Final Response to RC1 and RC2

The comments of the reviewers have led to additional data analysis, modification of the autoregressive distributed lag climate model (ARDL model) and revision of the manuscript. Importantly, the main result remained unchanged: a non-linear relationship between the global average surface temperature (GSAT) and anthropogenic effective radiative forcing (AN) emerged during 1969 to 1978. Further, a partitioned autoregressive distributed lag model (P-ARDL) of GSAT as a function of thermal inertia ($GSAT_{t-1}$), anthropogenic effective radiative forcing (AN), solar/volcanic ERF (NAT), and the Relative Oceanic Nino Index (RONI) can reproduce the GSAT record from 1980-2025 with high fidelity and is more accurate than FaIR during this period. The non-linear relationship is well supported by observation and is highly significant (F-test $p = 0.004$). The prognostic value of the P-ARDL model needs to be validated against future observations over the next 5-10 years.

A summary of the main changes and additional analyses prompted by the reviews follows:

Edits and additions:

- The Title has been changed to "Emergence of a non-linear global surface air temperature response to rapidly increasing *anthropogenic* effective radiative forcing".
- Total effective radiative forcing (ERF) has been partitioned into anthropogenic effective radiative forcing (AN) and solar/volcanic ERF (NAT).
- The primary ARDL model is now a partitioned model (P-ARDL) that uses both AN and NAT.
- The El Nino Southern Oscillation (ENSO) index used in the original ARDL model has been changed to the Relative Oceanic Nino Index (RONI) in the P-ARDL model.
- The P-ARDL model is fit to the data in a one step process. All of the independent variable coefficients and the AN exponent (ν) are estimated simultaneously. The specification of ν from a separate univariate power-law analysis has been removed.
- P-ARDL models were fit for each start year from 1951-1986 through 2025 and used to determine if a non-linear GSAT response to AN emerged over start years from 1951–1986.
- The primary analysis was conducted for all years from 1980-2025, inclusive ($n = 46$). No years are excluded.
- 5,000 simulated linear-response climates test whether the rise in ν across start years could arise by chance.
- The P-ARDL model is fit separately to 1920–1949, 1950–1979 and 1980–2025 (new Table 1).
- A 3-year moving-block bootstrap resampling analysis re-estimates all six coefficients and gives a range for ν that does not depend on the residuals being independent, or having equal variance, or being normally distributed.
- Several robustness checks were added, including tests of differing zero points for AN (1850–1900, 1950 and 1979), assessment of adding the Pacific Decadal Oscillation (PDO) to the model, and refitting of the P-ARDL model using the 5th and 95th percentile AN histories.

- A new table gives 2050 GSAT projections by forcing target for the P-ARDL, FaIR, AR6 and the linear fit of the P-ARDL model.

Sections and analyses removed:

- Section 2 describing the two-compartment energy balance model has been removed. The prior published work of Pretis provides the theoretical rationale for the use of econometric methods to model climate data and is cited in the manuscript.
- The SIMEX correction for measurement error in ERF was removed.
- The expanding-window recursive validation for 1994–2025 was removed.
- The AIC/BIC comparison of start years 1974–1980 was removed.
- The comparison of GSAT averaged over 2041–2060 under three SSPs was removed.
- The figure synthesizing estimates of ν (Figure 9) was removed.

The number of Figures went from 10 to 6.

Partitioning total ERF into AN and NAT was an important revision to the model because large volcanic eruptions can affect the shape of the GSAT-ERF relationship. The original estimate of ν was 1.89 (95% CI 1.23-2.57) and is now 1.75 (95% CI 1.25-2.24). This change improved the fit of the P-ARDL model but did not materially change the estimate for GSAT in 2050.

All of the new data, Python scripts, and analysis output are available on Zenodo [Smith, C. R.: Replication data and code for "Emergence of a non-linear global surface air temperature response to rapidly increasing anthropogenic effective radiative forcing", v2.0.0, Zenodo [code], https://doi.org/10.5281/zenodo.24016461, 2026a.]

Final Detailed responses to RC1 and RC2:

Each referee comment is followed by my response and the change made to the manuscript. All code and outputs are in the updated replication archive (https://doi.org/10.5281/zenodo.24016461).

The revised manuscript replaces the model described in AC1, a partitioned model estimated in *two steps* over 1977–2025, with the 1980–2025 partitioned ARDL (P-ARDL), in which all six coefficients, including the exponent ν, are estimated *jointly*. Where my initial response (AC1) to reviewer 1 gave results for the initial model, the results for the final model are given in this final response.

The revised 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 ERF = atmospheric carbon dioxide, methane, nitrous oxide, and halogenated gas concentrations, tropospheric and stratospheric ozone concentrations, stratospheric water vapor from

methane oxidation, aerosol–radiation interactions, aerosol–cloud interactions, contrails and contrail cirrus, land-use albedo, and black carbon on snow.

- NAT = solar + volcanic ERF.
- ρ represents thermal inertia.
- β and ν describe the response to anthropogenic forcing.
- η is the response to natural forcing.
- δ is the ENSO effect, represented by the Relative Oceanic Niño Index (RONI).

The model follows the econometric treatment of energy-balance models of Pretis (2020), with AN entering as a power law; $\nu = 1$ recovers the linear case. Estimated by non-linear least squares over 1980–2025 (n = 46):

Coefficient	Estimate (SE)
a	0.274 (0.051)
ρ	0.277 (0.082)
β	0.111 (0.038)
ν	1.745 (0.251)
η	0.188 (0.028)
δ	0.121 (0.014) °C per unit RONI

The residual standard deviation is 0.056 °C, and the residuals are uncorrelated (lag-1 autocorrelation −0.04). A linear response ($\nu = 1$) is rejected at $F(1, 40) = 9.54$, $p = 0.004$. Using heteroskedasticity-consistent standard errors (HC) for the analysis, $\nu = 1$ is also rejected (HC1 $p = 0.016$, HC3 $p = 0.031$). In a 3-year moving-block bootstrap resampling with all six coefficients re-estimated, the 95 % range of ν is 1.03–2.35 and $P(\nu \leq 1) = 0.025$.

Referee 1 comments:

Comment 1. “In order to accept it, I need some physical interpretation of why T should have this form. The author is right that at high temperatures we expect feedbacks to become non-linear. To the next order of approximation, we would get $R = F - N = \lambda T + qT^2$, with $\lambda > 0$ and $q < 0$ … so $T = F/\rho - qF^2/2\rho^2$. There is an F^2 term, but it doesn’t dominate the linear term. Also, there isn’t a constant term, as in the author’s model.”

Response. The analysis asks whether the observed GSAT–ERF relationship over the period of rapidly rising anthropogenic forcing is non-linear, and whether a simple model built from observational data reproduces observed warming on a decadal time scale. The hypothesis was that the GSAT response to rapidly increasing ERF may differ from the response when ERF was low and rising slowly. It is based on the accumulating evidence, summarized in the Introduction, that feedbacks may become non-linear as GSAT rises. The model is agnostic about mechanism. $\nu > 1$ means that the warming produced by an additional unit of anthropogenic forcing rises with the level of forcing already reached; $\nu = 1$ is the linear case. The model does not identify which feedbacks or other processes produce the non-linear relationship.

The referee's second-order expansion is a useful point of comparison. When the power law is replaced by $b_1\,AN_{t-1} + b_2\,AN_{t-1}^2$, keeping ρ, NAT and RONI, the quadratic fits as well as the power law (BIC difference 0.1). Its squared term is positive and significant ($b_2 = 0.062$, SE 0.020, $p = 0.004$), which agrees in sign with $q < 0$ in the referee's expression. The linear term is not significant ($b_1 = 0.074$, SE 0.075). At the 2025 value of AN, the squared term contributes 0.55 °C and the linear term 0.22 °C. The observed curvature is therefore larger than the expansion gives with $|qF| \ll \rho$ (the referee's climate resistance, not the P-ARDL coefficient ρ). The referee's expression describes the long-run relation between F and T with constant κ. The P-ARDL describes the year-to-year response with the deep-ocean temperature held constant over the estimation period. The comparison is therefore one of sign and approximate size, not an identification of q.

The constant arises for three reasons:

1. GSAT is relative to 1850–1900 while ERF is relative to 1750.
2. The climate system was not in equilibrium at the start of the sample.
3. With the deep-ocean temperature held constant over the estimation period, its contribution to the surface energy balance enters as a constant.

The static power-law fit to FaIR output over 1977–2025 reported in AC1 also requires a constant (0.26 °C), although FaIR has none in its equations.

Change. The Introduction and Methods state the hypothesis and what ν represents. The Results report the quadratic alternative. The Discussion gives the marginal long-run response, $\theta\nu\,AN^{\nu-1}$, at the 1980, 2025 and 2050 forcing levels, and states that no mechanism can be inferred.

Comment 2. "I am inclined to think that if the relationship between F and T is non-linear, it may be evidence of other degrees of freedom in the system having an effect, through unforced variability."

Response. Unforced variability enters the model through RONI, which replaces ONI in the revised manuscript (RC2 Comment 7). I conducted three additional analyses to check for other factors:

- Adding the Pacific Decadal Oscillation, in the same year or the previous year, leaves ν at 1.76–1.79 ($p = 0.003$–0.004).
- Level shifts in the North Pacific near 1989, 1998 and 2013/14 are not significant (RC2 Other Comments, 8.1).
- A linear response ($\nu = 1$) is rejected for every start year from 1979 to 1986. In 5,000 simulated linear-response climates built with the observed forcing, RONI and resampled residuals, a rise in ν across start years as large as observed occurred with probability 0.006 (individual residuals) and 0.008 (3-year blocks).

These checks do not exclude every form of unforced variability. Unforced variability not represented by RONI remains in the residuals, which show no serial correlation, heteroskedasticity or departure from normality (Table 2). Unmodelled variability would bias ν only if it were correlated with AN.

Change. Methods: the PDO index is added as a sensitivity analysis, and 5,000 GSAT records simulated from the linear model test whether the rise in ν across start years could arise from a linear response. Results: with the PDO added, ν = 1.76–1.79 (p = 0.003–0.004), and a rise in ν across start years at least as large as observed occurs with probability 0.006–0.008 in the simulated records.

Comment 3. "Simple climate models like FAIR are useful because they are formulated on a physical basis, and then calibrated to agree with more complex models (AOGCMs)…"

Response. I agree. FaIR is used in the revised manuscript as the comparison model. It is a constant-feedback model calibrated to the physical indicators assessed in AR6.

Run as a free simulation from the observed 1979 value, the P-ARDL reproduces GSAT over 1980–2025 with a root-mean-square error (RMSE) of 0.053 °C. The FaIR median has an RMSE of 0.095 °C. The P-ARDL is more accurate than every one of the 841 members (Diebold–Mariano $p < 0.0001$ against the median). Part of this advantage comes from RONI, which FaIR does not contain.

FaIR's own output, plotted against its total ERF input over 1980–2025, is itself non-linear (a power law on GSAT vs. total ERF gives ν = 1.71, 5–95 % range across members = 1.61–1.81). With volcanic forcing removed in FaIR, the result is close to a straight line (AC1). In the P-ARDL model, volcanic and solar forcing (NAT) enter linearly, so the volcanic years do not drive the estimate of the AN exponent. FaIR's temperature response is linear in ERF; the curvature in its GSAT vs. total ERF fit comes from the delayed ocean response to volcanic forcing. In the P-ARDL the non-linearity is in the response to AN. Fitted to FaIR's GSAT with the same specification and start year, the P-ARDL gives ν = 1.11 (5–95% range across members = 0.94–1.29), against 1.745 for the observations. Thus, the P-ARDL recovers a near-linear response from the output of a constant-feedback model. This means the non-linear exponent obtained from observation in the P-ARDL model is not a property of the model specification; it is a result of the observations.

Change. Methods: the P-ARDL is compared with the 841-member FaIR constrained ensemble as a free-running simulation over 1980–2025, and the P-ARDL is fitted to FaIR's own GSAT output. Results: root-mean-square error is 0.053 °C for the P-ARDL and 0.095 °C for the FaIR median (Figure 5). Fitted to FaIR output, the P-ARDL gives ν = 1.11 (0.94–1.29) and ρ = 0.90.

Comment 4. "I think that an essential step is … to test the ARDL model's predictive capacity on AOGCM data. … If the model is fitted to 1977–2025 in a historical AOGCM simulation, does it match that AOGCM's SSP projections to 2060 or beyond?"

Response. AOGCMs and simple climate models such as FaIR are valuable models for many reasons, but they are not the climate system. They are known to be imperfect, especially for changes in clouds, which dominate the AOGCM spread in λ (referee, lines 62–63). A constant-feedback model cannot answer whether the GSAT response to anthropogenic forcing has become non-linear. This question can only be answered from observation. The P-ARDL is fitted only to observations, and its projections are conditional and testable. Forecasts of annual GSAT for

2026 and 2027 from the P-ARDL and FaIR were deposited before the observations became available (https://doi.org/10.5281/zenodo.24022614). Observations over the next 5–10 years will show which model performs better.

Perfect-model tests are appropriate for simple mechanism-based models such as FaIR, whose response parameters are *calibrated* to AOGCM output. Scoring them against AOGCM output tests what they are designed to do. The P-ARDL is different. It is not calibrated to any model; it is estimated from observations, and its purpose is to describe the observed GSAT response. The relevant question for this model is whether the estimation procedure would find a non-linear response in a climate that responds linearly. That question is addressed directly with the observational data. In 5,000 simulated climates with a linear response, built from the observed forcing, RONI and residuals, a rise in ν across start years as large as observed occurred with probability 0.006 (individual residuals) and 0.008 (3-year blocks) (RC2 Comment 1).

A perfect-model test treats a physics-based, mechanistic model's output as the "true" climate. AOGCMs, ESMs and simple climate models such as FaIR approximate the climate system, but they are not the "true" climate system. An observation-driven model should be tested against future observations, not against a physical model. Nevertheless, the test reported in AC1 was repeated for the final model reported in the revised manuscript and presented here. Fitted to FaIR output with the observed ENSO effect and residual noise added, the P-ARDL rejected $\nu = 1$ in 3.7 % of the 841 members, and its 2050 projection exceeded FaIR's own 2050 GSAT by a median of 0.30 °C (5–95 % across members 0.05–0.58 °C). The exponent recovered from FaIR output with the ENSO effect and noise added was 1.29 (5–95 % across members 1.04–1.51), below the observed 1.75.

Change. None. The Discussion states that applying the specification to output from ESMs and simple two-layer energy-balance models would show whether non-linearity emerges in physical models as well.

Specific comments.

Line 48. "…the variation of λ(t) over the historical period by the 'SST pattern effect' … was not noticed first by them, but several years earlier, in those AGCM experiments … AOGCM historical experiments do not reproduce these variations in λ. … 'climate models' … isn't sufficiently precise."

Response: Agreed.

Change: Introduction. "…concluded that climate models underestimate the pattern effect at decadal time scales" is replaced with "…concluded that λ varied more in observations than in atmosphere-only models forced with observed sea-surface temperatures. Variation of λ with the sea-surface temperature pattern over the historical period was first found in such experiments (Gregory and Andrews, 2016; Zhou et al., 2016) and has since been confirmed in many models, whereas coupled historical simulations do not reproduce it (Andrews et al., 2022)."

Line 49. Give Meyssignac et al.'s values in the positive-stable convention.

Response: Agreed.

Change: Introduction. "−1.0 to −3.2 W m^{-2} K^{-1} (using the alternative sign convention for λ)" becomes "1.0 to 3.2 W m^{-2} K^{-1}".

Line 52. "Constant ocean heat uptake efficiency κ … is not an assumption in those models in general … it's an approximation to the emergent behavior … Constant climate feedback λ … is indeed an assumption … only part of the linearity $F \propto \Delta T$ is an assumption."

Response: Agreed.

Change: Introduction. "A central feature of energy-balance climate models is the assumption that the relationship between ΔT and ERF is approximately linear, ERF = (λ + κ) ΔT (Forster et al., 2021)." is replaced with "In energy-balance climate models the relationship between ΔT and ERF is approximately linear, ERF = (λ + κ) ΔT (Forster et al., 2021), where κ is the ocean heat uptake efficiency (W m^{-2} $°C^{-1}$). Constant λ is an assumption these models make, following AOGCMs. Constant κ is not built in but approximates emergent behavior over the first several decades of steadily increasing forcing (Gregory et al., 2024).

Line 59. ΔT and ΔN are linear only if λ is constant, V is negligible and ΔF is linearly related to ΔT, which holds approximately under steadily increasing forcing for some decades but not in stabilization scenarios.

Response: Agreed.

Change: Introduction. After "…the dependence of GSAT on N is linear" insert "provided λ is constant, V is negligible and ΔF is linearly related to ΔT, which holds approximately for some decades of steadily increasing forcing but not in stabilization scenarios."

Lines 62–63. The first-order expansion is justified for the Planck feedback, but its adequacy for water vapor, surface albedo and cloud feedbacks is an emergent result from AOGCMs.

Response: Agreed.

Change: Introduction. "Over much of the last 150 years, a first-order Taylor series expansion of net radiative flux from the Stefan-Boltzmann law is well motivated." is replaced with "Over much of the last 150 years, a first-order Taylor series expansion of net radiative flux is well motivated for the Planck response by the Stefan–Boltzmann law. For water vapor, surface albedo and cloud feedbacks its adequacy is an emergent result from AOGCMs rather than expected a priori."

Line 69. The approach of Hébert et al. must also assume constant κ.

Response: Agreed.

Change: Introduction. "…assumes a linear stationary relationship between forcing and temperature" becomes "…assumes a linear stationary relationship between forcing and temperature, which also requires constant ocean heat uptake efficiency,".

Lines 70–72. “It’s unclear what scenarios you have in mind, with what models. ΔF and ΔT are not linearly related in general.”

Response: The sentence refers to AOGCM experiments with abrupt CO_2 doubling and quadrupling, in which the warming per unit forcing at quadrupling exceeds that at doubling in most models (Bloch-Johnson et al., 2021).

Change: Introduction. “The linear assumption has been verified for a doubling of CO_2” becomes “In AOGCM experiments with abrupt CO_2 increases, the linear approximation holds for a doubling of CO_2”. “When a CO_2 quadrupling has been evaluated … non-linearity emerges” becomes “…non-linearity emerges in most models (Bloch-Johnson et al., 2021)”.

Lines 74–76. “In the figures of Forster et al 2026 I don’t see a sharp increase specifically in the last decade, and I can’t find such a remark in the paper. … The graphs suggest that you might say this began in about 1980. ‘New regime’ sounds like a discontinuity, but I can’t see evidence for that.”

Response: The referee is correct. Forster et al. (2026) do not describe a sharp increase in the last decade. They report the following:

- anthropogenic ERF increased by 0.38 W m^{-2} (14 %) in the six years since AR6;
- EEI more than doubled between 1976–1995 and 2006–2025.
- the rate of human-induced warming, 0.27 °C per decade over 2016–2025, matches the all-time high in the instrumental record.

The manuscript does not claim a discontinuity. The revised analysis finds that the non-linear response emerged gradually, with ν rising across start years 1969–1978, and the primary analysis begins in 1980, as the referee suggests.

Change: Introduction:

- The sentence “Recent observations suggest the climate system may have entered a new regime.” is deleted.
- The Forster et al. (2026) sentence is replaced with “Forster et al. (2026) reported that anthropogenic ERF increased by 0.38 W m^{-2} (14 %) in the six years since AR6, that EEI more than doubled between 1976–1995 and 2006–2025, and that the rate of human-induced warming, 0.27 °C per decade over 2016–2025, matches the all-time high in the instrumental record.”
- The last sentence of the paragraph becomes “These converging lines of evidence suggest that linear approximations of the global warming response to rapidly increasing radiative forcing should be re-evaluated.”

Line 96. Start a new paragraph at “Econometric models”.

Change: Introduction. A new paragraph begins at “Econometric models can be used to emulate two-layer energy balance models (Pretis, 2020).”

Lines 102, 105. The global-mean energy balance is emergent rather than underlying. “We can’t infer that a statistical description is sufficient for the real climate system on the basis of its similarity to the behavior of a simple climate model, or that it will apply in a different climate state.”

Response: Agreed. The energy balance is a consequence of energy conservation in all the physical processes. The manuscript does not claim that the P-ARDL is sufficient for the climate system. It states the following:

- the model is applicable over the sampled forcing range (AN_{t-1} from 0.66 to 2.98 W m^{-2});
- it cannot be used to evaluate mechanisms or to estimate equilibrium quantities;
- its projections to 2050 are conditional and require prospective validation.

Change: Introduction. “…cointegrating relationships consistent with the underlying energy-balance equation” becomes “…cointegrating relationships consistent with the energy-balance equation”. “…can legitimately capture key aspects of the global climate response and provide robust scientific insight” becomes “…can reproduce key aspects of the observed global climate response”.

Line 122. “As the forcing takes the climate system into states we haven’t observed before, new behavior may emerge which can’t be captured in a statistical model…”

Response: Agreed. This applies to any model calibrated on the historical record, including simple climate models such as FaIR. The 2050 values are presented as conditional projections for a horizon of 25 years. The manuscript states that observations over the next 5–10 years are needed to determine whether the model can be prospectively validated. As a first step, forecasts of annual GSAT for 2026 and 2027 from the P-ARDL and FaIR were deposited before the observations are available (https://doi.org/10.5281/zenodo.24022614).

Change: Introduction, final paragraph: “Conditioned on future ERF and RONI, the model makes specific predictions about future changes in GSAT through 2050 that require prospective validation.” Discussion: “The projections are conditional on the prescribed ERF trajectories and require prospective validation.”

Lines 141–143. “I don’t know what a ‘cointegrated system’ or a ‘cointegrating relation’ is.”

Response. Two series that trend over time are cointegrated if some combination of them does not trend, so they move together and do not drift apart. In climate terms, GSAT and forcing both rise, but the top-of-atmosphere imbalance formed from them, ERF − λT in the two-layer model, stays bounded. That combination is the cointegrating relation (Pretis, 2020). The preprint section deriving the ARDL from Pretis’s cointegrated system, including assumptions A1–A5, has been removed. The revised Methods state the model directly and explain its terms. The bounds test is retained, and the Methods now describe it as a test for a level relationship between GSAT and the anthropogenic forcing term.

Change: Methods. The derivation and assumptions A1–A5 are removed.

Line 145. “‘enters’ and ‘specification’ might be technical terms…”

Response. “Enters” means appears in the equation as a regressor; “specification” means the equation chosen for estimation (which variables, lags and functional form).

Change: Introduction. “Pretis enters forcing linearly” becomes “In Pretis (2020) forcing is linear”.

Line 149. “I don’t know what ‘weakly exogenous’ means. … On what criterion is it ‘weak’?”

Response. Weak exogeneity (Engle et al., 1983) means that ERF can be treated as given when the GSAT equation is estimated, without modelling how ERF itself is generated. It corresponds to “external forcing” in climate science. “Weak” distinguishes it from strong exogeneity, which also requires that past GSAT not help predict ERF.

Change: Assumption A2 has been removed with the derivation (line 141).

Line 151. “What does ‘orthogonal to the ERF regressor’ mean?”

Response: Uncorrelated with ERF over the sample. In the revised model, unforced variability is represented by RONI and the regression error, and the estimates require only that the error be uncorrelated with the regressors.

Change: Assumption A3 has been removed with the derivation.

Line 152. “Are you saying that the ERF is raised to some power? What would be the physical meaning of that?”

Response: Yes. In the revised model, anthropogenic ERF (AN) in the previous year is raised to the power ν. $\nu > 1$ means that the warming per unit of additional anthropogenic forcing rises with the level of forcing already reached. The marginal long-run response is 0.21 K per W m^{-2} at the 1980 value of AN, 0.62 at the 2025 value and 0.89 at the 2050 value on the 5.15 W m^{-2} path. The normalization F_{ref} in the preprint is no longer needed. The power law does not identify a mechanism (RC1 Comment 1).

Change: Methods: anthropogenic ERF enters “as a power law, so that $\nu = 1$ recovers the linear case.” Discussion: the marginal long-run response, $\theta \nu AN^{(\nu-1)}$, rises from 0.21 K per W m^{-2} at the 1980 value of AN to 0.62 K per W m^{-2} at the 2025 value.

Line 160. “I don’t know what an ARDL equation is…”

Response: An autoregressive distributed lag (ARDL) equation predicts this year’s value of a variable from its own previous value (the autoregressive part) and from current and past values of other variables (the distributed lag part). In the P-ARDL, GSAT this year depends on:

- GSAT last year;
- anthropogenic ERF last year;
- natural ERF this year;
- RONI this year.

Because a fraction ρ of each year's anomaly is carried into the next, a sustained change in forcing has a long-run effect $1/(1-\rho)$ times its first-year effect. A fraction $1-\rho^k$ of it is realized after k years: 72 % in the first year, 92 % by the second and 98 % by the third.

Change: Methods. The model and the meaning of each term are stated where the model is introduced.

Line 162. "What does 'ONI' stand for?"

Response: Oceanic Niño Index. Following Referee 2, it has been replaced by the Relative Oceanic Niño Index (RC2 Comment 7).

Change: Methods. RONI is defined where it is introduced.

Line 165. "By 'lag coefficient' do you mean the lag-one autocorrelation coefficient of GSAT…?"

Response: No. ρ is the regression coefficient on the previous year's GSAT, estimated jointly with the forcing and ENSO terms. It is the fraction of the previous year's anomaly carried forward after allowing for forcing and ENSO, not the lag-one autocorrelation of GSAT.

Change: Methods. "ρ represents thermal inertia … Because GSAT_t−1 carries forward a fraction ρ of each year's response…"

Lines 167–187. Skipped because of terminology.

Response: This passage re-parameterized the ARDL into error-correction form to derive a long-run level. It has been removed. The only long-run quantity retained is the long-run multiplier $\theta = \beta(1-\rho)^{-1} = 0.15$, defined in the Discussion.

Change: Methods. The passage is removed.

Line 188. Definitions of climate sensitivity, climate resistance and ocean heat uptake efficiency.

Response: I agree with the referee's definitions. The preprint's definition of climate sensitivity and the derived quantities at lines 188–193 have been removed. The manuscript offers no estimate of equilibrium climate sensitivity, transient climate response or effective climate sensitivity.

Change: Methods. Lines 188–193 are removed. Discussion: "No estimate of equilibrium climate sensitivity, the transient climate response, or effective climate sensitivity is offered…"

Lines 208–209. "Since the linear specification is a special case of the power law, with $\nu = 1$, why is it considered separately? What is the physical motivation for considering ν different from unity…?"

Response: The referee is right. In the revised manuscript the linear case is tested as the nested restriction $\nu = 1$ within the single P-ARDL, by an F-test. The motivation is the hypothesis that the warming per unit forcing depends on the level of forcing (RC1 Comment 1). The power law is the simplest one-parameter form that contains the linear

case, rises monotonically and is defined for all positive AN. The quadratic is tested as an alternative and fits equally well.

Change: Methods: “The linear case was tested with an F-test of the nested restriction ν = 1.” The quadratic form $b_1 AN_{t-1} + b_2 AN_{t-1}^2$ is estimated as an alternative, and the forms are compared by BIC.

Lines 226–356. Unfamiliar terms.

Response: Several of these methods have been removed:

- the simulation-extrapolation (SIMEX) correction, because it assumed independent errors in ERF (RC2 Comment 5);
- expanding-window recursive validation, because it mainly tests the persistence and ENSO terms (RC2 Comment 3).

For the terms that remain:

- **Attenuation bias:** random error in a regressor biases its estimated effect toward no effect; here, random error in AN biases ν toward one.
- **I(0) and I(1):** a series is I(0) if it fluctuates about a stable level and I(1) if it trends so that its year-to-year changes are I(0).
- **Augmented Dickey–Fuller and Kwiatkowski–Phillips–Schmidt–Shin tests:** they classify series as I(0) or I(1), from opposite null hypotheses.
- **Pesaran–Shin–Smith bounds test:** tests for a level relationship (line 141) when the regressors may be a mixture of I(0) and I(1).
- **Breusch–Godfrey and Ljung–Box tests:** test whether the residuals are correlated from year to year.
- **Heteroskedasticity:** residual variance that changes over the sample; the Breusch–Pagan, White and ARCH tests detect it.
- **Diebold–Mariano test:** tests whether two models’ prediction errors differ significantly.

Change: Methods. SIMEX, expanding-window validation and the jackknife are removed. The remaining tests are named with what each tests for. A supplementary table of models and tests (test, purpose, assumptions, result) will be provided if the editor requests it (RC2 Supplementary tables).

Lines 390–391. “Some authors argue that the unusual SST trend in the Pacific, related to the PDO pattern, ended in the 2010s e.g. Loeb et al. (2020).”

Response: The 1976/77 Pacific shift is no longer used to justify the start year. The revised manuscript starts in 1980 on four grounds that do not use the GSAT record (RC2 Comment 1). Adding the PDO index leaves the result unchanged (RC1 Comment 2). If the Pacific SST trend ended in the 2010s, that is consistent with the waning of the pattern effect since about 2014 that satellite observations suggest (Andrews et al., 2022).

Change: Methods and Discussion. The Pacific-shift argument is removed. The PDO sensitivity analysis is added.

Line 426. "What does 'admitted an interpretation within a two-layer energy-balance framework' mean? … the linear form is an approximate solution of the two-layer model for linearly increasing forcing…"

Response: Agreed. The admissibility criterion and the table of functional forms have been removed. The revised manuscript compares three forms within the same dynamic model: linear, power law and quadratic.

Change: Results and Discussion. Table 1 of the preprint is removed. The linear, power-law and quadratic forms are compared by the F-test and BIC.

Lines 734–735. Perfect-model test.

Response and change. See RC1 Comment 4.

Referee 2

Comment 1 (summarized). The power law is not translation invariant, so predicted GSAT depends on the ERF baseline. Re-zeroing ERF to 1977 shifts the high 2050 estimate from about 3.0 to 2.6 °C. In the limit ERF → 0, the two-layer derivation implies an upward ocean heat flux at equilibrium. The model cannot capture negative ERF. The 1977 start involves uncorrected multiple testing and physically unjustified selection criteria.

Response: 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.
- It is fitted and interpreted only over the sampled range of previous-year anthropogenic ERF, 0.66 to 2.98 W m^{-2}.
- Natural ERF, including negative volcanic forcing, enters linearly, so negative forcing is accommodated; anthropogenic ERF is positive throughout the record.

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:

- ν falls (1.745, 1.68, 1.58 and 1.42), but its standard error falls in proportion.
- The evidence against a linear response 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. NAT 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:

1. The rate of increase in AN changed rapidly over 1950–1979; its second derivative peaked in 1974.
2. 1980 is the first full year of the satellite era.
3. 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).
4. 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.
- It rises from 1.12 for 1969 to 1.29 for 1976.
- It lies between 1.54 and 1.83 for every start year from 1979 to 1986, and the linear response is rejected for each of them ($p = 0.004$–0.050).
- 1980 does not give the largest exponent; 1983 and 1986 give 1.83 and 1.81.

The main result is a single test of $\nu = 1$ for a start year set by grounds that do not use the GSAT record. 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 linear-response 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.
- 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.

Changes:

- Methods: the derivation is removed; the start-year analysis and the simulation of linear-response climates are described; the AN zero-point sensitivity analysis is added.
- Results: start-year sensitivity (Figure 4).
- Discussion: added the rationale for the 1980 start.

Comment 2 (summarized). The model relies on a 3-year mixed-layer relaxation to extrapolate multi-decadal warming, where deep-ocean heat uptake occurs.

Response: The projections extend only to 2050, are conditional on the ERF pathway and require validation against observations over the next 5–10 years. Over this period the effect of the deep ocean on GSAT is small and is absorbed in the estimated coefficients. The fast response in the model is not an equilibrium response, and no equilibrium quantity is estimated. The revised manuscript states that an open question is whether the dependence on the forcing level survives when the deep-ocean temperature is allowed to evolve, and that testing it requires the full two-equation system.

Change: Discussion: the specification is estimated over AN_{t-1} from 0.66 to 2.98 W m^{-2} and applied over a horizon of two to three decades. Whether climate state dependence survives when the deep-ocean temperature is allowed to evolve is stated as an open question.

Comment 3 (summarized). The year-at-a-time validation is dominated by the persistence and ONI terms and does not test the power law. One-at-a-time removal assumes independence.

Response: I agree. The year-at-a-time validation mainly tests the persistence and ENSO terms, not the power law, and it is removed 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 resampling, 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.

Change: Methods and Discussion. The expanding-window validation and jackknife are removed. The leave-one-out check of influential observations is retained.

Comment 4 (summarized). To accept the headline result, the model should be at least as convincing as the alternatives (requirement (i) of the review).

Response: 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). 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, the slow response is carried by $\rho = 0.90$ (0.85–0.93), with $\nu = 1.11$ (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 place the non-linearity differently, and the observations show more curvature than FaIR once persistence, natural forcing and ENSO are modeled.

Change: Methods and Results: the P-ARDL is fitted to the GSAT output of each of the 841 FaIR members, giving $\nu = 1.11$ (5–95 % across members 0.94–1.29), against 1.75 for the observations.

Comment 5 (summarized). The ν uncertainties do not account for autocorrelation. The SIMEX correction assumes independent ERF errors. Using the 5th and 95th percentile ERF histories reduces projected GSAT at high ERF.

Response**:** 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. 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 correct that the SIMEX correction 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. Uncertainty in ERF is instead addressed with the 5th and 95th percentile histories, as in the referee's analysis:

- With the 95th percentile history, $\nu = 2.45$ ($p < 0.001$).
- In the 5th percentile history, AN is negative until 1982, so four years are excluded; $\nu = 1.41$ ($p = 0.056$) 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. This reproduces the referee's result. That 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.

Change: Methods: SIMEX is removed. Uncertainty is estimated by a 3-year moving-block bootstrap resampling, and the model is re-estimated with the 5th and 95th percentile AN histories. Results: $\nu = 2.45$ ($p < 0.001$) with the 95th percentile history and 1.41 ($p = 0.056$) with the 5th.

Comment 6 (summarized). "Does a power law GSAT(ERF) constrained in one period provide information about longer-term responses to large changes in ERF?" The referee also suggests emergent-constraint and large-ensemble approaches and finds in CMIP5 1pctCO_2 simulations that a power-law fit does not meaningfully predict equilibrium climate sensitivity.

Response: Whether the relationship estimated over 1980–2025 holds to mid-century cannot be settled with the present record. 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 at 5.15 W m^{-2} range:

- from 2.70 to 2.97 °C across start years 1979–1986;
- from 2.71 to 2.88 °C across AN zero points.

These ranges are 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 hypothesis is not without physical precedent:

- Over 1871–1980 the Earth warmed with radiative feedbacks consistent with long-term values. After 1980 the pattern of sea-surface temperature change made feedbacks temporarily more stabilizing, an effect that satellite observations suggest has been waning since about 2014 (Andrews et al., 2022).
- Coupled models show equilibrium sensitivity rising with CO_2 concentration, mostly through feedback temperature dependence (Bloch-Johnson et al., 2021).
- Equilibrium warming exceeds 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.

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.

Change: Introduction and Discussion. The projections are described as conditional, and the scope is limited to mid-century.

Comment 7. Use of RONI rather than ONI (minor comment)

Response: I accept the recommendation. 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). CPC adopted it for official ENSO monitoring from February 2026 (NOAA CPC, 2026).

Comparing the RONI and ONI versions of the model:

Quantity	RONI	ONI
ENSO coefficient, °C per unit (SE)	0.121 (0.014)	0.114 (0.012)
ρ	0.28	0.22
Residual SD	0.056 °C	0.054 °C
BIC	−248.7	−252.6
ν (SE, p)	1.745 (0.251, p = 0.004)	1.59 (0.235, p = 0.015)

Quantity	RONI	ONI
2050 projection	2.88 °C	2.54 °C

The fit with RONI is slightly looser and BIC favors ONI. Part of the difference in the 2050 projection arises because ONI contains part of the recent warming trend (ONI exceeds RONI by 0.27 on average over 2011–2025). The ONI model attributes that part of the trend to ENSO rather than to forcing; this is the bias the referee identifies.

Change: Methods. RONI replaces ONI throughout.

Other Comments.

8.1 North Pacific shifts and the PDO.

I added the NOAA ERSSTv5 PDO index, averaged from September to August as I did for RONI:

- The PDO coefficient is small and not significant: −0.021 (SE 0.011) in the same year and −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), and the linear response is rejected at p = 0.003 and 0.004.
- The PDO is correlated with RONI (r = 0.58).

I also added level shifts (i.e., dummy dichotomous variables) in GSAT at the North Pacific shifts near 1989 and 1998 (Overland et al., 2008) and at 2013/14 (Xiao and Ren, 2023):

- None is significant at the 5 % level, and BIC is higher with them than without.
- With the shifts included, ν rises to 2.81 and 2.74. Its standard error nearly triples, because steps in GSAT overlap with the steady rise in anthropogenic ERF.
- The linear response 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.

Change: Methods and Results: added PDO sensitivity.

8.2 The quadratic alternative and uncertainty at high ERF.

With $b_1\ AN_{t-1} + b_2\ AN_{t-1}^2$ in place of the power law, the quadratic fits as well as the power law (BIC −248.8 against −248.7). Its squared term is positive and significant (b_2 = 0.062, SE 0.020, p = 0.004). At 5.15 W m^{-2} it projects 2.95 °C for 2050, against 2.88 °C for the power law and 2.19 °C for the linear form.

With the block bootstrap at 2050 totals of 4.5 to 6.0 W m^{-2}, the width of the 66 % range rises:

- from 0.45 to 1.13 °C for the power law;

- from 0.39 to 0.92 °C for the quadratic;
- from 0.17 to 0.24 °C for the linear form.

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.

Change: Methods: the quadratic form is estimated as an alternative to the power law. Results and Table 3: the quadratic fits as well as the power law (BIC difference 0.1; b_2 p = 0.004) and gives 2.95 °C in 2050 at 5.15 W m^{-2}. Discussion: the power-law and quadratic forms cannot be distinguished over 1980–2025.

8.3 Fits to 25-year windows.

I agree that no in-sample test can substitute for out-of-sample evidence. Windows ending before about 2000 contain little of the period of rapidly rising anthropogenic ERF and would not be expected to identify the response the manuscript describes as emerging. The referee's finding that the quadratic performs similarly agrees with 8.2.

Change: none beyond RC2 Comment 6.

8.4 Coherent forcing.

Coherence of forcing is no longer used as a criterion for the start year. The power law applies to total anthropogenic ERF, so the model assumes that the GSAT response does not depend on how that total is divided between greenhouse gases and aerosols. To test this, I split AN 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.

Change: the coherence criterion is removed from the Methods.

8.5 Uncertainty outside the fitted range**.**

The block-bootstrap interval includes uncertainty in all six coefficients and year-to-year variability. It does not include uncertainty in the form of the relationship beyond the sampled range of AN, 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 linear form is 0.69 °C lower than the power law.

Change: Methods: "The intervals do not include uncertainty in the ERF trajectories, which are prescribed rather than forecast, or in the form of the relationship beyond the sampled range of AN."

Supplementary tables (minor comment).

Response: The revised model is a single equation estimated in one step, so the sequence of models the referee had to cross-reference (static power law, then dynamic model, then projection) no longer arises. A supplementary table of the models and tests (test, purpose, assumptions, result) will be provided if the editor requests it.

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