\ AN_{t-1}^{\nu} + \eta\ NAT_t + \delta\ RONI_t + \varepsilon_t,$$

where AN is anthropogenic and NAT natural (solar and volcanic) ERF. ρ represents thermal inertia, β and ν the response to anthropogenic forcing, η the response to natural forcing and δ the ENSO effect. The model follows the econometric treatment of energy-balance models of Pretis (2020), with anthropogenic ERF entering as a power law; ν = 1 recovers the linear case. The advantages of this approach are:

1) it is simpler,
2) it uses all 46 years of data from 1980 to 2025,
3) the uncertainty in ν carries through to every derived quantity, including the 2050 projection. In the original two-step approach, ν was treated as known once it had been fixed by the univariate analysis.
4) the residuals are uncorrelated (lag-1 autocorrelation −0.04), so the standard errors and the F-test are valid without corrections for autocorrelation.
5) the linear model is a special case (ν = 1), so the comparison of linear and non-linear forms is a direct test of nested hypotheses within a single model.
6) ν is estimated together with thermal inertia, natural forcing and ENSO. The univariate analysis left these out. Fitted to GSAT and AN alone (excluding $GSAT_{t-1}$, NAT and RONI) over 1980–2025 it gives ν = 1.49 (95 % CI 0.81–2.17), and its residual SD of 0.10 °C includes the variability from thermal inertia, natural forcing and ENSO.
7) natural forcing, including volcanic eruptions, enters linearly. The eruption years are therefore kept, and the power law is not driven by them.
8) the power law is applied only to anthropogenic ERF, which is positive throughout 1980–2025, so it is defined in every year without shifting the baseline.
9) the result does not depend on the order of estimation, so the question of fitting the power law first and then the dynamic model no longer arises.
10) the model only needs four inputs (the previous year's GSAT, RONI, and anthropogenic and natural ERF), so anyone with access to the AR6 data as updated can reproduce it.

Estimated by non-linear least squares over 1980–2025 (n = 46), a = 0.274 (SE 0.051), ρ = 0.277 (0.082), β = 0.111 (0.038), ν = 1.745 (0.251), η = 0.188 (0.028) and δ = 0.121 (0.014) °C per unit RONI. The residual SD is 0.056 °C, the residuals are uncorrelated (lag-1 autocorrelation −0.04), and a straight line (ν = 1) is rejected at $F(1, 40) = 9.54$, $p = 0.004$ (HC1 $p = 0.016$, HC3 $p = 0.031$).

For the 2050 projection, total ERF rises linearly to 5.15 W m^{-2} in 2050, natural ERF is held at its 2015–2024 mean and RONI is set to zero. Uncertainty is estimated by a moving-block bootstrap that resamples years in 3-year blocks and re-estimates all six coefficients in each of 1,000 replicates. The projected GSAT is 2.88 °C, with a 66 % range of 2.50–3.20 °C. A straight line gives 2.19 °C, the FaIR ensemble median is 2.43 °C and the AR6 assessed best estimate is 2.32 °C.

Specific comments:

1. Convincing-ness of the model

The referee's equilibrium argument takes the limit ERF → 0 of the long-run relationship derived from a two-compartment energy-balance model. The revised manuscript removes that derivation. The model is not a model of climate equilibrium and is not used at zero forcing. It attributes year-to-year changes in GSAT over 1980–2025 to thermal inertia, ENSO and ERF partitioned into its anthropogenic and natural components, and it is fitted and interpreted only over the sampled forcing range (previous-year anthropogenic ERF from 0.66 to 2.98 W m^{-2}). Natural ERF, including negative volcanic forcing, enters linearly, so negative forcing is accommodated, and anthropogenic ERF is positive throughout the record. The projections extend 25 years, to 2050. The model makes no claim about mechanism. It shows that over the last 46 years the relationship between GSAT and anthropogenic ERF is better described as non-linear than linear, and that projections to mid-century under this relationship are higher than current estimates, as other lines of evidence also suggest (point 6). With observed RONI, the model reproduces the 1980–2025 record more closely than FaIR (free-run RMSE 0.053 against 0.095 °C for the FaIR median, and more accurate than every one of the 841 FaIR members), and it can be evaluated from four inputs: the previous year's GSAT, RONI, and anthropogenic and natural ERF.

ERF is defined relative to 1750 by convention (Forster et al., 2021, 2026), and the hypothesis concerns the response to the level of forcing since pre-industrial conditions, so the 1750 reference is part of the hypothesis. To test the referee's concern directly, I re-estimated the model with the AN zero point moved to the 1850–1900 mean, 1950 and 1979, keeping every year. The exponent falls (ν = 1.745, 1.68, 1.58 and 1.42) but its standard error falls in proportion, and the evidence against a straight line is unchanged ($p = 0.004$ in every case). The 2050 projection changes from 2.88 to 2.71 °C. The 1979 zero point is the counterpart for the revised sample of the referee's 1977 zero point: it is the year before the sample begins, so the re-zeroed AN_{t-1} is zero in 1980 and positive thereafter, and no year is lost. In the partitioned model, natural ERF is unaffected by the AN zero point.

On the start year, the referee is correct that comparing BIC across samples of different length is not valid. The revised manuscript starts the primary analysis in 1980 on four grounds, none of which uses the GSAT record: the rate of increase in AN changed rapidly over 1950–1979 (its second derivative peaked in 1974); 1980 is the first full year of the satellite era; aerosol ERF became more negative by 0.25 W m^{-2} per decade over 1950–1979 and changed by less than 0.1 W m^{-2} per decade after 1980, when global sulfur dioxide emissions had passed their peak (Smith et al., 2011); and the 46 years provide about eight observations for each estimated parameter. The model was then fitted for every start year from 1951 to 1986, each ending in 2025. ν lies between 0.93 and 1.07 for start years 1951–1968, rises from 1.12 for 1969 to 1.29 for 1976, and lies between 1.54 and 1.83 for every start year from 1979 to 1986, for each of which the straight line is rejected ($p = 0.004$–0.050). 1980 does not give the largest exponent (1983 and 1986 give 1.83 and 1.81). The p-value for the 1980 start does not require adjustment for multiple testing. The start year is set by the four grounds above, which do not use the GSAT record, and the main result is a single test of $\nu = 1$ for that start. The other start years are a robustness check of that result, not a search from which the start year was selected. As a check, I simulated 5,000 straight-line climates ($\nu = 1$) from the linear model fitted over 1951–2025, with the observed forcing and RONI and resampled residuals, and applied the same procedure to each. A rise

in ν across start years as large as observed (0.024 per start year) occurred with probability 0.006 when residuals were resampled individually and 0.008 when they were resampled in 3-year blocks. Even if the 1980 start were treated as selected for the smallest p among all 36 start years, the selection-corrected p-value would be 0.037 and 0.045 respectively. Across start years 1979–1986 the 2050 projection at 5.15 W m^{-2} lies between 2.70 and 2.97 °C. A linear response is therefore rejected for the 1980 start ($p = 0.004$), for every start year from 1979 to 1986, and after allowing for selection across all 36 start years. The manuscript describes the non-linearity as emerging because ν rises from about 1 for start years before 1969 to 1.54–1.83 for every start year from 1979, and it presents the 2050 values as conditional projections to be validated against observations over the next 5–10 years.

2. Use of a short response time for projection to 2050

As stated in AC1, the projections extend only to 2050 and are conditional on the ERF pathway, and they require validation against observations over the next 5–10 years. The deep-ocean temperature is not held constant in a physical sense. Over this period its effect on GSAT is small and is absorbed in the estimated coefficients. The revised manuscript states that whether the dependence on the forcing level survives when the deep-ocean temperature is allowed to evolve is the most important open question, and that testing it requires the full two-equation system.

3. The expanding-window validation and the power law

I agree. The year-at-a-time validation mainly tests the persistence and ENSO terms, not the power law, and it is removed from the revised manuscript together with the jackknife. Because ν is now estimated jointly, the evidence for curvature comes from the test of $\nu = 1$ within the model and from the block bootstrap (point 5), which allows for autocorrelation. A leave-one-out check is retained only for influential observations ($\nu = 1.58–1.95$, $p \leq 0.036$). As the referee notes, the decisive test of the 2050 projections is out of sample, and the manuscript states that they should be compared with observations over the next 5–10 years.

4. A power law in GSAT against ERF is not unique to this model

FaIR's own output, plotted against its total ERF input over 1980–2025, gives $\nu = 1.71$ (5–95 % across members 1.61–1.81) for the 841-member calibrated ensemble. FaIR has constant feedback and represents the time-dependent response through its multi-layer ocean, deep-ocean efficacy and the shape of the forcing history. When the P-ARDL is fitted to FaIR's GSAT with the same specification and start year, that slow response is carried by $\rho = 0.90$ (0.85–0.93) and $\nu = 1.11$ (0.94–1.29). For the observations $\rho = 0.28$ and $\nu = 1.75$, above the 95th percentile of FaIR's exponent. The two models therefore place the non-linearity differently, and the observations show more curvature than FaIR once persistence, natural forcing and ENSO are modelled. The referee's CMIP5 1pctCO_2 analysis likewise shows $\nu > 1$ in many AOGCMs under a near-linear forcing ramp. The out-of-sample record will show which model performs best.

5. Autocorrelation and error in ERF

Because ν is now estimated within the dynamic model, whose residuals are uncorrelated, its standard error does not carry the autocorrelation of the static fit. As a check, the 3-year moving-block bootstrap gives a 95 % range of ν of 1.03–2.35 and $P(\nu \leq 1) = 0.025$, in agreement with the F-test.

The referee is also correct that the SIMEX correction in the original manuscript assumed independent errors in ERF. Its result depends on assumptions about the structure of the error that the data cannot determine, and it is removed from the revised manuscript. Uncertainty in ERF is instead addressed with the 5th and 95th percentile histories, as in the referee's own analysis.

I have repeated the referee's test using the 5th and 95th percentile anthropogenic ERF histories. With the 95th percentile history $\nu = 2.45$ ($p < 0.001$). In the 5th percentile history anthropogenic ERF is negative until 1982, so four years are excluded, and $\nu = 1.41$ ($p = 0.056$) on 42 years. Holding the 2050 forcing at the same absolute value, as in the referee's construction, gives 2.52 °C for the 95th percentile history, below the 2.88 °C from the best estimate, which reproduces the referee's result. This construction, however, gives the 95th percentile history a smaller future increase in forcing (about 1.2 W m^{-2} from its 2025 value of 3.83 W m^{-2}, against about 1.9 W m^{-2} for the best estimate). Because the uncertainty in anthropogenic ERF is dominated by aerosols and persists into the future, a higher historical forcing implies a correspondingly higher future forcing. With the same future increase applied to each history, the 2050 projections are 2.79, 2.88 and 3.33 °C for the 5th percentile, best-estimate and 95th percentile histories. The 5th percentile result rests on 42 years and the least reliable history.

6. Does a fit to one period inform future warming?

Whether the relationship estimated over 1980–2025 holds to mid-century cannot be settled with the present record, and the manuscript presents the 2050 values as conditional projections to be tested against observations over the next 5–10 years. For the best-estimate ERF history, the projections in this response range from 2.70 to 2.97 °C at 5.15 W m^{-2} across start years 1979–1986, and from 2.71 to 2.88 °C across AN zero points, ranges comparable to the effect of a single strong ENSO year (about 0.24 °C for a RONI of +2). The difference from FaIR (2.88 against 2.43 °C) is about twice that effect. The question at issue is therefore the magnitude of the non-linear response at the margin, not its existence.

The hypothesis is not without physical precedent. Over 1871–1980 the Earth warmed with radiative feedbacks consistent with long-term values, whereas after 1980 the pattern of sea-surface temperature change made feedbacks temporarily more stabilising, an effect that satellite observations suggest has been waning since about 2014 (Andrews et al., 2022). As this pattern effect weakens, warming per unit forcing increases, which would appear as curvature in GSAT against ERF over the estimation period. Coupled models also show equilibrium sensitivity rising with CO_2 concentration, mostly through feedback temperature dependence (Bloch-Johnson et al., 2021), and equilibrium warming exceeding values extrapolated from the first 150 years of simulation (Rugenstein et al., 2020). Observed warming has accelerated significantly over the past decade once ENSO, volcanic and solar influences are removed (Foster and Rahmstorf, 2026; Hansen et al., 2025). Much of this acceleration has been attributed to declining aerosol forcing (Samset et al., 2025; Hansen et al., 2025), which observation-driven ERF should already

contain. Acceleration alone does not establish a non-linear response to ERF. It would do so only if warming per unit ERF has increased or would appear to if recent aerosol forcing is underestimated.

The contribution of this paper is a transparent, observation-driven estimate of how large that marginal response is over the period of rapidly rising anthropogenic ERF, and the coming decade will show which model performs best.

7. Use of RONI rather than ONI

I accept the referee's recommendation. The Relative Oceanic Niño Index (RONI) subtracts the tropical-mean SST anomaly from the Niño 3.4 anomaly, which removes the dependence on a moving climatological base period in a warming climate (L'Heureux et al., 2024), and CPC adopted it for official ENSO monitoring and prediction from February 2026 (NOAA CPC, 2026). The revised manuscript uses RONI for the same reasons that CPC now reports it. With RONI, the ENSO coefficient is 0.121 (SE 0.014) °C per unit, compared with 0.114 (0.012) with ONI, and ρ rises from 0.22 to 0.28. The fit is slightly looser (residual SD 0.056 against 0.054 °C), and BIC favours ONI (−248.7 against −252.6). The jointly estimated exponent is 1.745 (SE 0.251, $p = 0.004$) with RONI and 1.59 (0.235, $p = 0.015$) with ONI. The 2050 projection is 2.88 °C with RONI and 2.54 °C with ONI. Part of the difference arises because ONI contains part of the recent warming trend (ONI exceeds RONI by 0.27 on average over 2011–2025), which the ONI model attributes to ENSO rather than to forcing; this is the bias the referee identifies.

8. Other points

8.1 North Pacific shifts and the PDO

The referee writes: "There are numerous identified post-1977 North Pacific shifts (e.g. Overland et al doi: https://doi.org/10.1016/j.pocean.2008.03.016). Is the power law regression sensitive to N Pacific phase? If yes, then are we only projecting forward assuming no similar shifts until 2050? And what makes 1977 sufficiently different that the other ones identified by Overland or similar ones visible in time series of PDO index during 1977—2025?"

I added the NOAA ERSSTv5 PDO index (NOAA NCEI, 2026), averaged from September to August as for RONI, to the revised model, first in the same year and then in the previous year. I also added level shifts in GSAT at the North Pacific shifts identified by Overland et al. (2008) near 1989 and 1998, and then a third at the 2013/14 shift reported by Xiao and Ren (2023). The PDO coefficient is small and not significant (−0.021, SE 0.011, in the same year; −0.016, SE 0.010, lagged), BIC changes little (−249.1 and −247.8 against −248.7), ν is essentially unchanged (1.76 and 1.79 against 1.745), and the straight line is rejected at $p = 0.003$ and 0.004. The PDO is correlated with RONI ($r = 0.58$), and once RONI is included it adds little information. None of the level shifts is significant at the 5 % level (0.068, SE 0.035, at 1989; 0.058, SE 0.041, at 1998; −0.027, SE 0.047, at 2014), and BIC is higher with them than without (−245.4 and −242.0). With the shifts included ν rises to 2.81 and 2.74, but its standard error nearly triples (0.70 and 0.67) because steps in GSAT overlap with the steady rise in anthropogenic ERF, and the straight line is still rejected ($p = 0.002$). The non-linearity is therefore not sensitive to North Pacific phase, and the projection does not depend on an assumption that no further shifts occur. As stated in section 1, the revised manuscript starts in 1980 on grounds that do not use the GSAT record; the Pacific shift is not among them.

8.2 The quadratic alternative and uncertainty at high ERF

The referee writes that "a quadratic fit shows uncertainty broadening as ERF increases, which makes far more sense", and that in the 25-year-window analysis "the quadratic model seems similarly good at predicting future GSAT".

I replaced $\beta\, AN_{t-1}^{\nu}$ in the revised model with $b_1\, AN_{t-1} + b_2\, AN_{t-1}^2$, keeping ρ, natural ERF and RONI, so that both forms have six parameters. The quadratic fits as well as the power law (BIC −248.8 against −248.7; −242.7 for the straight line), and its squared term is positive and significant ($b_2 = 0.062$, SE 0.020, $p = 0.004$). This agrees with the original manuscript, in which the quadratic also showed significant curvature, and it is why the title refers to a non-linear rather than a power-law response. At 5.15 W m^{-2} the quadratic projects 2.95 °C for 2050, against 2.88 °C for the power law and 2.19 °C for the straight line.

To test whether uncertainty broadens with ERF, I computed the 2050 projection at total ERF of 4.5, 5.15, 5.5 and 6.0 W m^{-2} with the 3-year block bootstrap for each form. The width of the 66 % range rises from 0.45 to 1.13 °C for the power law and from 0.39 to 0.92 °C for the quadratic, and from 0.17 to 0.24 °C for the straight line. In the revised model the power-law uncertainty therefore broadens with ERF in the same way as the quadratic, and the two non-linear forms agree to within 0.14 °C at every target (2.37–3.63 °C for the power law and 2.40–3.77 °C for the quadratic).

8.3 Fits to 25-year windows

The referee writes: "I tried fitting 25-year windows and predicting 2025 GSAT below. There are worryingly wild errors prior to fits ending around 2000 … No number of tests performed on in-sample data can truly provide this sort of test or justification."

I agree. Windows ending before about 2000 contain little of the period of rapidly rising anthropogenic ERF, and a fit to them would not be expected to identify the response that the manuscript describes as emerging. The referee's finding that the quadratic performs similarly to the power law agrees with section 8.2: both forms are non-linear and both project more warming than a straight line. As stated in sections 3 and 6, the 2050 values are presented as conditional projections to be compared with observations over the next 5–10 years.

8.4 Coherent forcing

The referee writes: "The argument that we should begin in 1977 also mentions that forcing should be 'coherent'. I don't see why that is a requirement – are we saying that the model only works when forcing agents are all moving in the same direction? There are changes in the relative strengths of GHG and aerosol through time too, and the ratio of GHG:aerosol forcing changes in future scenarios too."

The revised manuscript no longer uses coherence of forcing as a criterion for the start year, which is justified as described in section 1. The power law applies to total anthropogenic ERF, so the model assumes that the response of GSAT does not depend on how that total is divided between greenhouse gases and aerosols. To test this, I split

anthropogenic ERF into aerosol and non-aerosol ERF over 1951–2025, the period with the largest change in their ratio. The two coefficients are 0.30 and 0.32 °C per W m^{-2} and are not distinguishable ($p = 0.56$). Over 1980–2025 the two components are too closely correlated ($r = 0.77$) to be separated.

8.5 Uncertainty outside the fitted range

The referee asks: "What are the uncertainties in projecting to ERF outside of the training sample? … Crucially, I don't see how (ii) is tested at all."

The block-bootstrap interval includes uncertainty in all six coefficients and year-to-year variability, but not uncertainty in the form of the relationship beyond the sampled range of anthropogenic ERF, which only future observations can test. Within the sampled range, the power law and the quadratic fit equally well and differ by 0.07 °C at 5.15 W m^{-2} in 2050, while the straight line is 0.69 °C lower than the power law. The revised manuscript states what the interval includes and what it does not.

8.6 Emergent constraints and the CMIP5 1pctCO_2 analysis

The referee suggests "approaches somewhat like emergent constraints … mixed with a more-rigorous and consistent treatment of uncertainties informed by the climate's behaviour (e.g. large ensemble Monte Carlo …)", and finds in CMIP5 1pctCO_2 simulations that "it seems unlikely that knowledge of a power-law fit will meaningfully tighten uncertainties around future warming".

The manuscript makes no estimate of equilibrium climate sensitivity, and its projections are limited to mid-century, so whether ν predicts equilibrium sensitivity is outside its scope. Emergent constraints (Caldwell et al., 2018) and large-ensemble Monte Carlo methods (Glaser et al., 2024) are valuable directions but are beyond the scope of this paper.

9. Supplementary tables

I will include supplementary tables and any other supplemental materials the editor requests.

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