On Hens, Eggs, Temperatures and CO2: Causal Links in Earth's Atmosphere

Supplementary Information

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Abstract This report contains Supplementary Information of the paper shown in the title It comprises two sections, namely *Additional analysis of climate model behaviour* (SI1) and *On correlations of temperature with CO_2 emissions* (SI2).

SI1 Additional analysis of climate model behaviour

As explained in the main paper, here we provide an additional analysis, similar to case studies #16 to #23 but with a particular member of the model ensemble instead of the mean, namely the UK Earth System Model (UKESM1). The characteristic indices are shown in Table SI1 and the calculated IRFs are shown in Figure SI1 for the cases that no roughness constraint was used (case studies #34 - #37) and in Figure SI2 for the cases where the calculations included the roughness constraint (case studies #38 - #41).

By comparing with the corresponding Table and Figures of the main paper we observe that there is no remarkable difference between the results for the UKESM1 and those for the CMIP6 mean. These results, based on climate model outputs, are opposite to those found when the real measurements are used.

Table S1 Additional case studies of this Supplementary Information and resulting summary indices (annual time scale). The h_c is the time lag maximizing the cross-covariance $c_{yx}(h)$, or equivalently the cross-correlation $r_{yx}(h) \coloneqq c_{yx}(h)/\sqrt{c_{xx}(0)c_{yy}(0)}$; μ_h is the mean (time average) of the function $g(h)$; $h_{1/2}$ is the median of the function $g(h)$; e is the explained variance ratio; and ε is the roughness ratio. In parentheses are the true values for the cases that they are known.

Case system	**#**	**Direction**	h_c	μ_h	$h_{1/2}$	$r_{yx}(h_c)$	e	ε
T: UKESM1-0, SSP2-4.5; $[CO_2]$: SSP2-4.5, 1850-2100, w/o roughness constraint	34	$\Delta T \rightarrow \Delta\ln[CO_2]$	-9	-4.45	-7.03	0.19	0.84	0.021
	35	$\Delta\ln[CO_2] \rightarrow \Delta T$	9	13.98	16.10	0.19	0.04	0.65
As #34 and #35 but or 1850-2021	36	$\Delta T \rightarrow \Delta\ln[CO_2]$	-9	-8.67	-10.75	0.17	0.70	0.028
	37	$\Delta\ln[CO_2] \rightarrow \Delta T$	9	16.57	16.12	0.17	0.03	0.27
As #34 and #35 but with roughness constraint	38	$\Delta T \rightarrow \Delta\ln[CO_2]$	-9	-4.23	-6.66	0.19	0.82	3.9×10^{-5}
	39	$\Delta\ln[CO_2] \rightarrow \Delta T$	9	11.45	13.20	0.19	0.03	6.4×10^{-3}
As #36 and #37 but with roughness constraint	40	$\Delta T \rightarrow \Delta\ln[CO_2]$	-9	-8.83	-10.75	0.17	0.63	1.2×10^{-4}
	41	$\Delta\ln[CO_2] \rightarrow \Delta T$	9	15.50	15.50	0.17	0.02	6.4×10^{-3}

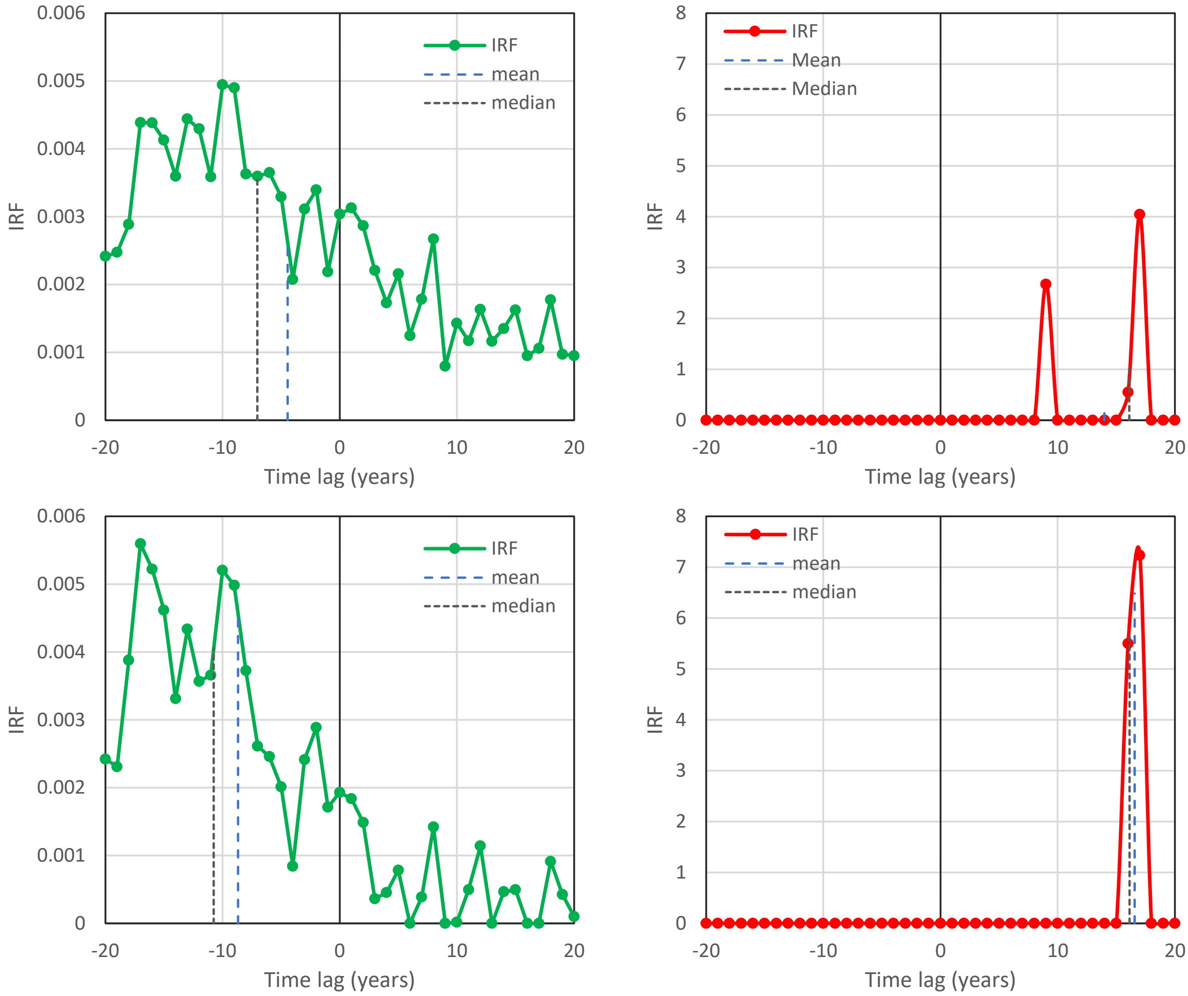

Figure S1 IRFs for temperature–CO_2 concentration based on the UKESM1-0 temperature and SSP2-4.5 CO_2 time series, respectively, calculated without using the roughness constraint; **upper row**: period 1850-2100—case studies #34 (**left**; $\Delta T \rightarrow \Delta\ln[CO_2]$) and #35 (**right**; $\Delta\ln[CO_2] \rightarrow \Delta T$); **lower row**: period 1850-2021—case studies #36 (**left**; $\Delta T \rightarrow \Delta\ln[CO_2]$) and #37 (**right**; $\Delta\ln[CO_2] \rightarrow \Delta T$).

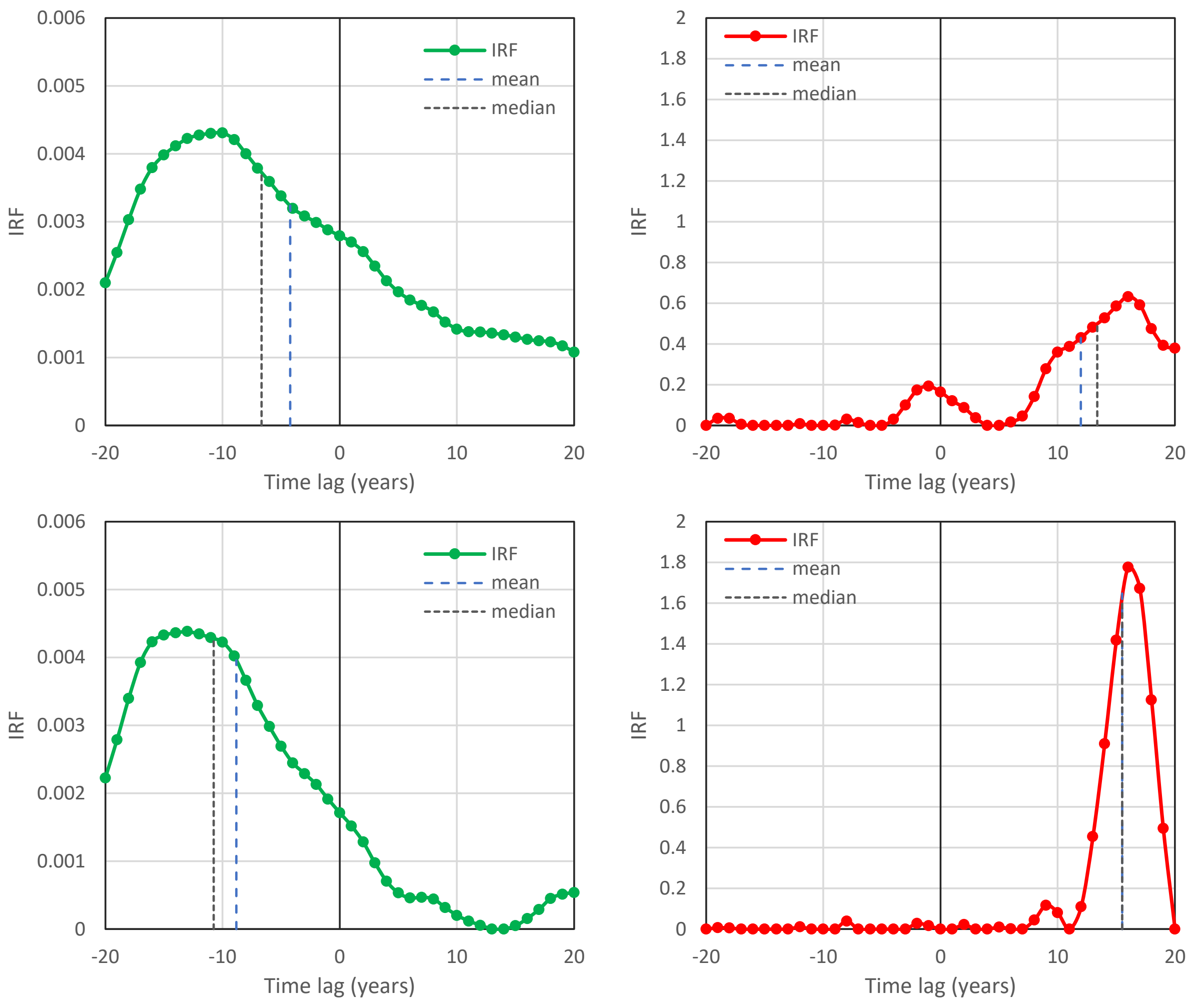

Figure S2 IRFs for temperature–CO_2 concentration based on the UKESM1-0 temperature and SSP2-4.5 CO_2 time series, respectively, as in Figure SI1 but calculated using the roughness constraint; **upper row**: period 1850-2100—case studies #38 (**left**; $\Delta T \to \Delta\ln[CO_2]$) and #39 (**right**; $\Delta\ln[CO_2] \to \Delta T$); **lower row**: period 1850-2021—case studies #40 (**left**; $\Delta T \to \Delta\ln[CO_2]$) and #41 (**right**; $\Delta\ln[CO_2] \to \Delta T$).

SI2 On correlations of temperature with CO_2 emissions

The fact that human CO_2 emissions have been increasing in recent times, while in recent decades the atmospheric temperature is also increasing has commonly been interpreted as evidence that the temperature increase is caused by human CO_2 emissions. Here we examine whether this has a scientific basis or not. We use the longest available data sets. The human CO_2 emissions are available by *Our World in Data* at https://github.com/owid/co2-data. The data set begins in 1750, while before that year human emissions were negligible. The longest available temperature data set is that of Central England, beginning in 1659 and available by the climexp platform at http://climexp.knmi.nl/getindices.cgi?STATION=Central_England_Temperature&TYPE=t&WMO=UKMOData/cet. The two time series are plotted in Figure SI3.

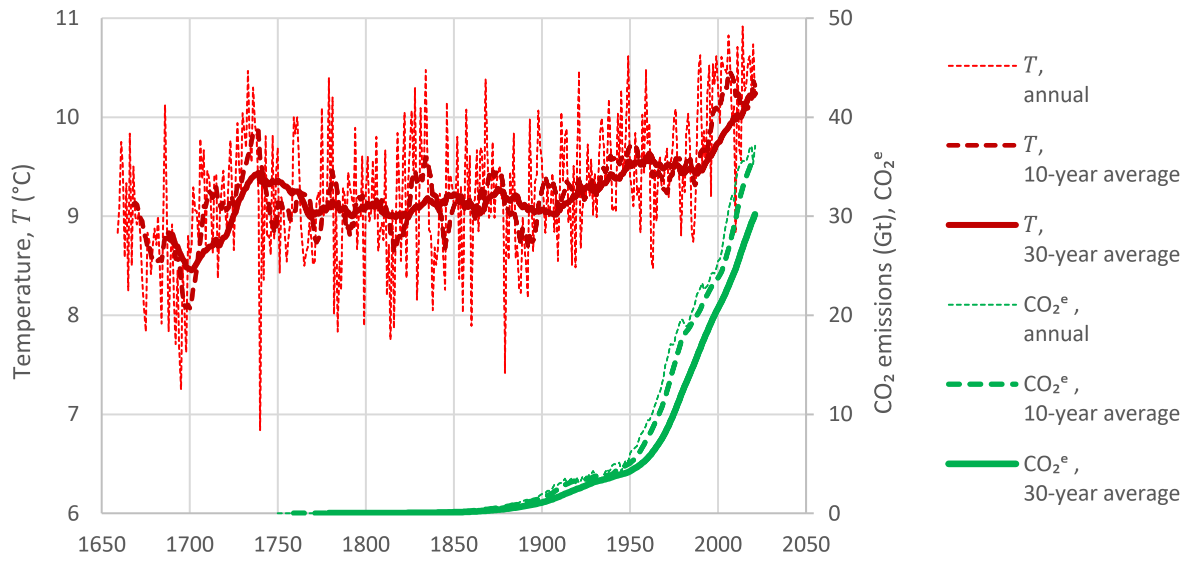

Figure S3 Comparative evolution of global human CO_2 emissions (CO_2^e) and temperature at Central England.

It is easy to be misled by Figure SI3 to develop the following line of thought.

1. Both temperature and emission time series show rising trends at the 20th century and beyond.
2. The cross correlation coefficient between the two time series is rather high (0.52).
3. Correlation may entail causation.
4. It is illogical to assume that the increased temperature is the cause for the increased human emission.
5. Therefore, the increased human emission is the cause of the temperature rise.
6. The commonly accepted theory of the greenhouse effect provides theoretical support of the conclusion in point 5.

However, careful inspection of Figure SI3 would reveal that there are periods of (a) increasing temperature without increasing emissions (1700-1750) and (b) decreasing temperature with increasing emissions (1880-1900; 1950-1970).

What is more, elementary knowledge of stochastics would suggest that, even in mutually independent processes with long term persistence, in which apparent trends are common, if in a substantial part of the time series there appear similar trends, then there will be high cross-correlation, which is spurious.

As explained in the main papers, a technique to avoid spurious results in such case is to difference the time series. This has been done in Figure SI4, where correlation is no longer apparent. The empirical cross-correlation function of the differenced time series at the annual and also the 10-year scale are shown in Figure SI5. Not only is the cross-correlation negligible, but for lag zero it is also negative at all examined cases and time scales.

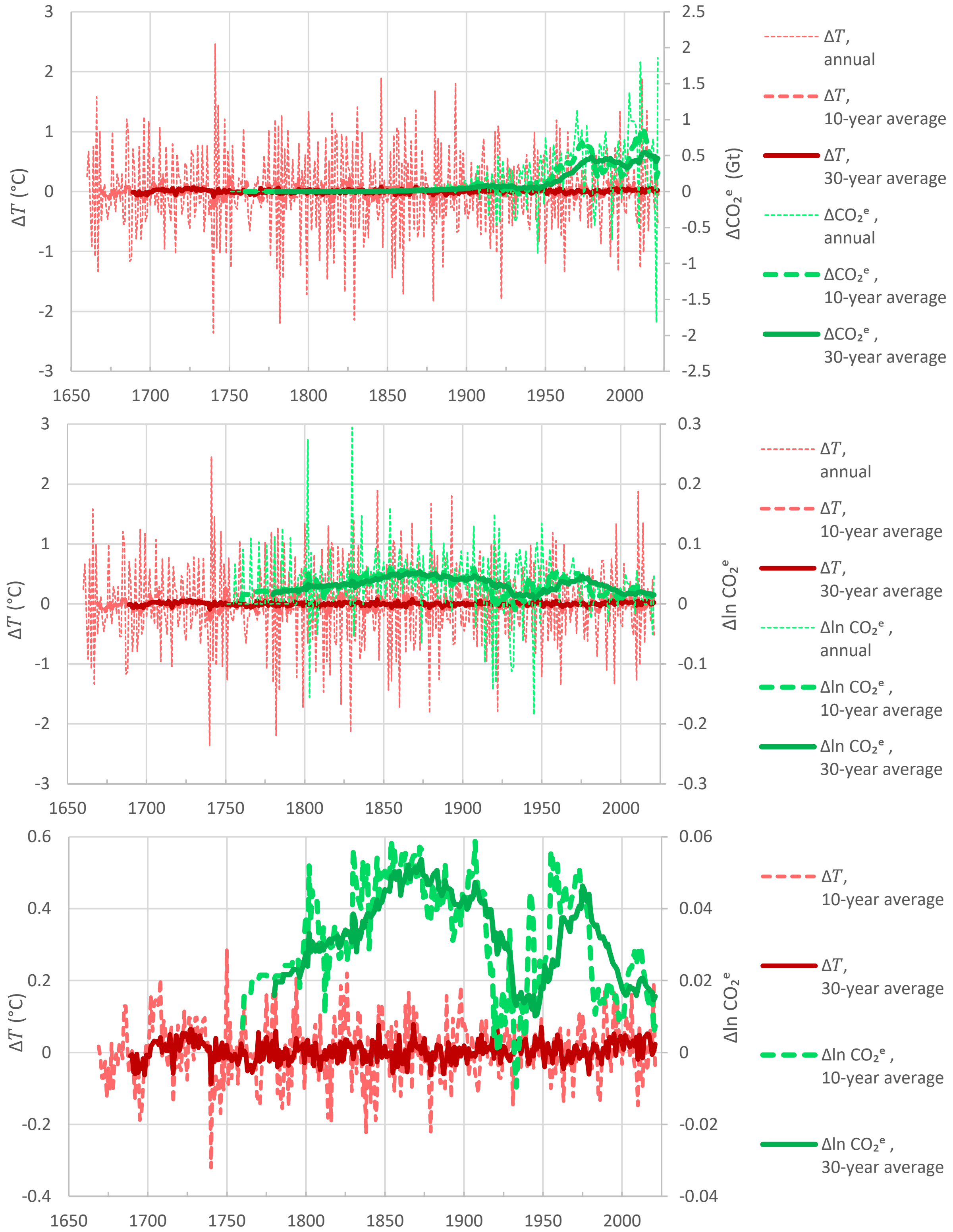

Figure S4 Comparative evolution of the differenced time series of temperature at Central England, and the global human CO_2 emissions (CO_2^e) (**upper**), as well as logarithms of CO_2^e (**middle**). The 10- and 30-year averages are also plotted, in addition to annual values or without them (**lower**) to improve legibility.

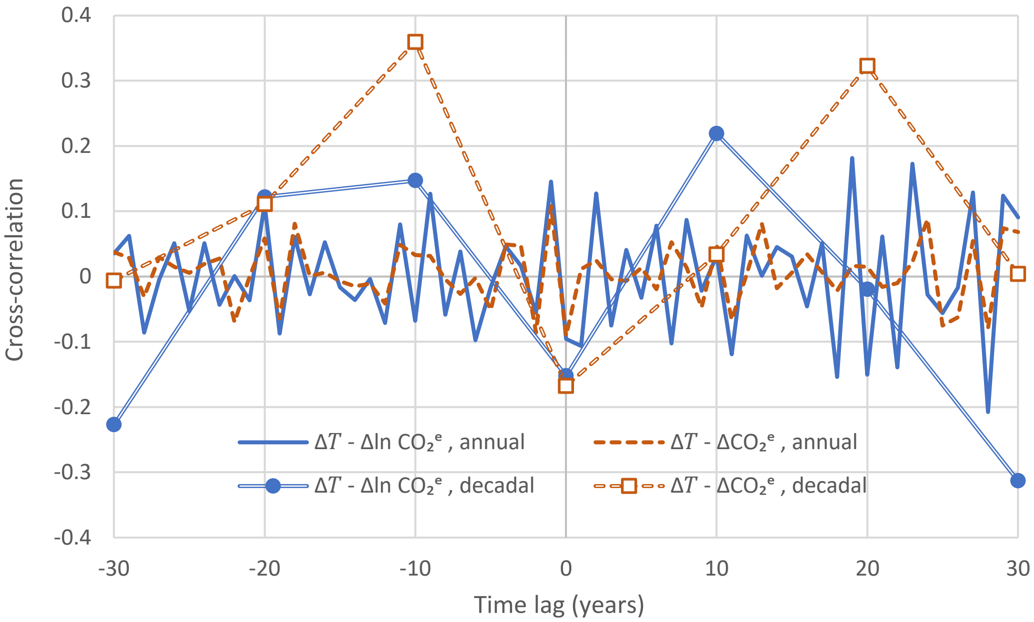

Figure S5 Empirical cross-correlation function between the time series of differenced temperature at Central England, and global human CO_2 emissions (CO_2^e), as well as logarithms of CO_2^e, at the annual and the 10-year time scale.