Challenges in the Detection and Attribution of Northern Hemisphere Surface Temperature Trends Since 1850

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Challenges in the detection and attribution of Northern Hemisphere surface temperature trends since 1850

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Abstract Since 2007, the Intergovernmental Panel on Climate Change (IPCC) has heavily relied on the comparison between global climate model hindcasts and global surface temperature (ST) estimates for concluding that post-1950s global warming is mostly human-caused. In Connolly et al. (2021), we cautioned that this approach to the detection and attribution of climate change was highly dependent on the choice of Total Solar Irradiance (TSI) and ST datasets. We compiled 16 TSI and 5 ST datasets and found by altering the choice of TSI or ST, one could (prematurely) conclude anything from the warming being "mostly human-caused" to "mostly natural". Richardson and Benestad (2022) suggested our analysis was "erroneous" and "flawed" because we did not use a multilinear regression. They argued that applying a multilinear regression to one of the 5 ST series re-affirmed the IPCC's attribution statement. They also objected that many of the published TSI datasets were out-of-date. However, here we show that applying multilinear regression analysis to an expanded and updated dataset of 27 TSI series, the original conclusions of Connolly et al. (2021) are confirmed for all 5 ST datasets. Therefore, it is still unclear whether the observed warming is mostly human-caused, mostly natural or some combination of both.

Key words: Sun: activity — (Sun:) solar–terrestrial relations — Solar System: Earth

1 INTRODUCTION

The "detection and attribution of climate change" statements of the Intergovernmental Panel on Climate Change (IPCC) have convinced many that the observed global warming since at least the mid-20th century has been mostly human-caused ("anthropogenic"). Since their 4th Assessment Report (AR4) in 2007 (IPCC 2007), the main basis for these statements has been through the comparison of Global Climate Model (GCM) "hindcasts" [1] to global surface temperature records.

Their key analysis is a two-step assessment. First, they try to hindcast the observed global warming since the late 19th century using "natural forcings only", i.e., changes in total solar irradiance, TSI ("solar") and/or the incidence of stratosphere-reaching volcanic eruptions ("volcanic"). Second, they repeat this process using a combination of "natural and anthropogenic forcings" – where "anthropogenic" describes multiple human-caused factors, chiefly an expected "greenhouse warming" from increased atmospheric concentrations of carbon dioxide and other greenhouse gases (GHG) – partially offset by an expected "aerosol cooling" from human-generated aerosol particulate matter.

[1] A hindcast is a retrospective "forecast" where the model tries to simulate what should have occurred in the past – given the model's assumptions about how and why climate changes.

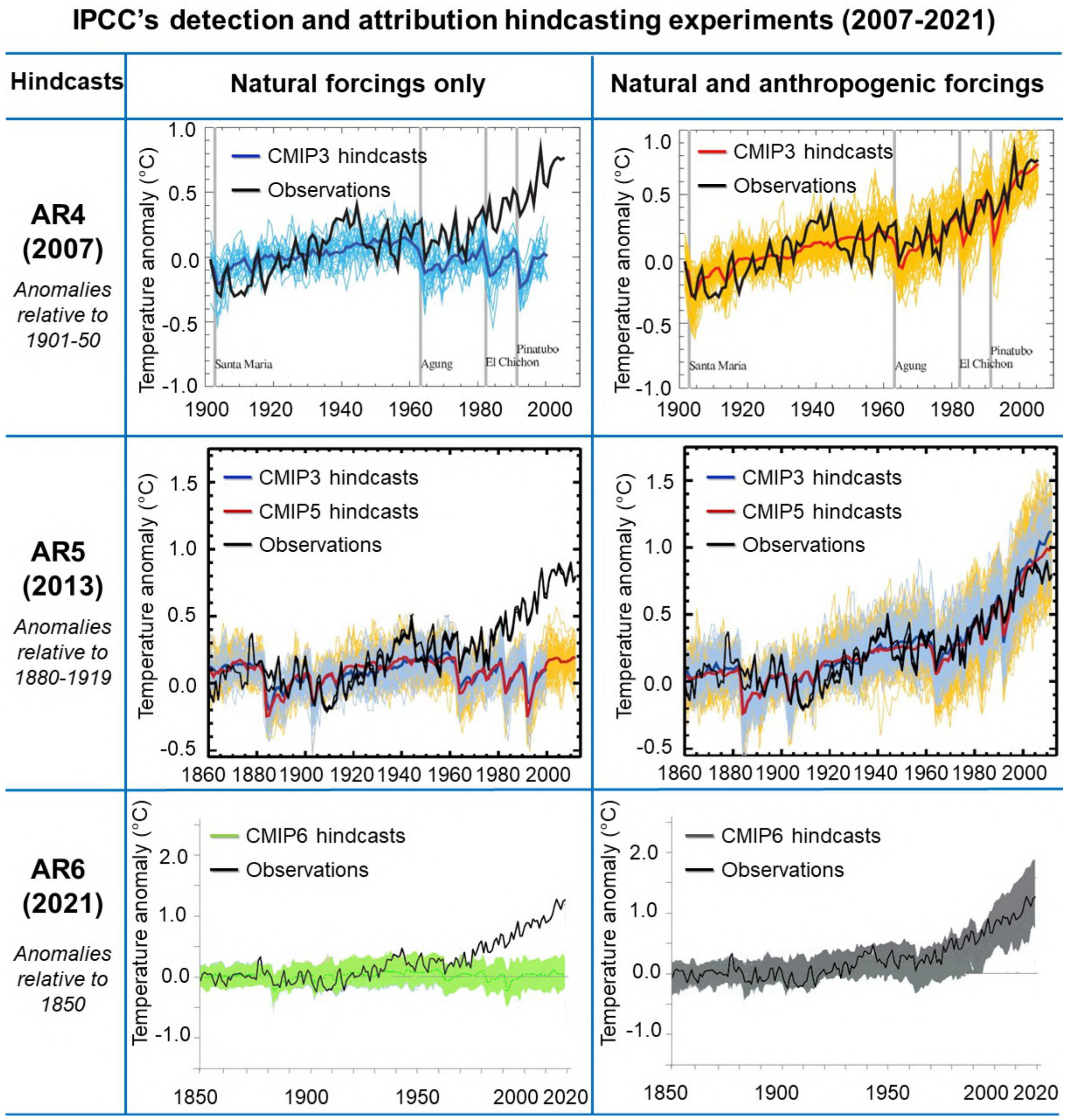

Fig. 1: Summary of the detection and attribution hindcasting experiments presented by the IPCC in (top) AR4; (middle) AR5; (bottom) AR6. Left-hand panels compare the hindcasts using "natural forcings only" to the average global surface temperature records (thick black lines labelled "Observations") considered by each report. Right-hand panels present the equivalent analysis using the hindcasts with both "natural and anthropogenic forcings". For AR4 and AR5, each thin colored line corresponds to a separate hindcast and the thick colored lines represent the multi-model mean hindcast. For AR6, the shaded envelope represents the 5–95$\%$ range of individual simulations and the dotted lines represent the multi-model mean hindcast. AR4 panels are adapted from Figure 9.5 of IPCC (2007). AR5 panels are adapted from Figure 10.1 of IPCC (2014). AR6 panels are adapted from Figure FAQ 3.1 of IPCC (2021).

The 5^{th} Assessment Report (AR5) was published in 2013 (IPCC 2014) and the 6^{th} Assessment Report (AR6) was published in 2021 (IPCC 2021). The relevant results for AR4 (2007), AR5 (2013) and AR6 (2021) are summarized in Fig. 1. The results are broadly equivalent for all three reports. The hindcasts using "natural forcings only" were unable to reproduce the observed long-term warming and even suggested a slight cooling in the most-recent decades. However, when the hindcasts were carried out using both "natural and anthropogenic forcings", the envelope of the hindcasts encompassed the observed temperature record, and the long-term warming of the hindcast average was quite similar to that of the observed warming.

Thus, the GCMs could not explain the observed temperature trends (especially since c. 1950s) in terms of only natural forcings, yet they could get a reasonable match if they also incorporated anthropogenic forcings. Hence, the IPCC concluded that the observed long-term warming since the mid-20th century is:

1. *Inconsistent* with natural warming, but
2. *Consistent* with anthropogenic warming.

This two-part argument is the main basis for the "attribution" statements of the last 3 IPCC reports, e.g., "It is **extremely likely** that human influence has been the dominant cause of the observed warming since the mid-20th century." – Summary for Policymakers, p15, emphasis in original (IPCC 2014).

Initially, the analysis of Fig. 1 seems both compelling and logical. However, in advance of AR6, we cautioned in Connolly et al. (2021) – henceforth "C2021" – that the IPCC's attribution analysis relied on several key assumptions that are still the subject of ongoing scientific debate and discussion. We noted two key problems the IPCC had underestimated or overlooked in their analysis for AR4 and AR5 (and that they subsequently repeated for AR6):

1. The land component of the "observed" global surface temperature (ST) records they considered is contaminated by urban warming biases (Soon et al. 2015; Zhang et al. 2021; Scafetta 2021). Although urban areas only account for a small percentage of the land, urban weather stations make up the majority of the thermometer records used for estimating global temperatures – and most of the older stations with thermometer records spanning a century or longer (C2021).
2. There are multiple different TSI datasets available in the literature – many of which imply quite different trends in TSI since 1850 (or earlier) (Soon et al. 2015; Scafetta et al. 2019). Yet the hindcasts used for AR5 and AR6 only considered a small subset of TSI datasets – and this subset consisted solely of estimates implying: (a) there had been very little TSI variability over the past few centuries and (b) if anything, TSI had slightly decreased since the 1950s (C2021).

In C2021, we attempted to answer a question closely related to the IPCC's attribution problem, i.e., "How much has the Sun influenced Northern Hemisphere temperature trends?" To minimise the urbanization bias problem, we developed five separate estimates of Northern Hemisphere STs: 1) only rural weather stations; 2) all available stations whether urban or rural (the standard approach); 3) only sea surface temperatures (SST); 4) tree-ring widths as temperature proxies; 5) glacier length records as temperature proxies. Urbanization bias should only be a problem for the "urban and rural land" estimates. To better address the TSI problem, we compiled from the literature a wide range of 16 different TSI reconstructions available that covered the period since 1850, or earlier.

Our analysis was less ambitious in scope than the IPCC's. We confined our analysis specifically to the Northern Hemisphere since there were very few long rural temperature records or temperature proxy records for the Southern Hemisphere. Furthermore, we primarily focused specifically on the solar contribution. For simplicity, we used a relatively simple and straightforward statistical technique for our analysis – a linear least squares fitting between TSI and ST.

The IPCC's hindcast analysis *seemed* to unequivocally rule out TSI as a major climate driver since 1850. As can be seen from Fig. 1, the modelled warming for the "natural forcings only" hindcasts suggests that TSI can only explain a modest warming during the early 20^{th} century – and they cannot explain *any* warming post-1950s. Instead they suggest, if anything, TSI might have led to a slight cooling post-1950s. However, our primary analysis suggested that by varying either the temperature estimates or the TSI dataset considered we could explain anything from (a) "none" to (b) "most" of the long-term warming since the late-19^{th} century being due to changing TSI. This showed that the first part of the IPCC's attribution analysis was heavily reliant on TSI choice.

We noted one exception – for the Northern Hemisphere land ST estimates based on urban and rural station records, "the recent warming period appears particularly unusual. This suggest to us that urbanization bias does remain a significant problem for current temperature trend estimates". None of the 16 TSI estimates we considered were able to fully explain the long-term warming of the "urban & rural" estimates up to the most recent year (2018). That said, we noted that several of the "high variability" TSI estimates were able to explain substantially more of the long-term warming than the Matthes et al. (2017) TSI estimate used for the hindcasts for AR6. Indeed, one of the older datasets (Bard et al. 2000) was still able to explain the majority of the warming of this urbanized time series *during the period of overlap*. However, we cautioned that this TSI reconstruction ended in 1998 and we suggested that "it is time to update the Bard et al. (2000) dataset".

Therefore, our *primary* analysis showed that the first part of the IPCC's argument for confidently claiming global warming was "mostly human-caused" was premature for at least two reasons:

1. The TSI datasets they were considering for their "natural forcings only" hindcasts only represented a small subset of the plausible datasets available – and that subset was one that implied a much smaller TSI contribution than others.
2. The "observed" global ST record they were comparing to the hindcasts was substantially contaminated by urban warming biases in the land component.

In order to assess the second part of the IPCC's argument, as a *secondary* analysis, we also attempted to see how much of the unexplained long-term warming after fitting the temperature data to TSI could be explained in terms of "anthropogenic forcings". That is, we fitted the AR5 "all anthropogenic forcings" time series to the statistical residuals left after the primary analysis. We found that in all cases, the percentage of the long-term warming trend that could be explained in terms of both components increased. Although only 61-89% of the long-term warming trends of the two proxy-based temperature records could be explained in terms of the two components (TSI and "all anthropogenic forcings"), for the other three temperature records, this second part often explained $> 100\%$ of the linear temperature trend, i.e., overestimating the long-term warming contribution of either TSI and/or anthropogenic forcings.

At any rate, we noted that regardless of what TSI series was considered, the sum of the "natural and anthropogenic forcings" fittings was able to explain most of the long-term warming, i.e., the second part of the IPCC's argument. However, the relative contributions of the "natural" (TSI) and "anthropogenic" components varied dramatically depending on the choice of TSI considered. If the TSI series used was unable to explain much warming (as was the case for the TSI series that were recommended to the AR5 and AR6 modelling groups for their hindcasts) then we replicated the IPCC attribution that the long-term warming was "mostly anthropogenic", but if alternative TSI series were used then this often reversed the attribution to anything from "both natural and anthropogenic" to "mostly natural". That is, the second part of the IPCC's argument was also heavily influenced by TSI choice.

We emphasized that our analysis had **not** established whether the long-term warming was either "mostly anthropogenic", "mostly natural", or some combination of both. However, it had established that the IPCC's confident "mostly anthropogenic" attribution was over-confident and premature. We called on the scientific community to revisit this important question more robustly. We offered several recommendations on how to go about this. Unfortunately, the literature cut-off date used by AR6 apparently ended 10.5 weeks too early for C2021 to be considered by IPCC (2021). Hence, none of these recommendations were considered for AR6.

Recently, Richardson & Benestad (2022) – henceforth "RB2022" – claimed to have found "errors" in the *secondary* part of our analysis. Further they asserted that C2021 was "flawed". They insisted that our analysis "should not be treated as credible and the IPCC statements on solar attribution remain intact".

Essentially, RB2022 argued that our two-stage fitting approach was "erroneous" and insisted that we should have carried out a single-step multiple regression using both natural and anthropogenic forcings. They speculated that this was the reason why the conclusions of C2021 differed from that of the IPCC. They insisted that the first stage of our analysis, i.e., evaluating the contribution of "natural forcings only", was irrelevant.

To support their claim, RB2022 repeated our analysis for one of the five ST records – the "urban and rural" record, i.e., the one we had highlighted as *anomalous*. As C2021 had noted, for this particular record that was contaminated by urbanization bias, TSI was unable to fully explain the long-term warming especially for recent decades. Therefore, their chosen ST was arguably the worst of the five ST records for evaluating their claim.

At any rate, as we will discuss, most of the claims RB2022 made about C2021 are themselves erroneous – and already explicitly discussed in advance by C2021. Indeed, building upon the datasets of C2021, Harde (2022) found that analysing the datasets of C2021 using energy-radiation-balance climate model simulations, "solar variations [over the last 140 years] can well explain two thirds of the increase..." in Northern Hemisphere ST (land and oceans). This already contradicts RB2022's suggestion that C2021's conclusions were solely due to the two-stage statistical fitting approach. Furthermore, explicitly referring to C2021 and RB2022 as well as previous work, Scafetta (2023) has recently carried out a multi-linear regression analysis using a subset of the C2021 TSI datasets but applying the analysis to global land ST (based on urban and rural data) and global ocean ST records used by IPCC rather than C2021's ST data. That analysis found changes in solar activity could explain as much of the observed warming as anthropogenic factors – and explicitly noted that the global land ST data considered was probably significantly contaminated by urbanization bias (Scafetta 2023).

Nonetheless, several of the concerns RB2022 raised about the limitations of the available data echoed those made by C2021. Furthermore, now AR6 has been published. Therefore, in this follow-up article, we will update, improve and expand on the analysis of C2021 in light of both the publication of AR6 and the comments of RB2022:

1. C2021 had stressed that the published versions of most of the 16 TSI reconstructions we had identified did not reach up to present – two ended in the 1990s and only one covered up to the final point of the temperature records (2018). Also, we have since identified several more TSI reconstructions that have been published in recent years. Hence, we will expand our compilation of plausible TSI estimates and use satellite TSI composite records (Scafetta et al. 2019; Schmutz 2021; de Wit et al. 2017) to update all time series to cover a common time period – 1850-2018.
2. RB2022 agreed with C2021 that volcanic forcing was not a plausible candidate for long-term warming. Nonetheless, it is one of only two "natural forcings" considered by the IPCC hindcasts. Therefore, for completeness, we repeat our analysis using AR6's recommended volcanic forcing as well as TSI to represent "natural forcings".
3. C2021 had explicitly stated that the use of multi-linear regression analysis (i.e., the approach recommended by RB2022) was worth considering "for future research". However, RB2022 apparently had confined their reanalysis to just one of our five ST records, i.e., the one contaminated by urbanization bias. Furthermore, for comparison with the IPCC's attribution experiments, the "natural and anthropogenic forcings" results should also be compared with the "natural forcings only" results. The IPCC attribution also sometimes considers "anthropogenic forcings only". Therefore, we will carry out separate multi-linear regressions along these lines for all five ST records for each of the new and updated TSI records.

2 ASSESSING RB2022'S ATTEMPTED REBUTTAL OF C2021

RB2022 boasts of having identified allegedly serious and basic "errors" in C2021. They assert that these alleged "errors" majorly undermine the analysis, findings and conclusions of C2021. As we will see, RB2022's boastful claims are themselves erroneous. In our opinion, most of their claims are already satisfactorily addressed in advance by C2021 – often with explicit detailed discussions in the text. Hence, we are sceptical whether the authors of RB2022 actually took the time to carefully read C2021 before writing their alleged critique.

Nonetheless, given the overconfident assertions of RB2022, many readers might initially think RB2022 had genuinely identified serious "errors" in C2021. Therefore, it is important to look at the claims of RB2022 and assess if they had any implications for C2021. Below, we will show that the *only* genuine scientific concerns raised by RB2022 had already been raised by C2021.

In this section, we will first describe some basic errors in RB2022 – some probably typographical. Then, we will describe the strawman arguments RB2022 used to describe C2021. Finally, we consider some of the points where RB2022 was essentially repeating explicit recommendations made by C2021 (although they neglected to mention they were agreeing with C2021).

2.1 Typographical errors made by RB2022

Ironically for a letter that frequently uses words such as "errors", "erroneous" and "flawed", RB2022 contains some rather sloppy errors or mistakes. Still, "it's only those who do nothing that make no mistakes, I suppose." – Conrad (1896), p. 183. So, while RB2022 do not appear to have identified any genuine "errors" in C2021, we would prefer to focus on RB2022's more substantive points and not dwell too much on their obvious mistakes – especially the typographical ones.

That said, given the hubris with which they boasted of having identified alleged "errors", we feel obliged to point out the following:

1. In their Eqn. 1, they introduce a term they call ΔT_{TSI} that seems to be meant to be compared with another term they call ΔF_{anthro}. However, in the text they never define or refer to the former term. Instead they refer in the text to ΔF_{TSI}. It seems probable that this was a typographical mistake. Still given that this was their sole equation, it seems to be a rather "basic error" (to quote RB2022).
2. C2021 had provided five different estimates for NH ST – each with an upper and lower uncertainty envelope. However, RB2022 apparently only got around to evaluating one of the five ST series (the one identified by C2021 as "anomalous"). They also seem to have overlooked its uncertainty envelope – ironically, since RB2022 had stressed the importance of considering the uncertainties associated with ST time series.
3. In their Section 2.3, they claim to have evaluated additional ST series in their Figure 5. However, their caption for this figure refers to four panels (a)-(d), while the figure itself only has two panels (a) and (b). Also, while the title for their (a) panel matches with the caption, the title for their (b) panel does not.

2.2 RB2022's "straw man" errors in their description of C2021

A "straw man" argument is a logical fallacy where someone sets up and then disputes a position that was not actually made by the group being criticised. Instead, the group's arguments or points are either exaggerated, misrepresented, or completely fabricated by the critics. All of the alleged "errors" that RB2022 have claimed to identify in C2021 are exclusively of this type.

This straw-manning starts in their abstract where they quote a fragment of a sentence from the abstract of C2021 out-of-context to imply that C2021 had reached a conclusion it had not. That is, RB2022 only reported the *italicized* fragment from the following sentence: "For all five Northern Hemisphere temperature series, different TSI estimates suggest everything from no role for the Sun in recent decades (implying that recent global warming is mostly human-caused) to *most of the recent global warming being due to changes in solar activity* (that is, that recent global warming is mostly natural)."

In their "3.3 Failure to Account for Relevant Information" subsection, RB2022 claim that C2021 "is also selective in its reporting of past findings" because we discussed certain controversial studies neutrally without taking sides. Yet, RB2022 neglected to mention that C2021 had explicitly informed the readers of the relevant controversies and provided the readers with representative literature presenting the key perspectives on each side. Moreover, RB2022 falsely claimed that C2021 "did not discuss" the scientific debates over the purported influence of galactic cosmic rays on climate change, even though this was discussed in detail in C2021's Section 2.6.4.

More fundamentally, in the preamble of their Section 2, they itemize six points as the alleged “errors” that RB2022 was claiming to have identified in C2021. However, even a cursory read of C2021 will reveal that all six points are strawman arguments. For four of the six points, RB2022 were repeating caveats already explicitly discussed in detail by C2021:

- *“1. Use of sequential rather than simultaneous regression”*. C2021 cautioned that the approach used was “... a relatively simplistic approach...” and “... it might be argued that the various contributions should be estimated simultaneously, e.g., via the use of a multilinear regression analysis or an energy balance model or a general circulation model. Indeed, several of us have carried out such analyses in the past [...] and are also planning similar approaches for future research.” (p53) See Section 5 of C2021 for a detailed discussion of the pros and cons of the intentionally simple approach used by C2021.
- *“2. Linear regression to quantify changes in the nonlinear $\Delta T(t)$ series”* and *“6. That this is a purely correlational analysis and does not consider physics.”* C2021 explicitly cautioned that, “For this analysis, we are explicitly assuming that there is a direct linear relationship between incoming TSI and Northern Hemisphere surface temperatures. However, as discussed in Sections 2.5 and 2.6, there is a lot of evidence to suggest that the relationships between solar activity and the Earth’s climate are nonlinear and a lot more subtle. [...] The goal of this analysis is not to dismiss these more nuanced approaches to investigating the Sun/climate relationships. Indeed, many of us have contributed to the literature reviewed in Sections 2.5–2.6, and we plan on pursuing further research along these avenues. Rather, we want to emphasize that, as will be seen shortly, even with this approach, a surprisingly wide range of results can be found. As researchers actively interested in resolving these issues, we find this wide range of plausible results disquieting.” (p. 52).
- *“3. Drawing conclusions using results calculated from other periods, such as one case where changes in “recent decades” are based on an 1815–1994 fit”*. C2021 explicitly based their analysis on the TSI records *as published* and carried out the fits over the maximum period of overlap between each TSI and ST record. However, we actively encouraged updating the TSI records, e.g., by using either the ACRIM or PMOD satellite composite to extend the records. As examples, Section 2.3 of C2021 demonstrated how this could be applied to four TSI records.

For their other two points, RB2022 were making demonstrably false claims:

- *“4. Lack of assessment of any uncertainties”*. All 5 ST series included an upper and lower uncertainty envelope and the fitting results explicitly considered these uncertainties. Meanwhile, a key finding C2021 discussed was that *the uncertainties associated with TSI choice* remain substantial and that varying TSI choice between each of 16 estimates yielded different results. C2021 explicitly cautioned that the IPCC were not correctly accounting for these uncertainties in their attribution statements.
- *“5. Use of non-global data (e.g., Northern Hemisphere (NH) land) to make assertions about global changes”*. C2021 was explicitly studying “How much has the Sun influenced *Northern Hemisphere* temperature trends” (emphasis in italics) due to the shortage of suitable ST data from the Southern Hemisphere. However, we provided five different estimates of ST averaged from 27 individual estimates – sorted into two instrumentally-based land ST estimates; one instrumentally-based ocean ST estimate; two types of land temperature proxy. RB2022 only analysed one of these – although they

briefly discussed two of the 27 individual estimates considered by C2021, i.e., the NH components of the Berkeley Earth "urban and rural" land component and HadSST4's sea-surface temperatures records.

2.3 "Steel-manning" where RB2022 agreed with C2021

Rather than repeating RB2022's straw-manning approach, we believe it is more productive to take an opposite approach known on the internet as "steel manning"[2]. Essentially, this involves addressing the best and most constructive form of someone's argument – even if it is not the form they originally presented.

Although they neglected to mention this, RB2022's most substantive points actually echoed recommendations that C2021 had made for future research:

- For a more direct comparison, the period of analysis should be the same for all TSI series and the end point should be relatively recent – ideally the end of the ST records, i.e. 2018 for the three thermometer-based ST series; 2002 for the tree-ring proxies; 2000 for the glacier-length proxies.
- RB2022's analysis only considered one of C2021's 5 ST series (NH land based on urban and rural stations) and did not assess the uncertainty envelopes provided by C2021. RB2022 suggested that this "use of non-global data (e.g., Northern Hemisphere (NH) land)..." and "lack of assessment of any uncertainties" could limit the relevance of the analysis. Therefore, RB2022's analysis should be updated to consider C2021's additional ST series and their accompanying uncertainty envelopes.
- RB2022 agreed with C2021 that volcanic forcing was not a plausible candidate for long-term warming. Nonetheless, RB2022 correctly note that a more comprehensive attribution analysis should consider it as a relevant climatic driver.
- RB2022 speculated that the conclusions of C2021 would have been different if a multilinear regression had been carried out instead of C2021's sequential regression analysis. While we disagree with RB2022 on this speculation, C2021 had also encouraged such a multilinear regression analysis for future research.
- RB2022 agree with C2021 that this analysis explicitly assumes a direct linear relationship between TSI and ST, so it is important to stress that this assumption is *not* a given and that researchers should be aware of literature debating this assumption. C2021 provided a substantial review of much of this literature in their Sections 2.5-2.6. RB2022 supplemented this review with some additional commentary and relevant literature.

In this manuscript, we will follow up on these recommendations made by *both* C2021 and RB2022. We will then carry out a multilinear regression analysis as suggested by both C2021 and RB2022. However, as we will see, we find that contrary to RB2022's speculations, this updated analysis seems to confirm C2021's conclusions.

[2] E.g., see `https://themerelyreal.wordpress.com/2012/12/07/steelmanning/`; `https://conversion-rate-experts.com/steel-manning/`; `https://themerelyreal.wordpress.com/2016/08/11/saving-the-steelman/`.

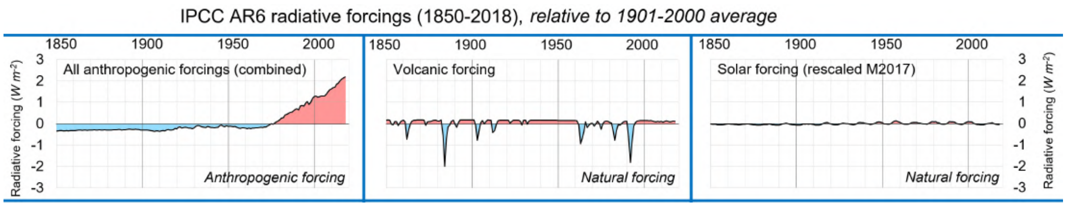

Fig. 2: The (left) anthropogenic, (middle) volcanic and (right) solar components recommended by IPCC AR6 for GCM hindcasts – taken from IPCC AR6 WG1 Annex III dataset (IPCC 2021) that we downloaded from `https://doi.org/10.5281/zenodo.5705391` All three components are plotted for the period 1850–2018 in terms of "radiative forcing" in units of W m^{-2} relative to their 20th century average.

3 DATA AND METHODS USED

1. All five ST estimates and their uncertainty envelopes were downloaded from the Supplementary Materials for C2021 at `https://doi.org/10.5281/zenodo.7088728`, along with the 16 TSI reconstructions and the four additional reconstructions provided by C2021 as examples of using satellite composites to update older TSI reconstructions (Foukal 2012, 2015; Solanki & Fligge 1998, 1999).
2. We expand our analysis to include additional TSI reconstructions identified since C2021 (Wu et al. 2018; Kopp 2018; Coddington et al. 2019; Wang & Lean 2021; Xu et al. 2021; Penza et al. 2022; Dewitte et al. 2022). The new expanded dataset contains 27 TSI reconstructions for 1850–2018.
3. We update all TSI records to ensure they all cover the same period, 1850-2018. We do this by calibrating one of three contemporary TSI estimates, i.e., the ACRIM or PMOD satellite composite or the sunspot number (SSN) record to match each TSI record that finishes before 2018 over the last 12 years (i.e., > 1 solar cycle) of the overlap period. If the reconstruction is a SSN reconstruction, we use SSN. If the reconstruction shows an increase in TSI during the 1980s-1990s, then we will use the ACRIM composite updated to 2018 following the approach of Scafetta et al. (2019). Otherwise, we use the PMOD composite (Montillet et al. 2022). After calibration, this is used to extend the TSI reconstruction up to 2018.
4. The Solanki & Fligge (1998) A and B models (1874–1992) were extended back to pre-1850 using the digitized equivalent reconstructions of Solanki & Fligge (1999) after calibration over the overlapping period – although we note that these earlier components were smoothed by Solanki & Fligge (1999) with an 11–year running mean.
5. The Xu et al. (2021) model A reconstruction was extended using their model B reconstruction recalibrated over the common period of models A and B.
6. For volcanic and anthropogenic components, we use the relevant time series from the IPCC AR6 WG1 Annex III dataset (IPCC 2021) that we downloaded from `https://doi.org/10.5281/zenodo.5705391`.
7. We carry out multi-linear regressions for "natural forcings only", "natural and anthropogenic forcings" and "anthropogenic forcings only" for the five temperature records using each of the 27 TSI records over the same period: 1850–2018 for the three instrumentally-based ST series; 1850–2002 for the tree-ring proxies; 1850–2000 for the glacier-length proxies.

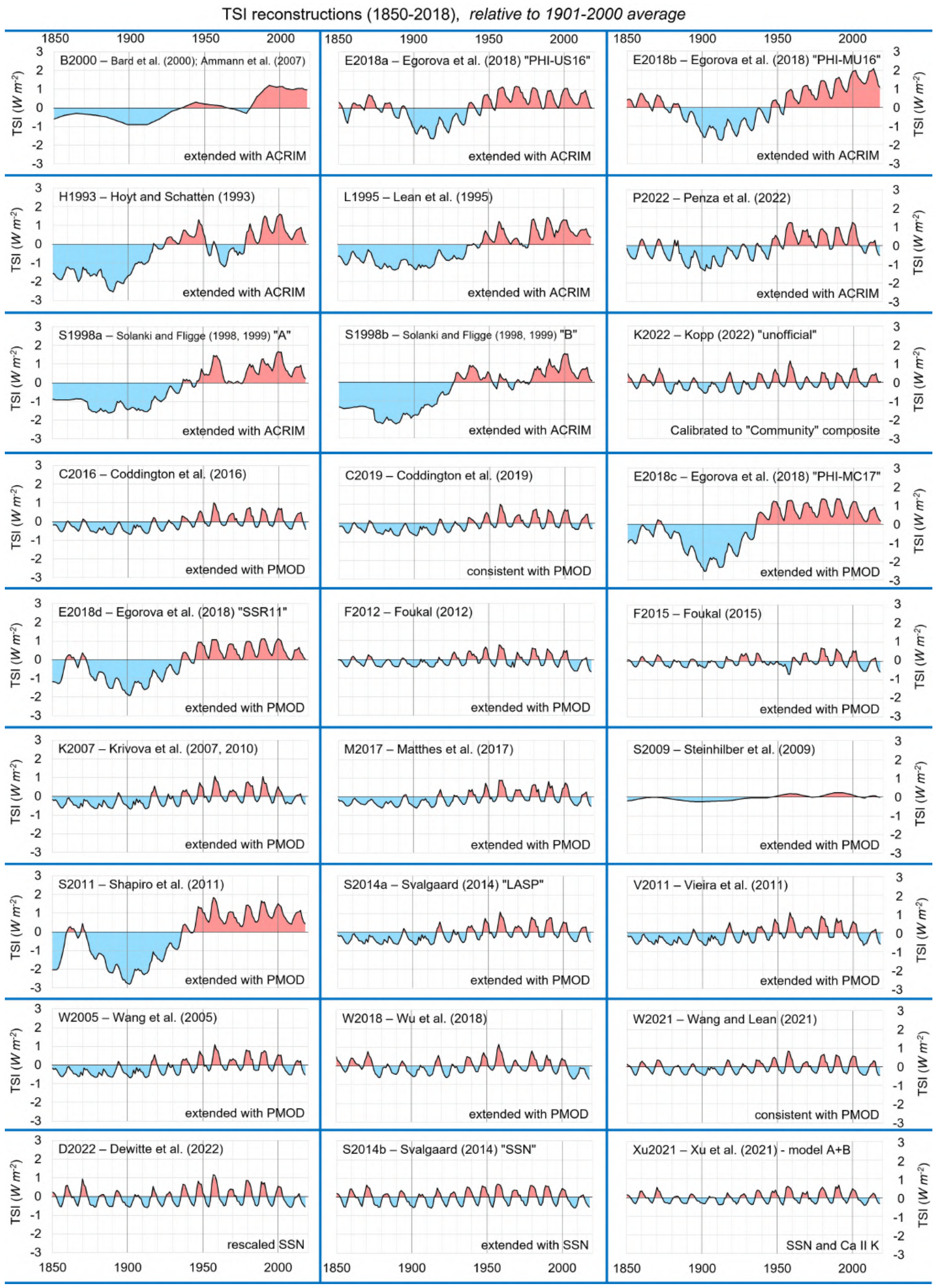

Fig. 3: All 27 TSI estimates for the period 1850–2018, extended up to 2018 using either ACRIM or PMOD or SSN depending on the reconstruction. All estimates are plotted in units of W m^{-2} relative to their 20th century average. All estimates are denoted by the 1st letter and year of the original study – followed by a lower case letter if multiple estimates are available. The first 8 panels are extended using ACRIM and listed alphabetically. K2022 was developed with the “Community” satellite composite (de Wit et al. 2017). The next 15 panels were extended or consistent with PMOD and are listed alphabetically. The final 3 panels are TSI estimates derived by scaling the SSN record, although Xu2021 also incorporates a rescaled Ca II K component.

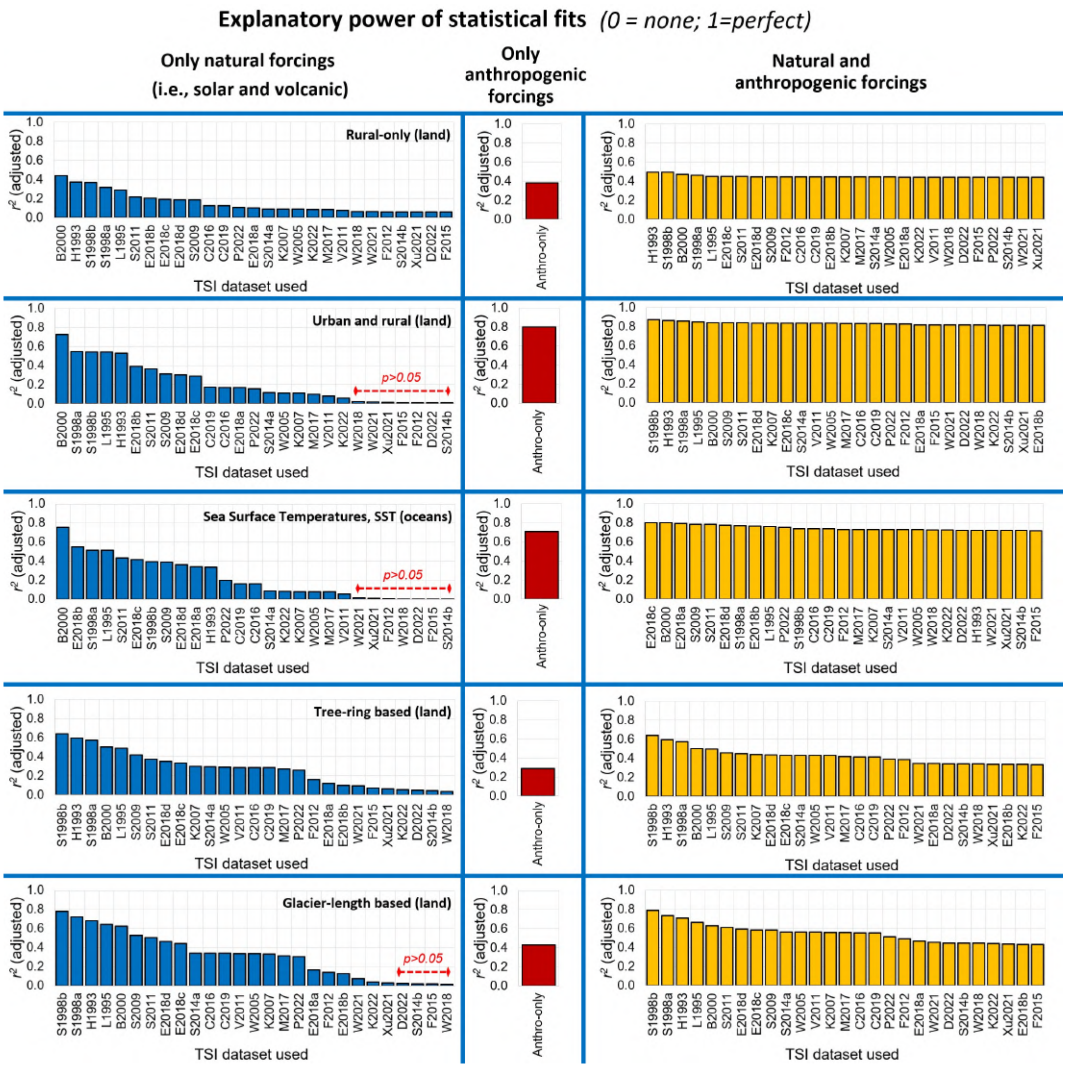

Fig. 4: Adjusted r^2 statistics for all multi-linear regression fittings. The higher the r^2 value (from 0 to 1), the more of the observed temperature series could be explained in terms of the components used in the statistical fitting. Left hand panels correspond to the fittings using only natural forcings (solar and volcanic) with the results for each TSI dataset ranked from best fit (left) to worst fit (right). All fits were statistically significant ($p < 0.05$), except for the weakest fits highlighted with the $p > 0.05$ label. Middle panels show the results using only the anthropogenic forcings series. Right hand panels correspond to the combined “natural and anthropogenic” fits. Each row corresponds to a different ST record – from top to bottom: rural-only; urban and rural; sea surface temperatures; tree-ring based; glacier-length based.

8. C2021 had carried out separate fits for the mean, upper, and lower bounds of each ST series. For simplicity, the regressions here are carried out only to the mean series (as RB2022 did). However, in our visual analysis of the fits, we will include the upper and lower bounds of each ST series.

Our multi-linear regression fits are ordinary least squares (OLS) fits between the target ST series and up to three components (anthropogenic, volcanic and solar). In the case of “anthropogenic forcings only”, since there is only one component, those results are equivalent to those from a simple OLS linear fit. However, for “natural forcings only” and “natural and anthropogenic forcings”, the fitting simultaneously considers two (volcanic and solar) or three components (anthropogenic, volcanic and solar) respectively. The fitting

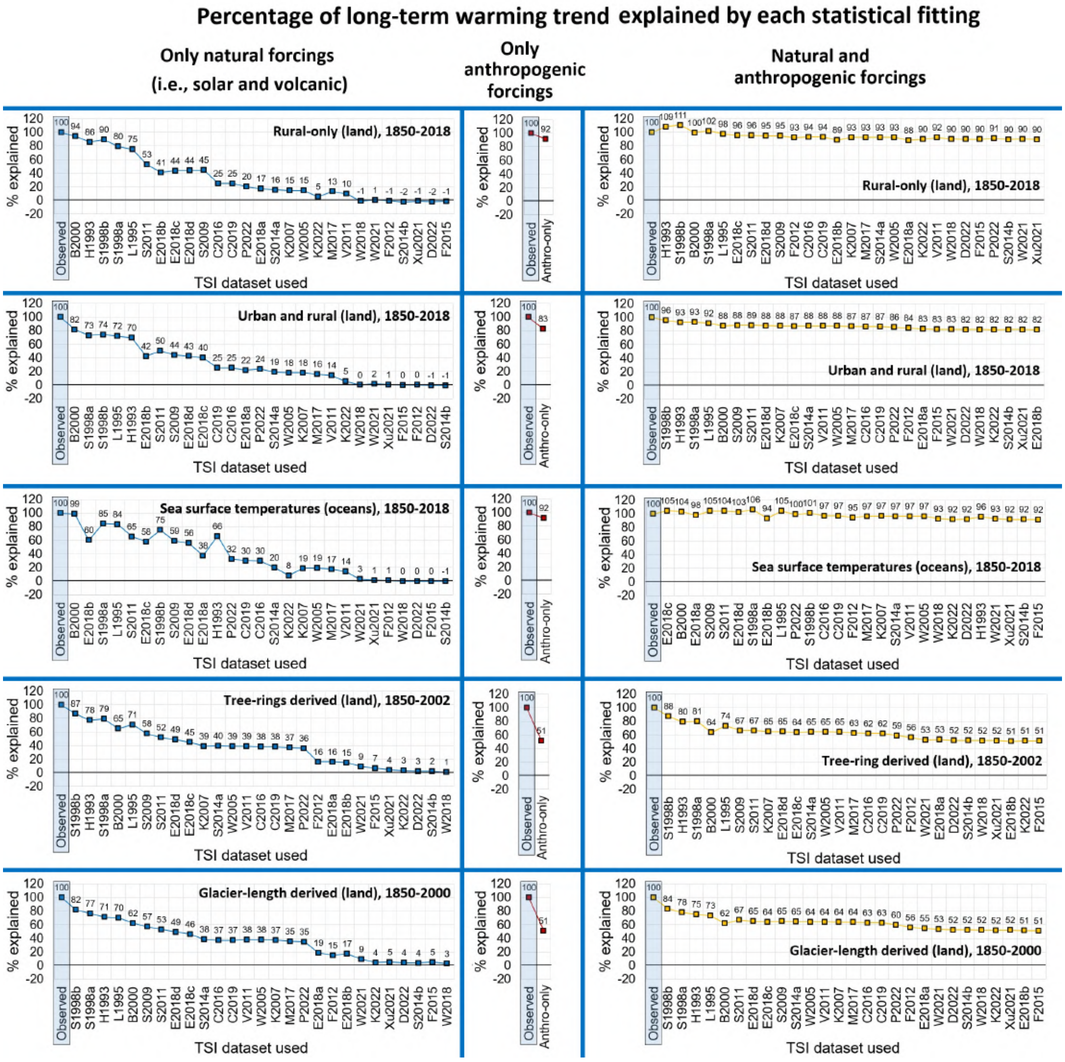

Fig. 5: Percentages of the long-term warming linear trend for all multi-linear regression fittings to each of the temperature series. The linear trends were calculated over the maximum overlap period: 1850–2018 for the three instrumental estimates; 1850–2002 for the tree-ring based proxies; 1850–2000 for the glacier-length based proxies. As for Figure 4, left hand panels correspond to the fittings using only natural forcings (solar and volcanic) with the results for each TSI dataset ranked as in Figure 4, i.e., from best fit (left) to worst fit (right). Middle panels show the results using only the anthropogenic forcings series. Right hand panels correspond to the combined “natural and anthropogenic” fits. Each row corresponds to a different ST record – from top to bottom: rural-only; urban and rural; sea surface temperatures; tree-ring based; glacier-length based.

coefficients and fitting statistics for all fits are provided in the Supplementary Materials file. The annual values for the model fits as well as the contribution from each component are also provided.

The anthropogenic, volcanic and solar components recommended by IPCC AR6 for GCM hindcasts are plotted from 1850–2018 in Figure 2. The updated and expanded TSI datasets are plotted from 1850–2018 in Figure 3. The TSI component recommended by AR6 shown in Figure 2 is Matthes et al. (2017), which is labelled “M2017” in Figure 3. However, AR6 reports the solar component in terms of “radiative forcing” (RF) that has been rescaled to account for various factors – geometrical projection; planetary albedo; troposphere/stratosphere inter-relationships. Hence, the scaling of "M2017" in Figure 2 and Figure 3 are different. While AR6 effectively only considered 1 TSI estimate, in this study we will consider all 27 TSI estimates.

4 RESULTS AND DISCUSSION

The statistics associated with the multi-linear regression fittings for all combinations of 27 TSI estimates, one volcanic estimate (AR6's) and one combined "all anthropogenic forcings" series (AR6's) to the five ST estimates are provided in Figures 4 and 5. In Figure 4, the r^2 statistics (adjusted to account for the multiple components of the fitting, as is standard for multi-linear fits) are plotted. r^2 provides a useful metric for describing the "statistical explanatory power" of each fit. The higher the value (between 0 and 1), the better the statistical fit describes the observed data, i.e., ST. Since we have used different combinations of natural forcings and anthropogenic forcings for each of our fits, this allows us to assess how much of the observed ST can be *statistically explained* by the natural and anthropogenic forcings.

Note that these results are "statistical explanations" rather than being "physical explanations" explicitly derived from physical grounds. Nonetheless, each of the components being fitted are believed to be climatic drivers. Therefore, if a statistical relationship exists between any of these drivers and ST, then this is *consistent with* a physics-based attribution. Although, as we will see, our analysis will reveal many statistical fits that are often mutually contradictory, e.g., in many cases the "only anthropogenic forcings" fits yield comparable statistical results to some "only natural forcings" fits.

At any rate, by comparing the fits using only natural forcings (left-hand panels) to those using only anthropogenic forcings (middle panels), we can see a few key points:

1. The fits for "only natural forcings" vary dramatically from quite good (left) to very poor (right) depending on TSI choice. As indicated by the red dashed lines and labels, for three of the ST estimates, the weakest fits are not statistically-significant, i.e., $p > 0.05$ (where p is determined from the relevant f statistic associated with the fitting).
2. For the TSI series with the best fits, the r^2 for "only natural forcings" is, at a minimum, comparable to that for "only anthropogenic forcings" – for some STs, the best "only natural forcings" fits are superior.
3. Five of the TSI series ("H1993", "L1995", "S1998a", "S1998b" and "B2000") have the top five r^2 values for four of the 5 ST estimates. For the remaining ST estimate (i.e., SST), all five of these TSI series also perform well. All five of these TSI series have been updated using the ACRIM composite – see Figure 3.
4. The fits using the three TSI series based on SSN ("S2014b", "Xu2021" and "D2022") are consistently poor, ranking in the bottom six r^2 values for all ST.
5. Of the PMOD-calibrated TSI series, four consistently rank in the bottom-10 worst fits in terms of r^2 for all 5 STs ("F2012", "F2015", "W2018" and "W2021").
6. AR6's recommended TSI series ("M2017") consistently performs poorly in the bottom-12 worst fits for all 5 STs.

Not surprisingly, for the combined "natural and anthropogenic forcings" fits (right-hand panels of Figure 4), the r^2 values are higher than either "only anthropogenic forcings" or "only natural forcings". For the TSI series that perform poorly, the corresponding combined "natural and anthropogenic forcings" fits have an r^2 value that is at least as high as "only anthropogenic forcings". For the TSI series that perform best, adding anthropogenic forcings sometimes improves the corresponding r^2 value, but typically only modestly.

Figure 5 plots the percentage of the 1850–2018 linear temperature trend for each ST that is captured by each of the fits. The fits are presented in the same order as in Figure 4. As discussed by both C2021 and RB2022, analysis based on linear trends should be treated cautiously here since each of the ST series demonstrate non-linear, multi-decadal variability. Nonetheless, it is a convenient metric for assessing how much of the long-term warming implied by each ST can be explained in terms of the fitted components.

1. For four of the ST estimates, the best performing TSI series in the "only natural forcings" fits can nominally explain more of the long-term warming than the "only anthropogenic forcings". For the remaining ST estimate ("urban and rural"), the "only anthropogenic forcings" fit can explain 83% of the long-term 1850–2018 warming. The best performing "only natural forcings" fit ("B2000") can explain 82% of the warming, i.e., nearly the same but *slightly* less.
2. Using the worst performing TSI estimates, the "only natural forcings" fits are unable to explain more than a few percent of the long-term 1850–2018 warming. For example, the "W2018" TSI series only explains between -1 to 3% of the warming for any of the 5 STs. Similarly, the "D2022" series only explains between -2 to 4% of the warming. AR6's recommended series ("M2017") can only explain between 13-17% of the 1850–2018 warming for the three instrumentally-based STs – although it can explain 35-37% of the long-term warming for the two temperature proxy STs.
3. For the three instrumentally-based STs, the "only anthropogenic forcings" fits can explain 83-92% of the long-term 1850–2018 warming. For the "only natural forcings" fits, the top–three TSI estimates can explain 60-99% of the warming, yet the bottom–seven TSI estimates cannot explain more than 3% of the warming. This confirms C2021's conclusion that varying TSI choice can dramatically alter the attribution results.
4. For the two temperature proxy-based STs, the "only anthropogenic forcings" fits can only explain 51% of the corresponding long-term warming trends (i.e., 1850–2000 for glacier lengths and 1850–2002 for tree rings). However, the top–three TSI estimates are able to explain between 71-87% of the warming using "only natural forcings".
5. Again, for the combined "natural and anthropogenic forcings" fits (right-hand panels of Figure 5), the percentage of the long-term warming that can be explained is consistently higher than either "only anthropogenic forcings" or "only natural forcings". However, as C2021 had found, this often yields figures greater than 100%, i.e., it over-explains the long-term warming.

To better explore the relative fits, in Table 1, we summarize the main statistics for three representative fits for each ST and set of forcings. In Figures 6, 7 and 8, we graphically compare some of the most representative fits to the relevant ST along with the uncertainty envelopes associated with each ST estimate.

In Table 1, for each ST, we first list the long-term warming trend for the full period of overlap, i.e., 1850-2018 for the three instrumental STs; 1850-2002 for the tree-ring proxy ST; 1850-2000 for the glacier-length proxy ST. Comparing the different ST estimates, we confirm that the sea surface temperature record shows much less warming than any of the land-based estimates (as already noted by C2021). Meanwhile,

Table 1: Some key fitting statistics for each of the ST estimates in terms of different combinations of natural and anthropogenic forcings using one of three of the TSI series (as discussed in text). r^2 values for *non-statistically significant* fits ($p > 0.05$) are italicised.

Fitting approach	TSI used	r^2 (adjusted)	Long-term warming explained	Solar	Volcanic	Anthropogenic
Rural-only (land), 1850-2018 trend = 0.554°C/100y:						
Only anthropogenic	None	0.381	91.5%	–	–	91.5%
Only natural	Max solar (B2000)	0.440	94.4%	96.2%	-1.8%	–
Only natural	Min solar (S2014b)	0.057	-2.2%	-0.4%	-1.6%	–
Only natural	IPCC AR6 (M2017)	0.084	13.2%	14.8%	-1.8%	–
Natural and anthropogenic	Max solar (B2000)	0.470	99.6%	51.1%	-1.8%	50.4%
Natural and anthropogenic	Min solar (E2018b)	0.443	88.8%	-8.3%	-1.6%	98.7%
Natural and anthropogenic	IPCC AR6 (M2017)	0.442	92.8%	4.7%	-1.6%	89.7%
Urban and rural (land), 1850-2018 trend = 0.885°C/100y:						
Only anthropogenic	None	0.801	82.5%	–	–	82.5%
Only natural	Max solar (B2000)	0.725	81.5%	82.1%	-0.7%	–
Only natural	Min solar (S2014b)	*0.007*	-0.8%	-0.2%	-0.6%	–
Only natural	IPCC AR6 (M2017)	0.096	15.9%	16.5%	-0.6%	–
Natural and anthropogenic	Max solar (S1998b)	0.872	95.7%	30.2%	-0.5%	66.0%
Natural and anthropogenic	Min solar (W2018)	0.817	82.4%	-0.2%	-0.6%	83.1%
Natural and anthropogenic	IPCC AR6 (M2017)	0.833	87.0%	7.6%	-0.6%	80.0%
Sea surface temperatures (oceans), 1850-2018 trend = 0.376°C/100y:						
Only anthropogenic	None	0.707	91.8%	–	–	91.8%
Only natural	Max solar (B2000)	0.757	99.2%	99.7%	-0.8%	–
Only natural	Min solar (S2014b)	*0.002*	-0.5%	0.0%	-0.5%	–
Only natural	IPCC AR6 (M2017)	0.077	17.3%	17.8%	-0.5%	–
Natural and anthropogenic	Max solar (B2000)	0.799	103.5%	62.0%	-0.5%	42.0%
Natural and anthropogenic	Min solar (W2018)	0.727	92.8%	-0.5%	-0.5%	93.9%
Natural and anthropogenic	IPCC AR6 (M2017)	0.730	96.5%	7.7%	-0.5%	89.4%
Tree-ring proxy based (land), 1850-2002 trend = 0.440°C/100y:						
Only anthropogenic	None	0.288	51.4%	–	–	51.4%
Only natural	Max solar (S1998b)	0.642	86.8%	88.6%	-1.8%	–
Only natural	Min solar (W2018)	0.036	0.9%	2.7%	-2.0%	–
Only natural	IPCC AR6 (M2017)	0.272	37.0%	39.3%	-2.0%	–
Natural and anthropogenic	Max solar (S1998b)	0.640	87.5%	85.5%	-1.8%	3.9%
Natural and anthropogenic	Min solar (W2018)	0.337	50.9%	-4.5%	-3.0%	58.4%
Natural and anthropogenic	IPCC AR6 (M2017)	0.418	63.0%	25.0%	-2.7%	40.9%
Glacier-length based (land), 1850-2000 trend = 0.457°C/100y:						
Only anthropogenic	None	0.431	51.2%	–	–	51.2%
Only natural	Max solar (S1998b)	0.782	81.8%	81.4%	0.4%	–
Only natural	Min solar (W2018)	*0.016*	2.6%	2.2%	0.4%	–
Only natural	IPCC AR6 (M2017)	0.317	35.4%	35.2%	0.2%	–
Natural and anthropogenic	Max solar (S1998b)	0.789	83.6%	74.0%	0.2%	9.4%
Natural and anthropogenic	Min solar (F2015)	0.430	51.2%	-0.2%	-1.1%	52.5%
Natural and anthropogenic	IPCC AR6 (M2017)	0.555	63.9%	23.2%	-0.9%	41.4%

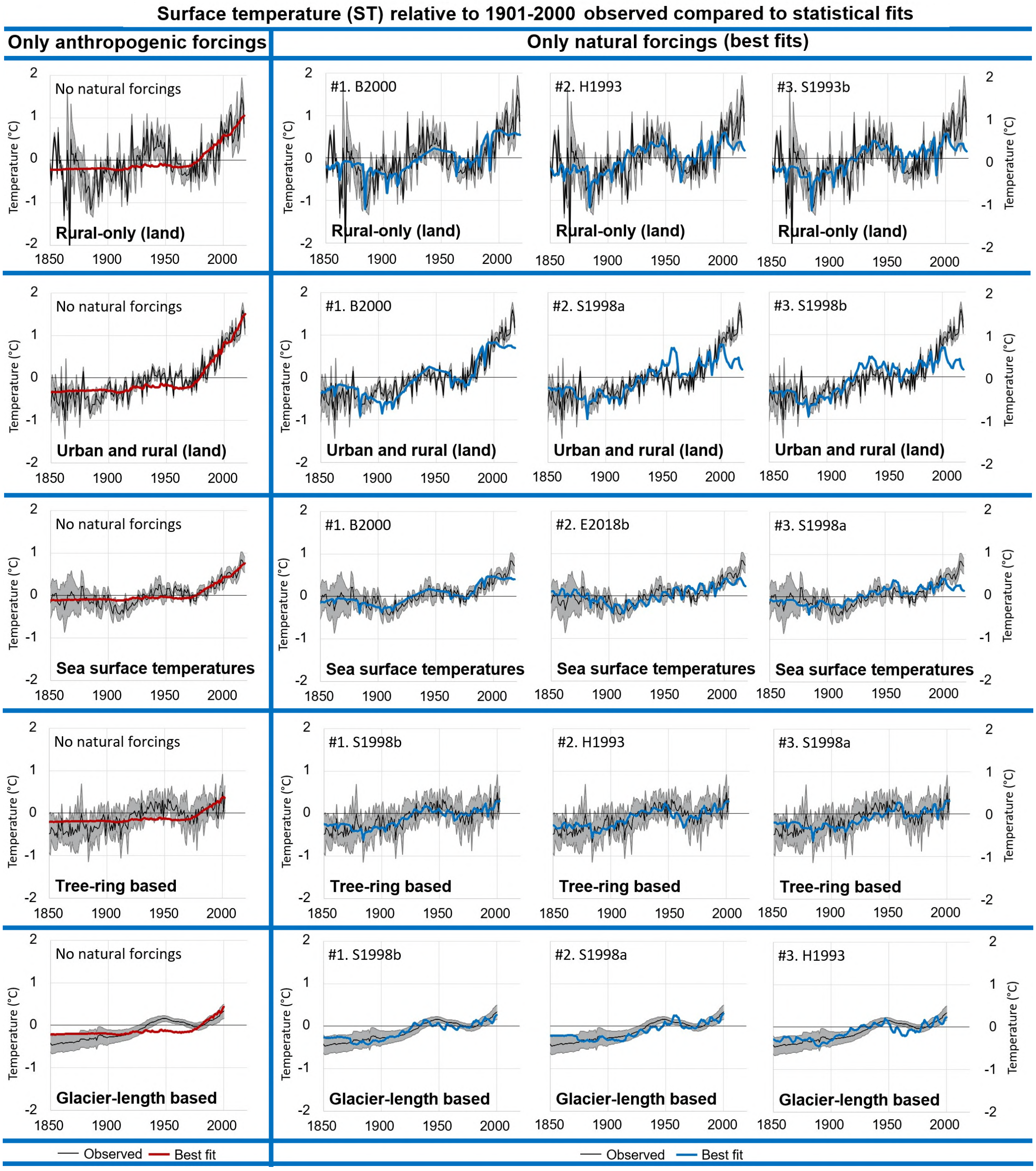

Fig. 6: Comparison of the various ST estimates (thin black line for mean estimates; gray envelope for associated uncertainty bands) to some of the statistical fittings. The left-hand panels correspond to the best fits using only anthropogenic forcings (thick red line). The other panels correspond to the three best statistical fits (in terms of r^2) using only natural forcings (thick blue line). Each row corresponds to a different ST record – from top to bottom: rural-only; urban and rural; sea surface temperatures; tree-ring based; glacier-length based.

the urban and rural ST implies 60% more warming than the rural-only ST (0.885°C/100y compared to 0.554°C/100y) and even more warming than any of the other ST estimates (also already noted by C2021). This is consistent with other studies that have argued that the land component of current global temperature estimates remains significantly contaminated by urbanization biases, e.g., Soon et al. (2015); Zhang et al. (2021); Scafetta (2021); Katata et al. (2023).

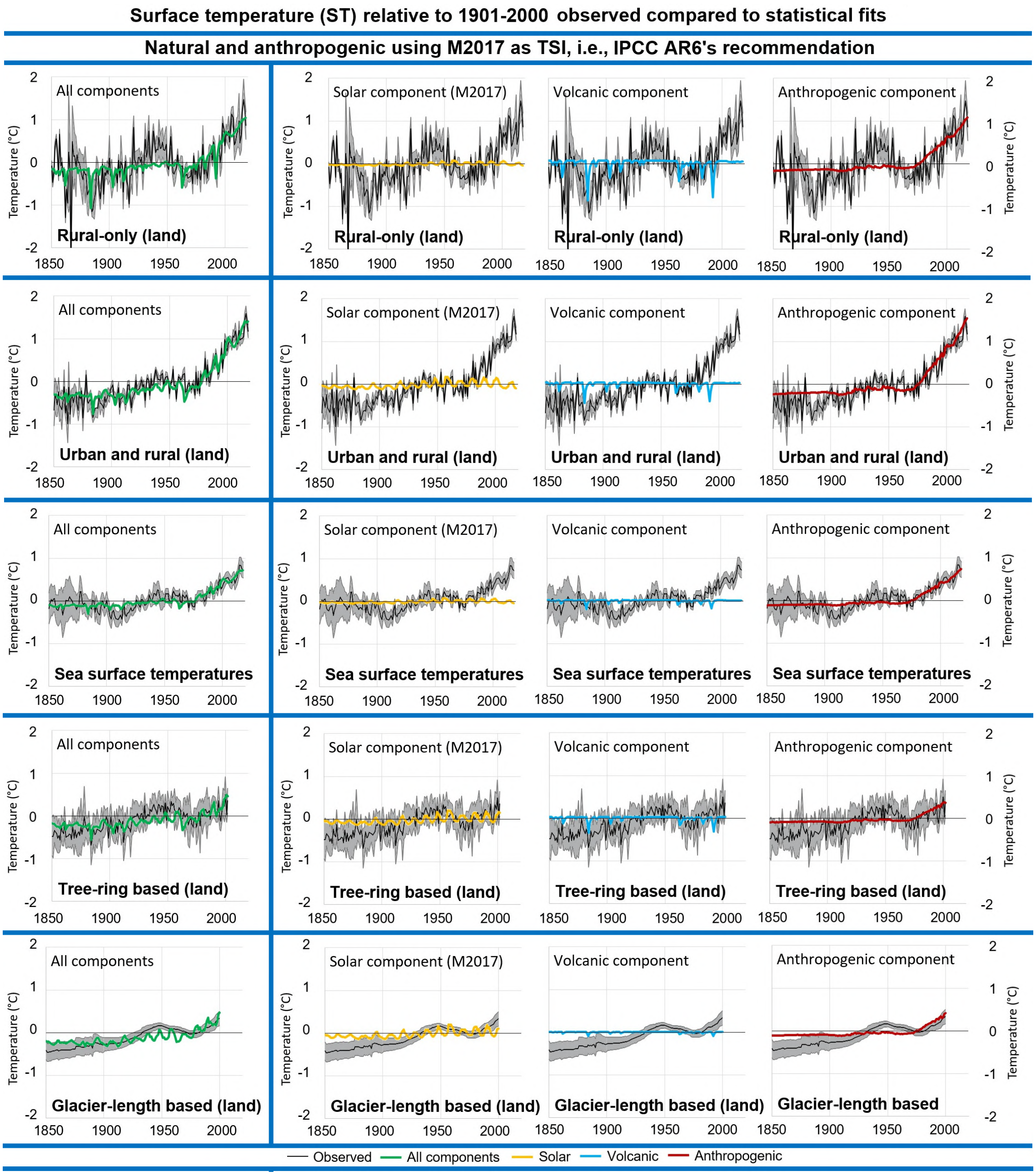

Fig. 7: Breakdown of the natural and anthropogenic statistical fits for each of the ST estimates (thin black line for mean estimates; gray envelope for associated uncertainty bands) using IPCC AR6's recommended M2017 TSI series. The left-hand panels correspond to the best fits using all components (thick green line). The other panels correspond to – from left to right: the solar component (thick yellow line); volcanic component (thick blue line); anthropogenic component (thick red line). Each row corresponds to a different ST record – from top to bottom: rural-only; urban and rural; sea surface temperatures; tree-ring based; glacier-length based.

We then list the TSI series used; the adjusted r^2 statistics; and the percentage of the long-term warming explained by the fits. The percentage of the long-term warming explained by each of the three components (solar, volcanic and anthropogenic) are also provided. For each ST, we present the results for the "only anthropogenic forcings". Then we present the "only natural forcings" results for three different TSI estimates:

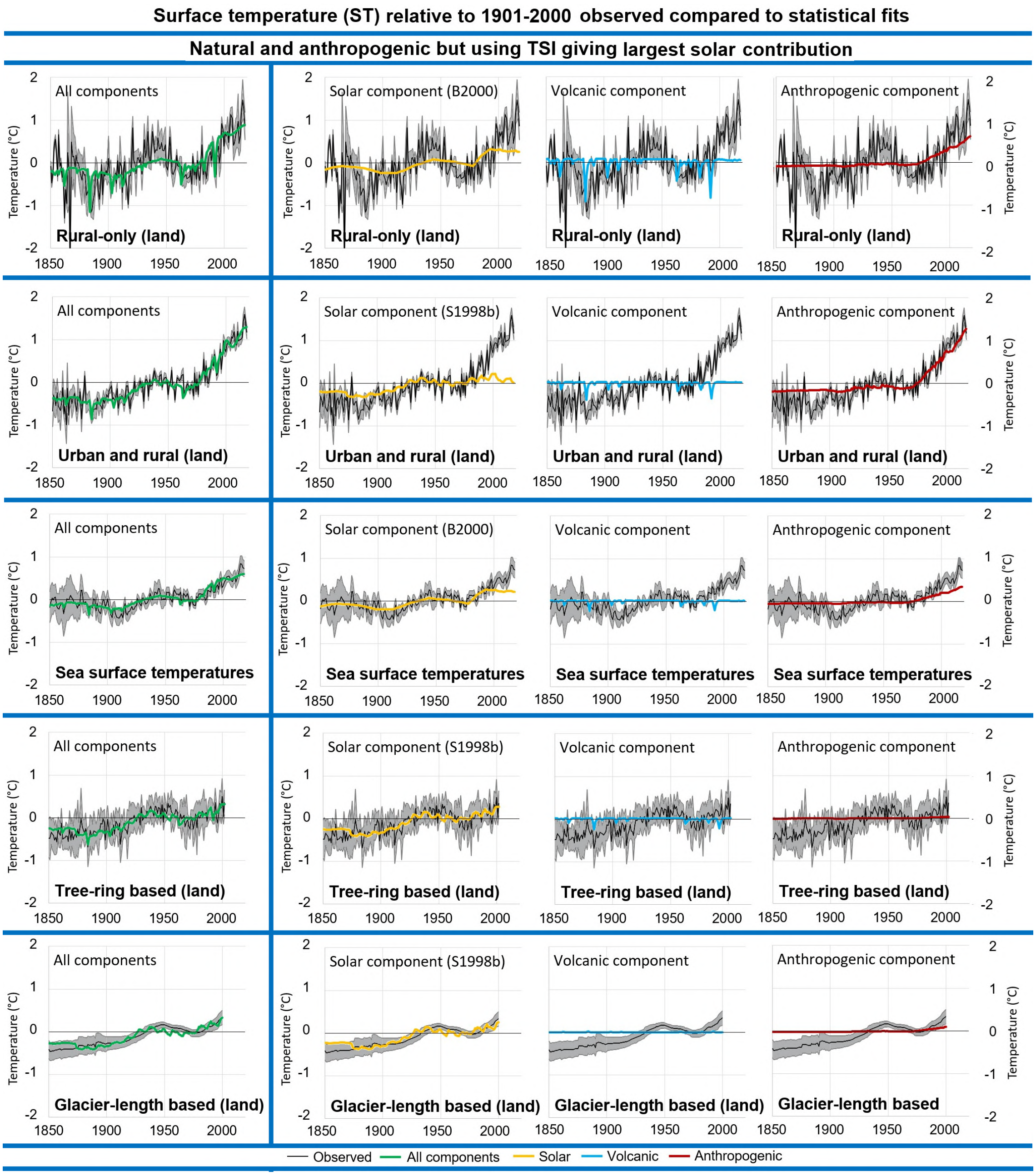

Fig. 8: Breakdown of the natural and anthropogenic statistical fits for each of the ST estimates (thin black line for mean estimates; gray envelope for associated uncertainty bands) using the TSI series that maximizes the solar contribution to the long-term warming. The left-hand panels correspond to the best fits using all components (thick green line). The other panels correspond to – from left to right: the solar component (thick yellow line); volcanic component (thick blue line); anthropogenic component (thick red line). Each row corresponds to a different ST record – from top to bottom: rural-only; urban and rural; sea surface temperatures; tree-ring based; glacier-length based.

(i) “Max solar”, i.e., the fit yielding the highest solar contribution; (ii) “Min solar”, i.e., the fit yielding the lowest solar contribution; and (iii) “IPCC AR6”, i.e., the fit using AR6’s recommended “M2017” TSI estimate. Then we repeat this for the “natural and anthropogenic forcings” fits.

Most of these results have already been presented graphically in Figures 4 and 5 and have already been discussed above. Nonetheless, we find the tabular format allows us to more easily compare and contrast the key results. It also allows us to compare the contributions of each component to the long-term warming for each fit. We note the following:

1. For the "only anthropogenic" fits, anthropogenic warming can explain most of the long-term warming for the three instrumental STs (82.5% to 91.8%) and slightly more than half of the long-term warming for the two proxy-based STs (51.2% to 51.4%).
2. Meanwhile, for the "only natural" fits, the solar contribution ranges from negative percentages for the "Min solar" TSI to almost all of the long-term warming for the "Max solar" TSI for each ST, i.e., everything from 81.4% of the glacier-length proxy ST warming to 99.7% of the SST warming.
3. While AR6's recommended "M2017" TSI estimate can consistently explain a bit more of the warming than the "Min solar", the fits explain much less warming than those using the 'Max solar". Specifically, using AR6's recommended TSI estimate, the maximum solar contribution to the long-term warming for the instrumental STs is 14.8% to 17.8% using "only natural forcings". This contribution is reduced further for the "natural and anthropogenic" fits to 4.7% to 7.7%. And the volcanic contribution is always a slight cooling (-1.6% to -0.5%). Therefore, we can see that because AR6 assumed "M2017" accurately described TSI estimate and that solar and volcanic were the only relevant natural forcings, their attribution analysis was guaranteed to conclude that most of the long-term warming was *not* natural in origin.
4. That said, if we consider the "only natural" fits, the "Max solar" results are slightly better than the "only anthropogenic" fits – in terms of both adjusted r^2 and the percentage warming explained – for 4 of the 5 STs, and very comparable for the remaining ST (i.e., urban and rural).
5. In general, the "natural and anthropogenic" fits can explain slightly more warming than the corresponding fits using either "only natural" or "only anthropogenic". However, statistically, the best fits for each set of forcings are comparable.
6. For the "natural and anthropogenic" fits *using the "Max solar" results*, even though the solar contribution is always reduced relative to the "only natural" fits, the solar contribution represents the majority ($> 50\%$) of the long-term warming for 4 of the 5 STs. For the remaining ST (urban and rural), anthropogenic warming accounts for more than twice the solar warming – although the solar warming contribution is still much greater than that using AR6's recommended TSI (30.2% compared to 7.6%). Therefore, with the sole exception of the urban and rural land component, using "natural and anthropogenic" fits, we can explain the long-term warming as being anything from "mostly anthropogenic" to "mostly natural" depending on TSI choice.

In Figure 6, we directly compare each of the ST time series (thin black lines) with the accompanying uncertainty intervals (gray envelope) to the statistical fits for "only anthropogenic forcings" (thick red line, left-hand panels) and the three best-performing (in terms of r^2) fits using "only natural forcings" (thick blue lines).

The "only anthropogenic forcings" fits consistently capture most of the post-1970s warming of all 5 STs. However, we note that, in general, the top-three TSI series appear to capture better the timing and relative magnitude of the various multi-decadal warming and cooling periods in terms of "only natural forcings" than the "only anthropogenic forcings" fits. This is particularly striking for the mid-20th century warm period, which is very poorly described in terms of "only anthropogenic forcings". That is, the modelled mid-20th century warming typically remains below the uncertainty envelope associated with each ST.

For the "only natural forcings", we note a growing divergence in the early 21st century between the fits and the "urban and rural" ST. However, this divergence is less pronounced for the other two instrumentally-based STs. This suggests that the "urban and rural" ST estimate is affected by urbanization bias (Soon et al. 2015; Zhang et al. 2021; Scafetta 2021). This is especially so if we consider the fact that 2014–2016 was associated with a very warm El Niño, and therefore our analysis in terms of only solar, volcanic and anthropogenic forcings might be underestimating natural "unforced" internal variability (Chylek et al. 2020).

Meanwhile, for the two temperature-proxy based STs, the best fits in terms of "only natural forcings" appear to match much better than those for "only anthropogenic forcings".

As a final comment on the "only natural forcings" fits, we note that for each ST, the top three fits are all reasonably plausible matches to the observed ST – the modelled fits remain within the uncertainty envelope for *most* of the record (although temporary deviations outside the envelope can be seen for the urban and rural fits). However, each of the fits implies a slightly different history of the expected naturally-driven warming and cooling periods from each other. Also, the ranking of the best fitting TSI changes between ST estimates. Therefore, even if we assume a good fit to the data is an indication of accuracy, it remains unclear which of these TSI estimates is most accurately capturing the true TSI changes over the 1850-2018 period.

Now, let us consider the "natural and anthropogenic" fits. In Figure 7, we plot the fits using AR6's recommended "M2017" TSI record for all 5 STs. In contrast, Figure 8 plots the results for the "Max solar" TSI for each ST. For both figures, the panels on the left-hand-side compare the model fit (thick green line) to the corresponding ST (black line with gray uncertainty envelope). The other three panels for each ST present the individual contributions from solar (left, thick yellow line); volcanic (middle, thick blue line); and anthropogenic (right, thick red line).

As discussed above, the solar contribution using M2017 is at best modest. Therefore, in Figure 7, other than the color, the anthopogenic components (right-hand panels) visually look almost identical to the complete model fits (left-hand panels). In other words, using M2017 implies that the long-term warming of all 5 STs was "mostly anthropogenic" (as AR6 concluded).

On the other hand, if we consider the "Max solar" TSI estimates (Figure 8), for the 3 instrumental STs, we find more nuanced fits where *both* natural and anthropogenic forcings contribute substantially to the temperature changes over the entire period.

From Table 1 we saw that the solar contribution was $> 50\%$ for both the rural-only and the sea surface temperature estimates. Meanwhile, for the urban and rural estimate, the anthropogenic contribution was 66%. So, technically, we could say that the long-term warming for the rural-only and sea surface temperature estimates was "mostly natural" while that for the urban and rural estimate was "mostly anthropogenic". However, we think that for these 3 STs, it could be misleading to focus on which component was $> 50\%$ since both the solar and anthropogenic components contributed substantially to the fits. Instead, for these fits it might be more informative to say that the long-term warming was “a mixture of natural and anthropogenic factors”. This is consistent with the recent attribution studies of Harde (2022) and Scafetta (2023) using “natural and anthropogenic” hindcasts.

That said, we note that for the two proxy-based STs, the anthropogenic components only imply a very modest long-term warming. This implies that for these two STs, at least, the long-term warming was probably “mostly natural”.

5 CONCLUSIONS

C2021 had cautioned that if IPCC AR6 continued AR5’s approach to the detection and attribution of global surface temperatures (STs) they would prematurely reach an overconfident conclusion that the global warming since the 19^{th} century was mostly anthropogenic. C2021 argued that AR5 had substantially underestimated the extent of urbanization bias in the land component of ST estimates. They also warned that the choices of solar forcing TSI datasets considered for the AR5 and AR6 attribution hindcasts were not representative of the full range of TSI choices in the relevant scientific literature.

C2021 demonstrated that by altering either TSI or ST choices, you could conclude the long-term warming was anything from “mostly human-caused” to “mostly natural” or “both human-caused and natural”. That is, the attribution approach adopted by the IPCC was not robust to changes in plausible dataset choices. Unfortunately, the IPCC have confirmed that C2021 was accepted for publication after the AR6 deadline and was therefore not considered by AR6 (Newman 2021).

RB2022 disputed the relevance of C2021’s findings and recommendations. They suggested that a secondary part of C2021’s analysis was “erroneous” and that this fundamentally undermined C2021’s conclusions. They argued that “the IPCC statements on solar attribution remain intact”. Essentially, RB2022 carried out a multi-linear regression in terms of “natural and anthropogenic forcings” using a subset of 14 of C2021’s 16 TSI series for one of C2021’s five STs. On the basis of that analysis, they claimed that C2021’s findings were “erroneous”.

In this study, we have updated and expanded on the analysis of C2021 in light of both the recommendations of C2021 for future research and the arguments of RB2022. We have expanded on the TSI series considered by C2021 (and RB2022) to include additional estimates published or identified since C2021. We have updated all TSI series to cover the same period 1850–2018.

We carried out multi-linear regressions for all five STs compiled by C2021 in terms of (a) “only natural forcings” (solar and volcanic); (b) “only anthropogenic forcings” (using IPCC AR6’s recommended net anthropogenic forcings series); and (c) “natural and anthropogenic forcings”.

Contrary to RB2022’s claim, our new and improved analysis confirms C2021’s original findings. For the three instrumentally-based STs, the “only anthropogenic forcings” fits can explain 83-92% of the long-term 1850–2018 warming. However, using “only natural forcings” fits, depending on TSI choice, the fits can explain from 0% to 99% of the long-term warming. The top–three TSI estimates can explain 60-99% of the warming, yet the bottom–seven TSI estimates cannot explain more than 3% of the warming.

The fits using “natural and anthropogenic forcings” also yielded a wide range of values for the natural contribution to the warming – again, depending on TSI choice. In general, the relative contributions for natural and anthropogenic components decreased for these fits relative to the fits using only natural or only anthropogenic forcings. This is unsurprising since more components were including in the combined fits.

For the urban and rural ST, the "natural and anthropogenic" fits all implied the long-term warming was "mostly anthropogenic", but the solar contribution varied from -0.2% to 30.2% of the long-term warming. For the rural-only and the sea surface temperature STs, more than 50% of the long-term warming could be explained in terms of solar warming for the best fitting TSI, i.e., the long-term warming was "mostly natural". However, the worst-fitting TSI implied if anything a slight long-term solar cooling – and the other natural component considered (volcanic) also implied a slight long-term cooling. Hence, those latter fits implied the long-term warming was "entirely anthropogenic". Meanwhile, using AR6's recommended TSI ("M2017") implied only a modest long-term solar warming (4.7% to 7.7% depending on ST), i.e., the long-term warming was "mostly anthropogenic".

Collectively, all of these results confirm C2021's conclusion that varying TSI choice can dramatically alter the attribution results. That is, for all three instrumentally-based STs (two land-based estimates and one ocean-based estimate), the fitting yields a wide range of conclusions from the long-term warming being "mostly anthropogenic" to "mostly natural" – as C2021 had found. This is consistent with three recent analyses that built upon the findings of C2021 and confirmed that much of the warming since the late 19^{th} century can be explained in terms of changing solar activity (Stefani 2021; Harde 2022; Scafetta 2023).

Given this, we suggest that the unabashed assertions of RB2022 offer a cautionary tale to researchers against engaging in unwarranted hubris.

Meanwhile, for the two temperature proxy-based STs, the "only anthropogenic forcings" fits can only explain 51% of the corresponding long-term warming trends (i.e., 1850–2000 for glacier lengths and 1850–2002 for tree rings). On the other hand, the top–three TSI estimates are able to explain between 71-87% of the warming using "only natural forcings". However, they are not able to explain 100% of the warming. Even using "natural and anthropogenic forcings" with the best fit TSI estimates only explain 84–88% of the warming. For comparison, using AR6's recommended TSI ("M2017"), the "natural and anthropogenic forcings" fits can only explain 63–64% of the warming.

Therefore, we reiterate the caveat of both C2021 and RB2022 that this type of analysis explicitly assumes that "all major forcing agents are captured" (RB2022) by the three components considered, i.e., TSI, volcanic and net anthropogenic forcings. Current climate models distinguish between climatic changes due to "external forcings" (natural or anthropogenic) and "unforced internal climate variability" (natural) (AR4; AR5; AR6). However, several researchers have found that the "unforced" variability components of current climate models perform poorly in replicating well known examples of natural internal variability like the El Niño-Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO) and the Quasi-Biennial Oscillation (QBO), e.g., Spencer & Braswell (2014); Chylek et al. (2020); Anstey et al. (2022); Harde (2022).

For this reason, we should allow for the possibility that additional climate drivers than those considered in this study need to be accounted for. Indeed, it is possible that some of the temperature variability we have fitted here in terms of natural forcings and/or anthropogenic forcings might also be explained in terms of unforced internal factors. Therefore, we encourage more research into investigating the roles of "natural unforced internal climate variability" (Akasofu 2010; Ziskin & Shaviv 2012; Spencer & Braswell 2014; Wyatt & Curry 2014; Tanaka & Tamura 2016; Kravtsov et al. 2018; Chylek et al. 2020; Lindzen & Choi 2021).

Moreover, our analysis also explicitly assumes that there is a direct linear relationship between ST and each of the forcings. However, many studies have suggested that the relationship between solar activity and ST is subtler and more complex than a simple linear relationship to TSI (Roy 2014; Kilifarska 2015; Sfîcă et al. 2018; Svensmark et al. 2021; Stefani 2021; Ogurtsov et al. 2022; Scafetta 2023; Kumar et al. 2023). Similarly, concerns have been raised over the modelled climate response to volcanic forcings, e.g., Lindzen & Giannitsis (1998); Chylek et al. (2020); Khaykin et al. (2022). Therefore, we also encourage further research into better understanding the climatic responses to "external forcings".

In terms of the results of our analysis, what is the best way to evaluate the relative contributions of natural and anthropogenic factors to the long-term warming of the various ST estimates?

- IPCC AR5 and AR6's conclusions that the long-term warming was mostly anthropogenic both involved two main arguments: (i) their "only natural forcings" hindcasts were unable to explain the long-term warming of their chosen ST; but (ii) their "natural and anthropogenic forcings" could. However, applying this approach to our larger range of results suggests that the long-term warming can be equally well explained in terms of being "mostly natural", "mostly anthropogenic" or "both natural and anthropogenic" depending on TSI and ST choice.
- C2021 had primarily focused on the first argument of the IPCC approach, i.e., whether AR5 was correct that it was not possible to explain the long-term warming in terms of "only natural forcings". C2021 found that by varying TSI and ST choice you could obtain any conclusion from the long-term warming being "mostly natural" to "mostly anthropogenic". Our results here confirm this finding.
- RB2022 argued against the IPCC's two-pronged approach and argued that only the combined "natural and anthropogenic forcings" results should be considered. Taking this approach, for the urban and rural ST, our analysis is unable to explain the long-term warming as "mostly natural". Since that was the only one of the 5 STs considered by RB2022, this nominally agrees qualitatively with their overall finding. However, we note that by varying TSI choice, the solar contribution can vary from a slight cooling (-0.2%) to 30.2% of the warming for this ST. The latter fit would therefore be better described as "both natural and anthropogenic". In contrast, according to their Figure 5(a), none of RB2022's fits were able to explain 10% or more of the long-term warming. Meanwhile, *for the other four STs*, by varying TSI choice, long-term warming can again be well explained in terms of being "mostly natural", "mostly anthropogenic" or "both natural and anthropogenic".
- Like RB2022, both Harde (2022) and Scafetta (2023) have also used the data from C2021 to carry out an attribution using the combined "natural and anthropogenic forcings" approach. However, they both found a much greater solar contribution to the long-term warming than either AR5, AR6 or RB2022. Moreover, both studies suggested that the climatic response to changes in TSI was not necessarily the same as that to anthropogenic forcings. Specifically, they both independently found that better fits to the observed ST were found if the climate sensitivity to changing TSI were greater than assumed in terms of "effective radiative forcing" calculations. Chylek et al. (2020) has also cautioned that the relative

climatic responses in terms of radiative forcing calculations does not seem to be identical for solar, volcanic and anthropogenic factors.

- In terms purely of statistics, we do not see a *statistical* reason to necessarily favor the best "natural and anthropogenic forcings" fits over the best "only natural forcings" or "only anthropogenic forcings" fits. It is true that the statistical power of the fit and the amount of the long-term warming was always *slightly* higher than the corresponding fits using "only anthropogenic" or "only natural" forcings. However, this is not too surprising since fits with multiple fitting parameters tend to yield better fits than those with fewer parameters – as the late John von Neumann allegedly used to quip, "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk" Dyson (2004).

To summarize, by varying ST and/or TSI choice and/or the attribution approach used, it is possible to conclude anything from the long-term warming being "mostly natural" to "mostly anthropogenic" or anything in between. While each of us has our own scientific opinions on which of these choices are most realistic, we are concerned by the wide range of scientifically plausible, yet mutually contradictory, conclusions can still be drawn from the data.

Given all of the above, we encourage others to carry out their own analyses of the data. With this in mind, we provide to the scientific community as supplementary material, the following: all 27 TSI series (1850-2018); the 5 Northern Hemisphere ST series (with uncertainty intervals); the relevant IPCC AR6 forcings series; and the fitting results for each ST. This dataset is available at `https://doi.org/10.5281/zenodo.8225275`.

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References

Akasofu, S.-I. 2010, Natural Science, 2, 1211 25

Anstey, J. A., Simpson, I. R., Richter, J. H., et al. 2022, Quarterly Journal of the Royal Meteorological Society, 148, 1568, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4048 24

Bard, E., Raisbeck, G., Yiou, F., & Jouzel, J. 2000, Tellus B: Chemical and Physical Meteorology, 52, 985, number: 3 5

Chylek, P., Folland, C., Klett, J. D., & Dubey, M. K. 2020, Geophysical Research Letters, 47, e2020GL087047, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2020GL087047 22, 24, 25

Coddington, O., Lean, J., Pilewskie, P., et al. 2019, Earth and Space Science, 6, 2525, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2019EA000693 11

Connolly, R., Soon, W., Connolly, M., et al. 2021, Research in Astronomy and Astrophysics, 21, 131, number: 6 Publisher: IOP Publishing 4

Conrad, J. 1896, An Outcast of the Islands, revised edition, 2009 edn., ed. J. H. Stape & H. v. Marle (Oxford: OUP Oxford) 8 de Wit, T. D., Kopp, G., Fröhlich, C., & Schöll, M. 2017, Geophysical Research Letters, 44, 1196, number: 3 _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016GL071866 7, 12

Dewitte, S., Cornelis, J., & Meftah, M. 2022, Remote Sensing, 14, 1072, number: 5 Publisher: Multidisciplinary Digital Publishing Institute 11

Dyson, F. 2004, Nature, 427, 297, number: 6972 Publisher: Nature Publishing Group 26

Foukal, P. 2012, Solar Physics, 279, 365, number: 2 11

Foukal, P. 2015, The Astrophysical Journal, 815, 9, number: 1 Publisher: IOP Publishing 11

Harde, H. 2022, Science of Climate Change, 2, 105 6, 23, 24, 25

IPCC. 2007, Climate Change 2007 - The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC (Cambridge ; New York: Cambridge University Press) 2, 3

—. 2014, Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1st edn. (New York: Cambridge University Press) 3, 4

—. 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) 3, 6, 11

Katata, G., Connolly, R., & O'Neill, P. 2023, Journal of Applied Meteorology and Climatology, -1, publisher: American Meteorological Society Section: Journal of Applied Meteorology and Climatology 18

Khaykin, S., Podglajen, A., Ploeger, F., et al. 2022, Communications Earth & Environment, 3, 1, number: 1 Publisher: Nature Publishing Group 25

Kilifarska, N. A. 2015, Journal of Atmospheric and Solar-Terrestrial Physics, 136, 216 25

Kopp, G. 2018, Kopp's 'unofficial' Historical Total Solar Irradiance Reconstruction, https://lasp.colorado.edu/lisird/data/historical_tsi 11

Kravtsov, S., Grimm, C., & Gu, S. 2018, npj Climate and Atmospheric Science, 1, 1, number: 1 25

Kumar, V., Dhaka, S. K., Hitchman, M. H., & Yoden, S. 2023, Scientific Reports, 13, 3707, number: 1 Publisher: Nature Publishing Group 25

Lindzen, R. S., & Choi, Y.-S. 2021, Asia-Pacific Journal of Atmospheric Sciences 25

Lindzen, R. S., & Giannitsis, C. 1998, Journal of Geophysical Research: Atmospheres, 103, 5929, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98JD00125 25

Matthes, K., Funke, B., Andersson, M. E., et al. 2017, Geoscientific Model Development, 10, 2247 5, 14

Montillet, J.-P., Finsterle, W., Kermarrec, G., et al. 2022, Journal of Geophysical Research: Atmospheres, 127, e2021JD036146, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021JD036146 11

Newman, A. 2021, The Epoch Times, https://www.theepochtimes.com/challenging 23

Ogurtsov, M., Helama, S., Jalkanen, R., et al. 2022, The Holocene, 32, 99, publisher: SAGE Publications Ltd 25

Penza, V., Berrilli, F., Bertello, L., et al. 2022, The Astrophysical Journal, 937, 84, publisher: The American Astronomical Society 11

Richardson, M. T., & Benestad, R. E. 2022, Research in Astronomy and Astrophysics, 22, 125008, publisher: National Astronomical Observatories, CAS and IOP Publishing 6

Roy, I. 2014, International Journal of Climatology, 34, 655, number: 3 _eprint: https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/joc.3713 25

Scafetta, N. 2021, Climate Dynamics, 56, 2959 4, 18, 22

Scafetta, N. 2023, Geoscience Frontiers, 14, 101650 6, 23, 24, 25

Scafetta, N., Willson, R. C., Lee, J. N., & Wu, D. L. 2019, Remote Sensing, 11, 2569, number: 21 4, 7, 11

Schmutz, W. K. 2021, Journal of Space Weather and Space Climate, 11, 40, publisher: EDP Sciences 7

Sfîcă, L., Iordache, I., & Voiculescu, M. 2018, Journal of Atmospheric and Solar-Terrestrial Physics, 177, 257 25

Solanki, S. K., & Fligge, M. 1998, Geophysical Research Letters, 25, 341, number: 3 _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98GL50038 11

Solanki, S. K., & Fligge, M. 1999, Geophysical Research Letters, 26, 2465, number: 16 _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1999GL900370 11

Soon, W., Connolly, R., & Connolly, M. 2015, Earth-Science Reviews, 150, 409 4, 18, 22

Spencer, R. W., & Braswell, W. D. 2014, Asia-Pacific Journal of Atmospheric Sciences, 50, 229 24, 25

Stefani, F. 2021, Climate, 9, 163, number: 11 Publisher: Multidisciplinary Digital Publishing Institute 24, 25

Svensmark, H., Svensmark, J., Enghoff, M. B., & Shaviv, N. J. 2021, Scientific Reports, 11, 19668, bandiera_abtest: a Cc_license_type: cc_by Cg_type: Nature Research Journals Number: 1 Primary_atype: Research Publisher: Nature Publishing Group Subject_term: Astronomy and planetary science;Climate sciences Subject_term_id: astronomy-and-planetary-science;climate-sciences 25

Tanaka, H. L., & Tamura, M. 2016, Polar Science, 10, 199 25

Wang, Y.-M., & Lean, J. L. 2021, The Astrophysical Journal, 920, 100 11

Wu, C.-J., Krivova, N. A., Solanki, S. K., & Usoskin, I. G. 2018, Astronomy & Astrophysics, 620, A120, publisher: EDP Sciences 11

Wyatt, M. G., & Curry, J. A. 2014, Climate Dynamics, 42, 2763, number: 9 25

Xu, H., Lei, B., & Li, Z. 2021, Earth and Space Science, 8, e2021EA001819, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021EA001819 11

Zhang, P., Ren, G., Qin, Y., et al. 2021, Journal of Climate, 34, 1923, number: 5 Publisher: American Meteorological Society Section: Journal of Climate 4, 18, 22

Ziskin, S., & Shaviv, N. J. 2012, Advances in Space Research, 50, 762, number: 6 25