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Research Article

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An Empirical Approach to the Analysis of Climate Data Dynamics in the Last 60 Years

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Abstract

The relationship between global temperature increases and the rise in greenhouse gases (GHG) is assessed by a simple statistical analysis of measured data (20-year averaging). A purely empirically derived (transient) relationship for the last 60 years, covering an interval of roughly 100 ppm CO_2 plus equivalent other greenhouse gases, is calculated. This is done by evaluating a differential quotient of temperature increase divided by GHG increase. Three different global temperature data bases are analyzed, i.e. GISTEMP, NOAA and HadCRUT5. All data sets show a very strict linear behavior (standard error relative to straight line ~1% for five 20-year-averaged values) if only CO_2 is considered. An average value for this empirical "CO_2 sensitivity" of the global temperature is around 0.011 °C/ppm CO_2 (temperature including equivalent GHG and other effects). It is shown that this finding is equivalent to a similar linear relationship documented in the AR6 report of the IPPC (temperature vs. cumulative CO_2 emissions). The role of other GHG and of aerosols is also discussed. According to the dynamic behavior of the temperatures in the last 60 years their influence seems to be smaller than assessed by the AR6 report for the time period of the last 170 years.

Keywords: Global Temperature, GISTEMP, NOAA, HadCRUT5, CO_2, Greenhouse Gas, Aerosols.

Introduction

A relationship between global temperature increases and the rise in greenhouse gases (GHG) is assessed by measured data. A purely empirically derived (transient) relationship for the last 60 years is calculated, covering an interval roughly between 317 and 414 ppm CO_2 plus equivalent other greenhouse gases. This is done by evaluating a differential quotient of temperature increase divided by GHG increase. It is performed with a simple averaging procedure using solely measured temperature data from three different global temperature data bases. The method and the uncertainty is described in detail below. It is a purely (rather simple) "experimental" work, analyzing only measured data and their dynamics in the last six decades. In addition also global land data are analyzed. This is compared with the recently published 6th Assessment Report (AR6) of the IPCC (IPCC 2021) which not only covers measured temperatures but also the results of attribution studies and "radiative forcing" studies of individual contributions over the last 170 years. It is shown that the main findings are compatible with the AR6 report but some differences are identified: The role of aerosols (mainly SO_2) seems to be negligible on a global scale, also the role of Methane seems to be overestimated, at least in the last 60 years. The ratio of global land temperature increase to global (land/ocean) temperature increase in the last 60 years is higher than given in the AR6 report.

Data and Methods

This study only uses publicly available temperature and GHG data (GISTEMP 2021, NOAA NCEI 2021, CRU 2021 etc.). The evaluation is carried out with simple tools such as Excel, gnuplot (gnuplot homepage 2021), awk etc. The results are therefore very easily reproducible for everyone who is familiar with such methods. GHG data are taken mainly from NOAA ESRL server 2021, partly also from Meinshausen et al. 2017 [14]. As an example, the most recent CO_2 concentrations in the atmosphere as a function of time (strictly speaking: mole fractions) from Mauna Loa, covering the years 1959 to 2020, are shown in Figure 1. It is shown that this can be approximated well by a polynomial of second order, thus quantifying the accelerated increase of CO_2 in the atmosphere in the last 60 years.

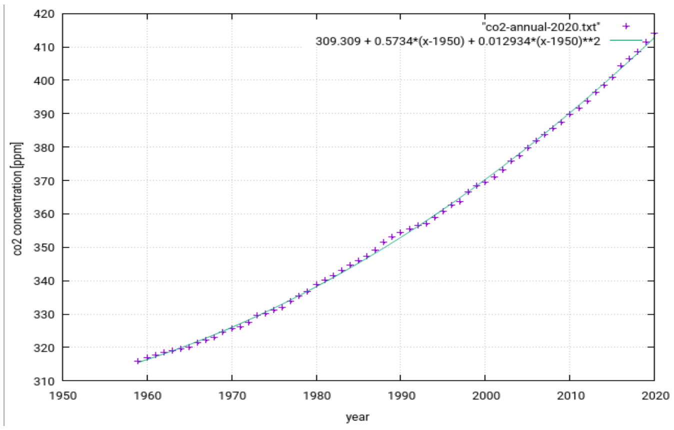


Figure 1: Overview of CO_2 concentrations in the atmosphere (NOAA ESRL 2021) since 1959 Individual points: Original data Mauna Loa, green line: fitting polynomial: F(y) = 309.3 + 0.5734*(y-1950)+ 0.01293*(y-1950) **2.

Results

A Simple Way to Determine CO_2 Sensitivities (Differential Quotient Temperature Increase vs. CO_2 Increase)

The temperature profile for a 20-year average of the global temperature is very "smooth" and will be taken as a base for the present investigation. The physical reasoning for this averaging procedure is that such a large averaging interval will wipe out "annual weather fluctuations" or short-term climate effects to a large extent and thus only long-term trends will become visible. Typical values for annual "temperature fluctuations" for the global temperature are of the order of 0.1 °C (1σ). Only the period of the last 60 years is considered and only one value is used for each decade, so that only a total of 5 value pairs, in which the climatic behavior of the last 60 years is condensed, is checked for linear (or maybe non-linear) behavior. The choice of reference points and the associated CO_2 values are summarized in the following table:

Table 1: Reference points for determining the differential coefficient (CO_2 sensitivity)

Points no.	Time period for averaging	CO_2 concentration [ppm]	Temperature GISTEMP [°C]	Temperature NOAA [°C]	Temperature HADCRUT5 [°C]
1	1961-1980	326.66	0.0165	0.055	−0.0769
2	1971-1990	339.63	0.162	0.1905	0.0706
3	1981-2000	354.54	0.323	0.35	0.24695
4	1991-2010	371.3	0.5025	0.515	0.4365
5	2001-2020	391.62	0.7325	0.724	0.6575

The temperature values in Table 1 are temperature anomalies (normalized to average zero for the last century in the case of NOAA, for the time period 1951-1980 in the case of GISTEMP and for the time period 1961-1990 in the case of HADCRUT5), therefore the absolute values are of minor importance. Before analyzing a correlation between temperature and CO_2 concentration, two aspects have to be emphasized:

- CO_2 is the major but not the only greenhouse gas. Methane and nitrous oxide (N_2O) also play some role [14]. Also, aerosols (mainly SO_2) may have some influence on global temperatures, even natural effects (e.g. volcanic) could have an influence.
- Complex feedback mechanisms may lead to time-delayed effects and thus to deviations from linearity. Often a logarithmic radiative forcing is assumed for CO_2.

Therefore, a strict linearity between global temperature and CO_2 concentration is not an obvious expectation. A straight line of the temperature (representing a mean differential quotient) is fitted for the 5 pairs of values for each temperature data set. This is done with the program gnuplot. The straight line is represented by the following function: T(x) = A + B*x (x = CO_2 concentration) The fitted values of A and B are calculated by gnuplot together with the associated standard errors. B is from now on referred to as "CO_2 sensitivity". This slope B represents the more important variable. For the three global temperature data sets, the results are summarized in the following table:

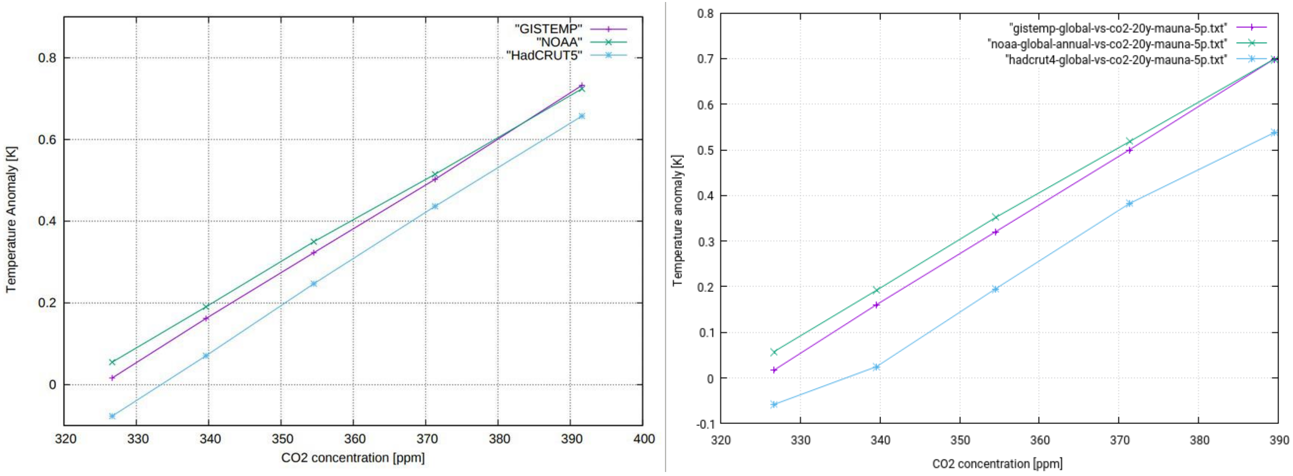
Table 2. Determination of the CO_2 sensitivity (B) and standard error for different temperature data sets

Temperature Data Set	A [°C]	Standard Error A (%)	B [°C/ppm CO_2]	Standard Error B (%)
GISTEMP (1961 - 2020)	−3.567	0.65	0.01097	0.65
NOAA global (1961 - 2020)	−3.301	0.81	0.01028	0.73
HADCRUT5 (1961 - 2020)	−3.779	0.96	0.01134	0.90
Average of three data sets	−3.549	0.81	0.0109	0.76

B is formally an averaged differential quotient: B = dT / dρ(CO2),

T being the measured temperature and $\rho(CO_2)$ being the concentration of CO_2 in the atmosphere. Again, it is emphasized that this quantity is not necessarily showing a strict physical (causal) relationship. Standard errors of one percent or even less are sensationally good. In particular, the fact that all temperature data sets show such a strict linearity is hard to believe and a bit of a miracle. Of course, one could argue that the standard errors are underestimated because the averaging intervals are overlapping but this should not be a large effect. In Fig.2(a) the data points from Table 1 are plotted and compared. For all data sets the visual impression of linearity is remarkable. The slope (B) is quite similar for all data sets (around 0.0109 °C/ppm CO_2). The standard error for using three different temperature libraries is of the order of 5% (1σ).

HADCRUT5 is a new and improved data set and available only since very recently. The previous version was HADCRUT4. HADCRUT4 was also analyzed for the time period till 2019, as were GISTEMP and NOAA, with the year 2020 missing. The results are shown in Fig. 2(b). While the results for GISTEMP and NOAA are almost identical to Fig.2(a), the HADCRUT4 results are totally different to HADCRUT5: First, the slope B has a much larger standard error (4%). Second, the slope B is significantly lower (14%) compared to HADCRUT5. The temperature increase of HADCRUT5 in the last 60 years is now very similar to GISTEMP. NOAA seems significantly lower.

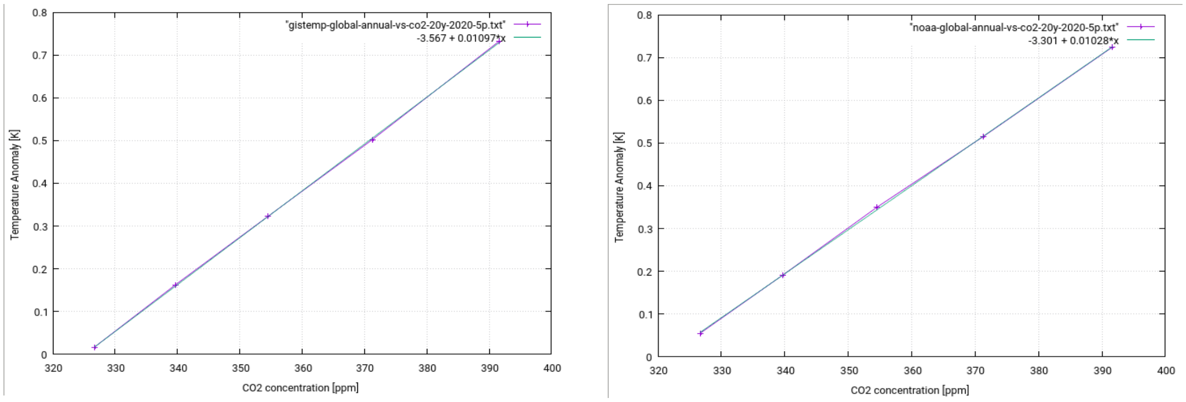


(a)Temperature data 2020 (with HADCRUT5)

(b) Temperature data 2019 (with HADCRUT4)

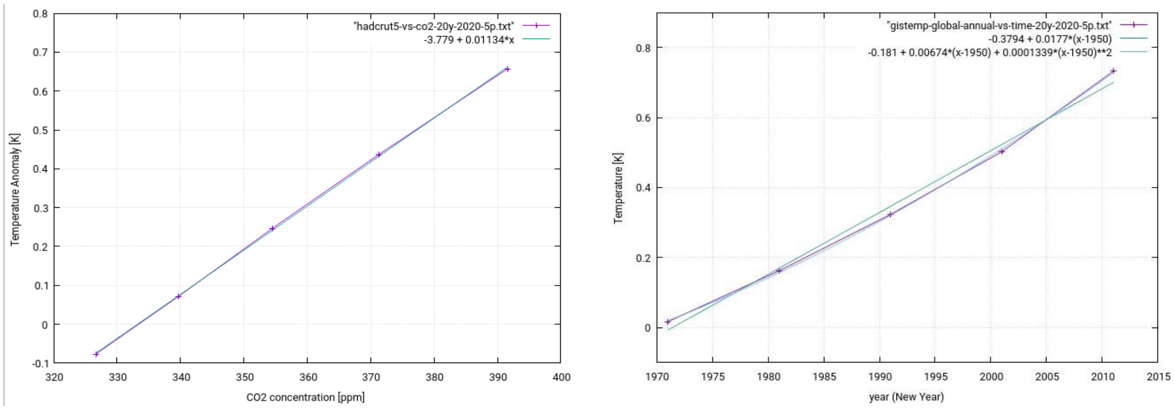
Figure 2: 20-year mean of different global temperature data sets vs. CO_2 concentrations (a) Time period 1961-2020 (including HADCRUT5), (b) Time period 1961-2019 (including HADCRUT4) violet : GISTEMP, green: NOAA , blue: HADCRUT4

As all three data sets show this outstanding linearity, a lucky random effect can be practically ruled out. A plausible explanation could be that the three temperature data sets are of very high quality and that the strict linear behavior is an indication of a complex law of nature, of course keeping in mind that CO_2 is not the only greenhouse gas. This is so far compatible with the assessment reports of the IPCC: In the most recent AR6 report (Masson-Delmotte et al. / IPCC 2021) the best estimate calculations give a 70-80 % contribution of CO_2 to total global warming on the basis of radiative forcing calculations (last 170 years). If the sensitivity B is multiplied by 100 ppm, one roughly obtains the temperature increase in the last 60 years, which is close to 1 °C. Of course, this finding is not really new. The most remarkable finding is the strict linearity of temperature vs. CO_2. There is no hint on a logarithmic behavior in the CO_2 range between 300 and 400 pcm. In Fig. 3 the results for the individual temperature data sets are plotted and compared with their corresponding fitting lines. In all three cases the data points are very close to the fitting straight lines. For illustration, in Fig.3(d) also the increase of the temperature (GISTEMP) is plotted versus time. Although the standard error for the straight line is not too bad (5.3%), it can be clearly seen that temperature increase is accelerating with time and that a much better fit can be obtained with a polynomial of second order (blue line). Thus Fig. 3(d) just shows the dynamics (acceleration) of the global temperature increase in a 20-year average.



(a) Temperature vs. CO_2 (GISTEMP)

(b) Temperature vs. CO_2 (NOAA)



(c) Temperature vs. CO_2 (HADCRUT5)

(d) Temperature vs. time (GISTEMP)

Figure 3: 20-year mean of different temperature data sets vs. CO_2 content, comparison with fitted lines (a) GISTEMP, (b) NOAA, (c) HADCRUT5, (d) GISTEMP vs. time

Assessment of Linear Correlation Parameters, Dynamics of Temperatures

In the previous investigations the strictness of the linearity of the correlation temperature vs. CO_2 concentrations was always analyzed with the same methods, i.e. the same averaging intervals (20 years) and the same number of intervals (five overlapping intervals with a distancing of 10 years). While the large 20-year interval was chosen to avoid "stochastic noise" and short-time effects as much as possible, one may correctly argue that overlapping intervals contain some auto-correlation effects, leading to an underestimation of the statistical errors (standard deviation). Moreover, the starting point of the time periods and the exact value of the averaging time intervals (e.g. 20 years instead of, say, 19 years), could have some statistical effects on the results. This was investigated in more detail for the global GISTEMP database and to a lesser extent also for the NOAA data. As time goes by, we now already have temperature data for 2021, so one can consider also the 60-year period between 1962 to 2021.

Generally, the standard deviation (statistical error) is expected to increase with decreasing interval width. The considered total time interval of 60 years can be divided in several ways into the following non- overlapping intervals: 3 intervals of 20 years each, 4 intervals of 15 years each, and 5 intervals of 12 years each. In addition, instead of 20-year intervals, one may consider three (non-overlapping) 19-year intervals covering the years 1965 to 2021. Several variants of five overlapping 20-year intervals were also considered: The "base case" covering the years 1961 to 2020 with equidistant spacing of 10 years ("GISTEMP 2020 5P"). In addition, also the last interval was modified: one covering the years 2000-2019 ("GISTEMP 2019 5P") and one covering the years 2002-2021 ("GISTEMP 2021 5P"). As a last variant, all intervals were shifted by one year ("GISTEMP 2021 5P alt"), thus covering the time period between 1962 to 2021. In addition, 3 non-overlapping 19-year-intervals are considered ("GISTEMP 2021 3P 19y").

One may ask which can be termed as a good or even excellent linear correlation. In my (ultimately personal) opinion, the following very rough standard deviation intervals could quantify the statistical quality of a linear correlation in view of the differential quotient B:

- below 1%: outstanding/sensational
- below 2%: excellent
- below 5%: good
- below 10%: fair
- above 10%: no clear evidence of a linear correlation

This is based on visual impressions after seeing hundreds of linear fits. Other people may come to other views. The results of choosing different time intervals, both overlapping and non-overlapping, are shown in the next table for the GISTEMP temperatures:

Table 3: Linear correlation parameters A, B and their standard deviations for various overlapping and non- overlapping intervals for global temperature (GISTEMP) and CO_2 concentrations (Standard errors of B less than 1% are marked in bold, first 4 rows with overlapping intervals, last 5 rows with non-overlapping intervals)

data lib	A	st.dev. A (%)	B	st.dev. B (%)
GISTEMP 2021 5P 20y	−3.504	0.45	0.01079	**0.44**
GISTEMP 2021 5P alt 20y	−3.467	1.67	0.01068	1.51
GISTEMP 2020 5P 20y	−3.567	0.65	0.01097	**0.652**
GISTEMP 2019 5P 20y	−3.524	0.41	0.01084	**0.38**
GISTEMP 2021 3P 20y alt	−3.516	0.58	0.01081	**0.53**
GISTEMP 2020 3P 20y	−3.584	0.141	0.01102	**0.13**
GISTEMP 2021 3P 19y	−3.483	0.08	0.01072	**0.07**
GISTEMP 2020 4P 15y	−3.482	2.2	0.01074	1.985
GISTEMP 2020 5P 12y	−3.519	2.20	0.01084	2.01
Average	−3.516		0.01082	**0.856**
st.dev. (%)	1.105		1.03	
overlapping intervals			0.01082	**0.7455**
non-overlapping intervals			0.01083	**0.945**

The results shown in this table can be interpreted as follows: The CO_2 sensitivity B is indeed very close to the mean value of 0.01082 °C/pcm CO_2 in all cases. The (relative) standard deviation of all 9 values of B is 1.03 %, which is calculated completely independently of the individual standard deviations calculated by GNUPLOT for the different time interval variants (last column). The average of these (individual) standard deviations is 0.86% which is in good agreement with the (only consistency checking) value of 1.03 %. Thus we can have full confidence in the standard deviations of B calculated by GNUPLOT, even if these values are somewhat underestimated due to auto-correlation effects. There is a tendency of increasing standard deviations when reducing the interval length (12/15 years) which is expected due to larger stochastic/short- term effects. It is probably a lucky random effect that all non-overlapping 19/20-year intervals show such an extremely low standard deviation. Thus a typical standard deviation for the "CO_2 sensitivity"of the GISTEMP temperatures is clearly around 1% which is a truly excellent linear quality. The author believes that this is also an indication of the excellent quality of the GISTEMP/NASA data. A further aspect can be noted: the temperature value at the end of the total time interval has a certain (rather small) influence: the temperature for 2020 was rather high while it was rather low in 2021. This is also seen in the calculated "CO_2 sensitivity" B. The best estimate value for B (GISTEMP) is 0.01082 °C/ppm CO_2, considering all variants. The many standard deviations of B below 1% (in bold in the last column) in Table 3 are almost unbelievable.

A similar exercise can be performed for the NOAA database, here not only for the global temperature but also for the global land temperature. The latter is important due to its higher value (about a factor of 1.5) compared to land/ocean and will be covered in the next sub-section. For the NOAA global temperature data, the corresponding values are compiled in the following table:

Table 4: Linear correlation parameters A, B and their standard deviations for various overlapping and non- overlapping intervals for global temperature (NOAA) and CO_2 concentrations (Standard errors of B less than 1% are marked in bold, first 4 rows with overlapping intervals, last 3 rows with non-overlapping intervals).

data lib	**A**	**stdev A (%)**	**B**	**stdev B (%)**
NOAA 2019 5p 20y	−3.282	1.05	0.01023	**0.94**
NOAA 2020 5p 20y	−3.301	0.81	0.01028	**0.73**
NOAA 2021 5p 20y	−3.221	1.55	0.01005	1.39
NOAA 2021 5p 20y alt	−3.187	1.61	0.009955	1.44
NOAA 2020 3p 20y	−3.302	1.51	0.01029	1.35
NOAA 2021 3p 20y alt	−3.218	2.16	0.01004	1.92
NOAA 2021 3p 19y	−3.201	2.63	0.009984	2.33
Average	−3.245		0.01012	1.44
Stdev (%)	1.508		1.42	
overlapping intervals			0.01013	1.125
non-overlapping intervals			0.01010	1.867

Again, the linear quality is excellent with a mean standard deviation of the CO_2 sensitivity B of 1.4 %. It is nice to see that the standard deviations of all calculated B-values is also 1.4% (just as a check). The best estimate value of B is 0.01012 °C/ppm CO_2 which is around 7% lower than the corresponding GISTEMP value. The parameters A and B define a long-term trend-line for the last 60 years. The temperature (20-year- average) follows this trend-line according to the equation $T(y) = A + B*\rho(y)$ ($\rho(y) := CO_2$ concentration ρ as a function of the year y) The actual measured annually averaged temperatures fluctuate around this trend-line. This is shown in the next Figure for the GISTEMP data, indicating more than 1°C temperature increase in the last 60 years:

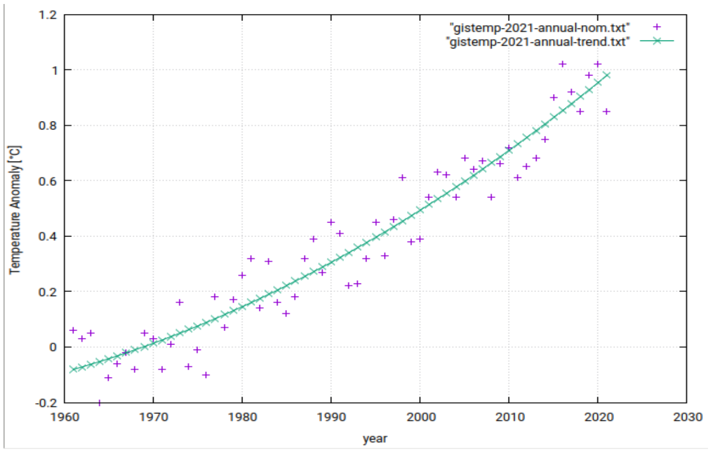


Figure 4: Annually averaged global temperatures (GISTEMP, in violet) as a function of time (covering the years 1961-2021), green points with line connection: 20-year trend-line with linear CO_2 dependency

Figure 4 shows that the temperatures in the years 2019 and 2020 were above this trend-line, whereas in 2021 the global temperature was significantly below this trend-line. This is also the main reason why the CO_2 sensitivity B is slightly higher for time periods ending 2010 than for periods ending 2021. An important aspect here is how much the individual annual values deviate from this trend-line. For the global temperature (GISTEMP) this mean standard deviation is of the order of 0.093 °C. It is almost the same in the first half of the period as in the second half (only very slightly decreasing). Only one annual temperature is slightly outside the 2σ-range, i.e. the value for the year 1976. Similar standard deviations of the order of 0.095 °C are obtained also for NOAA and HADCRUT5 which shows the good consistency of these data libraries. Generally, these deviations are lower for sea and higher for land. Examples for land/ocean/continents are given in Timm W. 2021 (preprint).

To sum up, the dynamics of the global temperature in the last 60 years is determined by a simple long- term trend which is strictly linearly correlated to the CO_2 concentration in the atmosphere. The annual temperature values may differ from this trend-line by around 0.1 °C (1σ) due to stochastic/short-term effects. This is an empirical (and quite obvious) finding. A causality is not claimed at this point. Nevertheless it is plausible that the trend shown in Fig. 4 will not stop immediately and the global temperature (20-year-average) will increase by slightly more than 0.2 °C till 2030. The temperature increase in the last 60 years is around 1 °C if just the trend-line is considered.

Global Land Data

A similar investigation can be performed for the global land temperatures. Global land covers only around 30% of the global surface. Temperature increase is higher on land and also the annual fluctuations relative to an imagined trend-line are higher. These higher temperature increases on land are also an important issue in the AR6 report (IPCC 2021). Focus here is on the land data of NOAA (NOAA NCEI 2021), there are also similar data provided by CRU/University of East Anglia (CRU 2021). So as an alternative, also the data set CRUTEM5alt was analyzed to some extent. The basic temperature data (in analogy to the sections above) are compiled in the following table:

Table 5: Reference points for determining the CO_2 sensitivity (B) of global land temperature

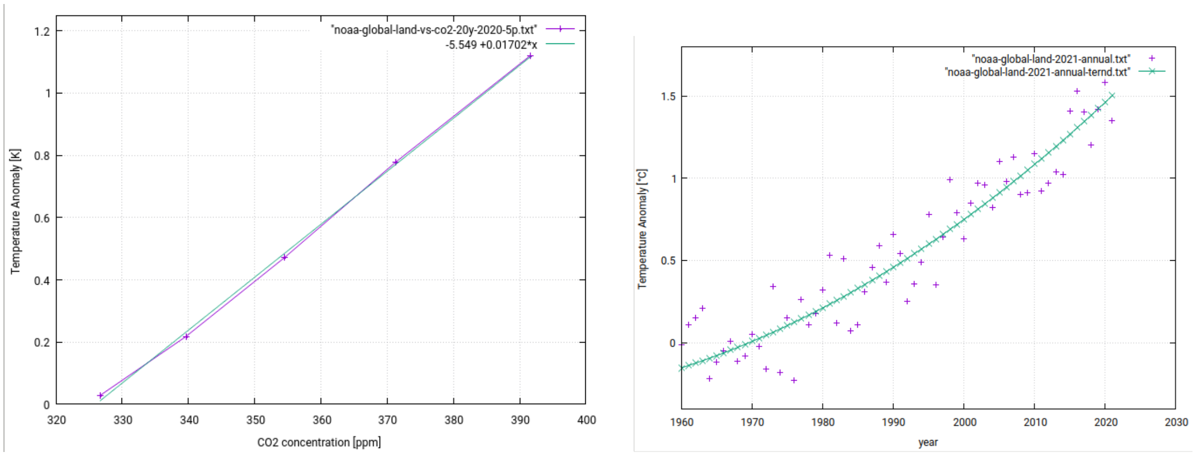
Points no.	Time period for averaging	CO_2 concentration [ppm]	Temperature NOAA land [°C]	Temperature CRUTEM5alt [°C]
1	1961-1980	326.66	0.028	−0.0897
2	1971-1990	339.63	0.2175	0.0604
3	1981-2000	354.54	0.472	0.3031
4	1991-2010	371.3	0.778	0.6095
5	2001-2020	391.62	1.1205	0.9462

The CO_2 sensitivities (B) for global land temperature which are derived from these data are given in the next table, where for comparison also one row for the standard CRUTEM5 data is included:

Table 6: CO_2 sensitivity (B) of global land temperature and standard error for different temperature data sets

Temperature Data Set	A [°C]	Standard Error A (%)	B [°C/ppm CO2]	Standard Error B (%)
NOAA global land (1961 - 2020)	−5.549	2	0.01702	1.80
CRUTEM5alt (1961 - 2020)	-5.445	3.9	0.01629	3.67
CRUTEM5alt (1971 - 2020)	-5.77	1.6	0.01716	1.50
CRUTEM5 (1971 - 2020)	-5.473	1.9	0.0163	1.77

CRUTEM5alt is taken as a reference compared to CRUTEM5 standard because it is (hopefully) an improvement due to its different treatment of gridding effects. For the CRUTEM5/CRUTEM5alt data the value for the earliest time interval 1961-1980 is a bit of an outlier (too high compared to the others, leading to an only "good" but not "excellent" linearity of 3.7% standard error), but the data for the last 50 years show indeed excellent linearity. The CO_2 sensitivity of the global land temperature is almost identical for NOAA and for CRUTEM5alt for the last 50 years (around 0.017 °C/ppm CO_2), which means that the dynamics of these temperatures are almost identical in this time period for the two data sets. Thus, in the last 50 years the ratio of temperature increases of global land to global (land/ocean) is around 1.56. Comparing only NOAA data (which is most consistent) this ratio is even close to 1.66. This is considerably higher than the best estimate value given in the AR6 report (IPCC 2021) for the temperature increase since 1850, i.e. around 1.45. The author thinks that the higher values will give better forecasts for the next decades, mainly because of the strict linearity of the global land temperatures vs. CO_2 in the last five decades. In the next Fig. 5 this is illustrated for the NOAA data. Fig 5(a) shows the global land temperature vs. CO_2 (20-year-average values) and Fig. 5(b) the dynamics of the global land temperature increase.



(a) Global land temperature (NOAA) vs. CO_2

(b) global land temperature vs. time (till 2021)

Figure 5: 20-year mean of NOAA global land temperature vs. CO_2 and land temperature trend-line vs. time (a) global land temperatures (20-years ave. NOAA) vs CO_2 for time period 1961-2020 (b) annual global land temperatures (NOAA, violet) and comparison with temperature trend-line (linear in CO_2 concentration till 2021, green with line-connection)

When taking a closer look at the dynamics of the global land temperature in Figure 5(b), one notices a similar effect at the end of the time interval as in the case of the global temperature: the annually averaged value for 2020 is higher than the trend-line, the value for 2021 is lower than the trend-line. However, there is a difference: While the standard deviation of the annually averaged global temperature (relative to the trend-line) only slightly decreases over time, this standard deviation decreases stronger with time for the global land temperature, as can be seen in Figure 5(b). The mean standard deviation for the total time period is 0.17 °C, for the first half of the time period it is 0.182 °C, for the second half of the time period it is 0.157 °C. This behavior is not homogeneous around the world: For large parts of Siberia there seems to be a significant decrease of temperature oscillations (relative to the respective trend-lines) in the last 30 years which is probably partly responsible for this global trend. In North America the trends are different: there is a strong increase of annual temperature oscillations in the North-East of the USA in the last 30 years.

In order to show that the excellent linear correlation of the NOAA global land temperatures vs. CO_2 are not a lucky random effect, intervals have been modified in a similar manner as in case of the global (land/ocean) NOAA temperatures (Table 4) in the previous section. The results are shown in Table 7. This Table shows that the average standard deviation of B (last column) is 1.9 % which can still be termed as an excellent linearity, although somewhat higher than the global NOAA temperature value. As a check also the standard deviation of the seven calculated values of B is given (1.65%) which is in reasonable agreement with the average standard deviation of B (gnuplot values). There is the same effect as already noted for the global temperature: The annual temperature for 2020 is above the long-term trend-line, the value for 2021 is below, so the values of B are somewhat lower for the time periods ending with 2021 than for the periods ending with 2020. If just the trend-line in Fig. 5(b) is considered, global land temperature increased by around 1.6 °C in the last 60 years. The dynamics of the global land temperature are important, as hints can be given on the influence of climate sensitive gases which are not "well-mixed" in the global earth surface. This will be covered in some sections below.

Table 7: Linear correlation parameters A, B and their standard deviations for various overlapping and non- overlapping intervals for global *land* temperature (NOAA) and CO_2 concentrations (first 4 rows with overlapping intervals, last 3 rows with non-overlapping intervals)

data lib	A	stdev A (%)	B	stdev B (%)
NOAA land 2020 20y 5p	−5.549	2	0.01702	1.80
NOAA land 2021 20y 5p	−5.386	1.8	0.01656	1.65
NOAA land 2019 20y 5p	−5.53	2.1	0.01699	1.9
NOAA land 2021 20y 5p alt	−5.356	1.9	0.01647	1.73
NOAA land 2020 20y 3p	−5.487	2.9	0.01685	2.61
NOAA land 2021 20y 3p alt	−5.311	3.2	0.01635	2.87
NOAA land 2021 19y 3p	−5.364	0.92	0.01647	**0.82**
Average	−5.426		0.01667	1.91
Stdev (%)	−1.736		1.65	
overlapping intervals			0.01676	1.77
non-overlapping intervals			0.01656	2.10

Discussion of the Present Findings in the Context of the AR6 Report of the IPCC

Comparison of Global Temperatures

The first part of the AR6 report is the "Summary for Policy Makers" (SPM) and describes the state of the current knowledge of global warming. The assessment of global temperatures is summarized on page SPM-5 of the AR6 report (IPCC 2021) and in Fig. SPM.2 (left column on page SPM-8) showing the temperature increase for the decade 2010-2019 since the period 1850-1900. A value of around 1.1 °C with an uncertainty of around 0.2 °C is shown in Figure SPM.2. On page SPM-5 it says accordingly: "*Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900*". Here, the uncertainty interval seems to be somewhat lower than in Fig. SPM.2. This can be easily compared with the results for the three temperature data libraries (GISTEMP, NOAA, HADCRUT5) which are used in the present investigation. These temperature data and also forecasts for the next 10 years are given in the next table:

Table 8: Global Temperatures [°C] for Various Temperature Data Sets and Forecasts for the Next Decade.

	average	average	difference	CO_2 trendline	“optimistic” forecasts with 2.5 ppm/year			“realistic” forecasts with 2.7 ppm/year		
year	1881-1900	2011-2020	2011/20-1890	2020	2030	2032	2034	2030	2032	2034
GISTEMP	−0.213	0.84	1.053	1.188	1.462	1.517	1.572	1.484	1.543	1.602
NOAA	−0.2095	0.824	1.0335	1.164	1.421	1.473	1.524	1.442	1.497	1.553
HADCRUT5	−0.392	0.759	1.151	1.308	1.591	1.648	1.705	1.614	1.675	1.736
average (three values)			1.079	1.220	1.492	1.546	1.600	1.513	1.572	1.631
Standard Deviation (three values, 1σ)			0.0630	0.0769	0.0887	0.0911	0.0936	0.0897	0.0923	0.0949

As for the considered temperature data sets only data from 1880 on are available, the 20-year-period 1881-1900 is taken as a reference (instead of 1850-1900 as in the AR6 report). The values for this period and for the period 2011-2020 are calculated for all three temperature data sets (first two data columns). These numbers are not directly comparable with each other, as the definition of “temperature anomaly” slightly differs. However, the difference for the two periods (third data column) are comparable. The average temperature increase is 1.08 °C which is indeed almost identical to the AR6/SPM value of 1.09 °C. Using three data, one can calculate a standard deviation which is around 0.06 °C which is substantially lower than the uncertainty indicated in the AR6 report. Maybe there are arguments why this uncertainty should be higher (Three data sets maybe not sufficient).

Table 8 contains more numbers: The trend-line value of the global temperature for the year 2020 which is just an extrapolation of the 20-year-average to the year 2020 (without annual stochastic effects). This is 1.2 °C relative to the period 1881-1900. So now we have passed a temperature increase of 1.2 °C.

The last six columns of Table 8 show a very simple forecast for the global temperatures for the next decade. These numbers just use the simple (purely empirical) linear correlation of temperature vs. CO_2 concentration. One “optimistic” scenario assumes that the annual increase of CO_2 is constant (2.5 ppm CO2) and thus the accelerated global increase of CO_2 is stopped in the next decade. A second “realistic” scenario assumes a moderately accelerated growth of CO_2 of 2.7 ppm/year as an average over the next decade. In both scenarios a temperature increase of 1.5 °C will be reached in 2030 and a temperature of around 1.6 °C in the year 2034. The differences between the two scenarios are not very significant. It is interesting to compare this with Table SPM.1 (pages SPM-17/18) of the AR6 report. For the near-term period (2021-2040) almost all scenarios give a mean temperature of 1.5 °C for the period 2021-2040, with a rather large uncertainty range. For gradually increasing temperatures, the average value will be close to the trend value in the middle of the time interval (2030/31). So the “best-estimate” forecasts of AR6 for the near-term future and the very simple forecasts of Table 1 are almost identical. The main difference is that the uncertainty of the present simple approach is much smaller. In contrast to these large uncertainties of Table SPM.1 in the AR6 report, the technical summary of the AR6 report (page TS-9) makes a much clearer statement:

“The central estimate of crossing the 1.5°C of global warming (for a 20-year period) occurs in the early 2030s”

So, in this respect the present purely empirical approach fits perfectly with the findings of AR6 report. In Fig. SPM.2 of the AR6 report of the IPCC (more precisely: first part, i.e. summary for policy makers) also the results of an attribution analysis and of radiative forcing studies (as the result of “complementary approaches”) are given. The “best estimate” result of the attribution study indicates that the “well-mixed” greenhouse gases contribute to a global warming of 1.5 °C whereas other human drivers (e.g. aerosols) contribute to a cooling value of around 0.4 °C. The role of greenhouse gases other than CO_2 and of aerosols in the last 60 years will be discussed in a section below. Just taking the best estimate value for CO_2 from radiative forcing studies and comparing it to the measured total global effect it can be stated the contribution of CO_2 to the total global warming is estimated by the IPCC to be around 70-80%. Here the obvious question comes to mind why the remainder contribution of 20-30% does not disturb this perfect linearity of temperature vs. CO_2 in the last 60 years, even if the dynamic behavior of the main other contributors (e.g. Methane/aerosols) is quite different compared to CO_2.

There is a general comment to the AR6 report: It should be made clear that the measured data (left column in Figure SPM.2) should have the highest relevance. This figure could suggest that there are “multiple lines of evidence” which are more or less equivalent in relevance. However, in my view this is not the case. The very large error bars on the middle and right column of this figure provide a lot of confusion and just give a hint on the general uncertainties of the radiative forcing/attribution studies. Especially the uncertainties for aerosol contributions are so high that anything between zero and a large negative contribution could be possible. When just analyzing measured temperature data in the last 60 years and their dynamics the author comes to the conclusion that the effect of aerosols (mainly SO_2) is almost negligible on a global scale which will be described in more details in a section below.

Linear Behavior of Global Temperatures in the AR6 Report

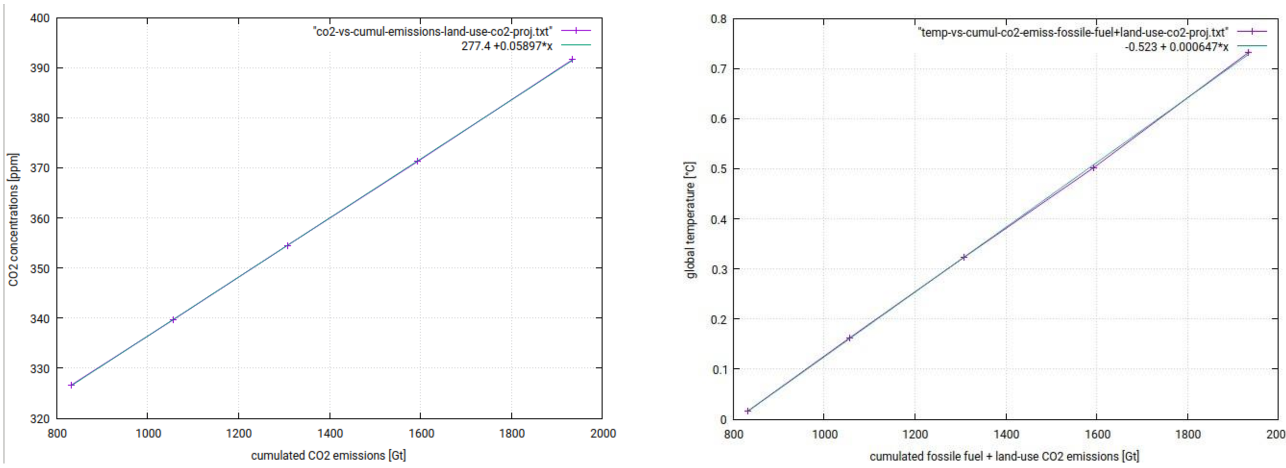
Strangely, in the AR6 report also a similar linear effect as in the previous sections is mentioned: This is shown in the Fig. SPM.10 of the AR6 report (page SPM-37), indicating a (rough) linear relationship between cumulative CO_2 emissions and increase in global temperature. Obviously, this relationship supports the concept of CO_2 budgets which is an important quantity in the AR6 report. Sadly, the value of this (measured/empirical) differential quotient is not mentioned or quantified in the SPM/AR6 report. Instead, a value for the result of climate response calculations is given on page SPM- 37, i.e. 0.45 Degrees per 1000 Gt CO_2, with a relatively large uncertainty interval of 0.27°C to 0.63°C. In contrast to this, Fig. SPM.10 in AR6 shows an "empirical" differential quotient, where it is not clear what the contribution of CO_2 to this temperature rise really is. I tried to quantify this "measured" differential quotient, with a (rough) look-up of numbers from Fig. SPM.10 and estimated a (very rough) value of 0.55 to 0.6 °C per 1000 GWt CO_2. This is in accordance with the ratio of 70-80% for the CO_2 contribution to the total global temperature increase if the "best-estimate" value of the radiative forcing calculations is taken as reference.

This is not the whole story. Figure SPM.10 (in AR6) shows a rather rough linearity. This is a bit in contrast to the present claiming in the previous sections of a very strict linearity between global temperature and CO_2 content in the atmosphere. However, this contrast is only seemingly. The present study is based on time-averaged values of temperatures and CO_2 content whereas the data in Figure SPM.10 contain annual fluctuations of the global temperatures. So, in addition to plotting time-averaged temperatures vs. CO_2 (as in the previous sections) one can also plot time-averaged temperatures vs. anthropogenic cumulative CO_2 emissions. Here, it is normally distinguished between fossil fuel and industry emissions on one side and land-use-change-emissions on the other. While the land-use-change-emissions are rather stable over the last decades the fossil fuel and industry emissions are continuously increasing over the last decades. The following table shows the best-estimate anthropogenic cumulative CO_2 emissions for the decades between 1970 and 2010.

Table 9: Global Cumulative CO_2 Emissions since 1881 for the Decades from 1970 to 2010

	cumulated CO_2 emissions [Gt] (since 1881)		
Year (including)	**land-use**	**fossil fuel**	**sum**
1970	427.6	405.5	833.1
1980	473.1	583.0	1056.1
1990	520.0	789.0	1309
2000	567.7	1026.4	1594.1
2010	612.0	1322.6	1934.6

These cumulated CO_2 emissions are based on annual CO_2 emission data of the CO_2 Project (Friedlingstein P. et al. 2021) which are documented by the web page "ourworldindata.org" (Ritchie, H. et al 2022). The author compared these data for fossil fuel emissions with data from Appalachian State University/ORNL (Gilfillan D. et al 2020) and found no significant differences, so they should be reliable. The cumulation was performed by a simple customary spreadsheet program. The data from Table 9 are then plotted both vs. CO_2 content in the atmosphere and global temperature (GISTEMP) for the five-time intervals which are used above (see Table 1). The result for CO_2 content vs. cumulative fossil fuel CO_2 emissions is given in the following Figure:



(a) (b)

Figure 6: Correlation of cumulative fossil-fuel + land-use CO_2 emissions (taken from "CO_2 project") (a) Global CO_2 concentration (20y average) vs. cumulative CO_2 emissions (b) Global temperature anomaly (GISTEMP, 20y-average) vs. cumulative CO_2 emissions

Figure 6(a) shows that there is a remarkably strict linearity between cumulative fossil-fuel plus land-use CO_2 emissions and CO_2 concentration in the atmosphere, at least when using time averaged values. This is not totally surprising as the AR6 report on page SPM-5 states: "*Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades.*"

Therefore, such a linearity could be expected, it is obviously not just a correlation but also a causal relationship. The standard deviation for the differential quotient (0.059 ppm CO_2 per Gt CO_2 emission) is only 0.25% (1σ) which is a truly sensationally strict linearity and by no means a trivial finding. Without these anthropogenic CO_2 emissions there would be a CO_2 concentration of around 277 ppm with this linear approach which is very close to the value of 280 ppm which is often estimated as a pre-industrial CO_2 level. Similarly, one can plot the global temperature (20-year average, GISTEMP) vs. cumulated fossil fuel CO_2 emissions. This is shown in Figure 6(b). As could be expected from Fig. 3(a) there is also an excellent linearity with a standard deviation of only 0.75% (1σ) for the correlation of global temperature vs. cumulative CO_2 emissions. The (empirical) correlation coefficient is 0.65 °C per cumulative 1000 Gt CO_2 with a very high accuracy. A causal relationship is not claimed at this stage. However, there is again the obvious question why this empirical correlation is so strictly linear, considering the physical effect of CO_2 is only 70-80% of the total temperature effect with the other main contributors having different dynamic characteristics. The above considerations show that the correlations of global temperature vs. CO_2 concentration in the atmosphere and of global temperature vs. cumulative CO_2 emissions (as in the AR6 report) are almost equivalent, if the relative up-take of CO_2 by land/ocean remains constant over the whole time period. In the opinion of the author, the CO_2 concentration in the atmosphere is a much simpler parameter since it can be easily measured and is the real origin of "radiative forcing". The empirical (measured) correlation coefficients are very accurate and the statistical errors seem almost negligible.

Potential Contributions of Other Climate Sensitive Gases

Fig SPM.1 of the AR6 report gives an overview of the main contributors to global warming. E. g. for natural effects such as solar/Vulcanic drivers the middle column of this Figure SPM.2 (page SPM-7) gives a hint: their influence on a 20-year-average scale should be negligible.

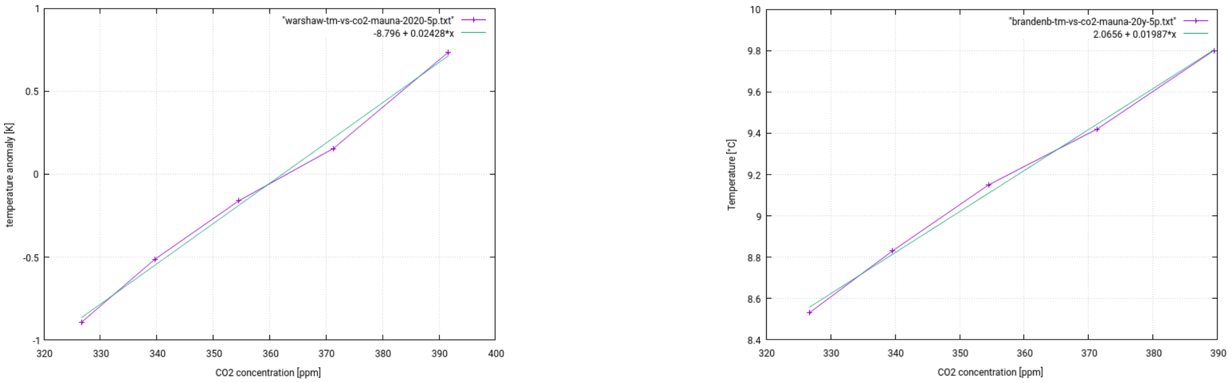
The main contributors to temperature change seem to be well-mixed greenhouse gases (strongly positive, with Methane as an additional significant contribution) and aerosols (negative). Aerosols and greenhouse gases (other than CO_2) will be discussed in the next sections.

Aerosols (Mainly SO_2)

Aerosols (especially SO_2) seem to play a major role according to AR6, see right column on Fig.SPM.2. Unfortunately, there is also a large uncertainty interval (almost touching the zero line). SO_2 is not a "well- mixed gas" in the atmosphere, its distribution in the atmosphere is heterogeneous and it has a relatively short lifetime. So the SO_2 effect on temperatures should be larger in areas with large industrial air pollution (with strong SO_2 emissions) than in "cleaner" areas. On a global scale, the SO_2 emissions since 1850 are shown e.g. by ourworldindata.org ("Global Sulphur dioxide (SO_2) emissions by world region", 2022). From this Figure on ourworldindata.org it is easily seen that there is a sharp peak of SO_2 emissions around the year 1980. The main origin of this peak is obviously located in Europe (yellow part), main emitters should be East Europe (former communist states with their heavy air pollution). After the breakdown of communism (around 1990) these emissions were strongly reduced which is seen in this Figure from ourworldindata.org.

There are several ways to test the hypothesis of a strong influence of SO_2 on global temperature (as claimed by the AR6 report). One very simple way is to take a look on the global land temperature. As SO_2 is essentially concentrated on land, the strong negative effect on temperature should be more pronounced on land (roughly a factor of three compared to land/ocean), so there should be a much slower increase of temperature before 1990 than after 1990. However, such an effect is not seen, see global land temperatures in Fig.5. The effect on the dynamics of the global land temperature seems to be negligible.

One can test this hypothesis more deeply when comparing the local temperature evolution in the former GDR (strong air pollution, at least in the period ~1960-2000) with Western Germany (with significantly lower air pollution). When looking at the Table 6 of Timm, W. (2021), one can compare the value of the differential quotient (B) for Brandenburg/Berlin (former GDR) with the rest of the German federal states. The value of B is around 8% lower than the mean value for Germany as a whole, so the difference is not very significant (Only slightly lower than for North-Rhine-Westphalia). The linear correlation can be termed as good (1 σ error of 3%), as the following Figure 7 (part (a)) shows:

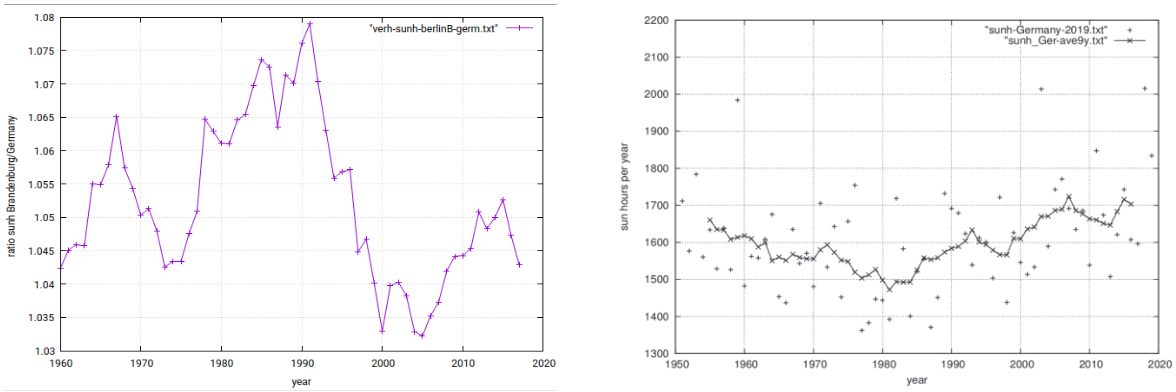


(a) (b)

Figure 7: Local Temperatures (20-year average) of Brandenburg/Berlin and Warsaw vs. CO_2 content in the atmosphere
(a) Local Temperature (20-year average) Brandenburg/Berlin (German federal state) vs CO_2 / DWD data
(b) Local Temperature (20-year average) Warsaw (Poland) vs CO_2 / NOAA data (lat. 52°, long. 21°)

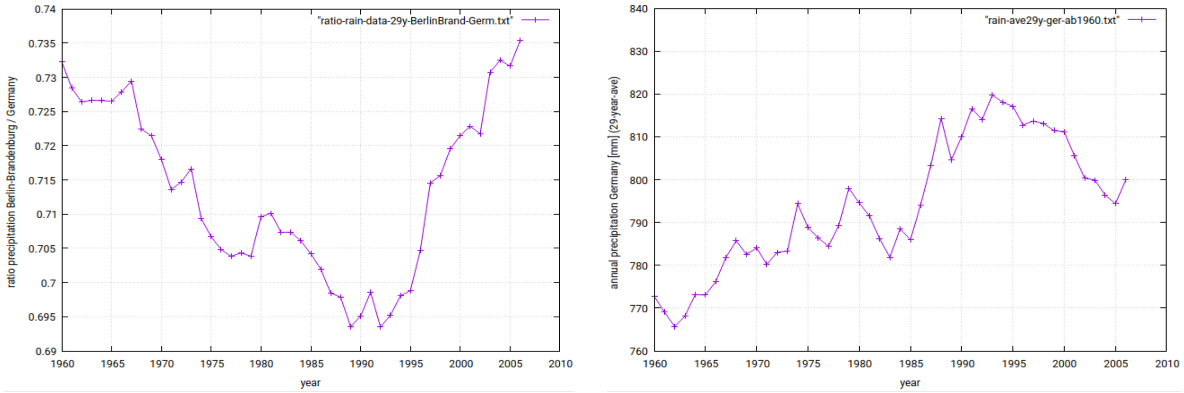
There is only a slight slowdown of the temperature increase in the period after the German unification (1990, 3rd point) which may be the reason for the somewhat lower slope B compared to the mean German value. But it could be argued that this may be a statistical effect only. However, for Warsaw (also communist state) this effect is very similar as can be seen in Figure. 7(b). Figure.7 shows that the (slight) slowdown of temperature increase does not occur during strong air pollution but in the transition from heavy to low air pollution (1990-2000). Often different air pollution effects (e.g. also fine dust emissions ("black carbon" in the AR6 report)) occur at the same time and these effects may compensate each other to some extent (fine dust should have a warming effect). Actually, a "GDR-effect" on local weather is indeed seen in the precipitation data and the annual sunshine duration: There is a stagnation of precipitation in the GDR from 1960 to 1990, contrary to an increase in Germany as a whole. Similarly, the duration of sunshine increases more significantly in the GDR than in total Germany. This is illustrated in Figure. 8, where the German federal state Brandenburg/Berlin is compared with Germany as a whole which is clearly dominated by Western Germany. Figure. 8(a) shows the ratio of the annual sunshine hours of Brandenburg/Berlin and total Germany. Here, only 9-year averages were compared as there are large annual fluctuations of sunshine hours and some smoothing is necessary to show trends over longer time periods. Fig 8(b) shows the measured annual sunshine hours (from DWD 2021) in Germany and the corresponding 9-year averages. For Germany as a whole there is a steady increase of sunshine hours from 1980 (around 1500 h) to 2010 (around 1650 h) which is quite significant (+10%). As Fig. 8(a) shows, the increase of sunshine hours is stronger in Brandenburg/Berlin from 1960 to 1990 (around 3%). 1990 is the end of the GDR and the year of the German unification. From that time on air pollution (incl. SO_2) gradually ceased. There is a significant decrease of sunshine hours in Brandenburg/Berlin between 1990 and 2000 (around 4%) and the level of the ratio returns to the values of around 1960. It may be argued that these percentages are rather small and may be partly just stochastic effects. However, the same effects are seen in other former GDR areas (e. g. the federal state Sachsen-Anhalt).

A similar effect is seen in the precipitation data (also from DWD 2021). For reliable and stable trends of precipitation vs. time, much larger time averaging intervals are necessary. In most cases an averaging interval of around 30 years appears to be appropriate for stable precipitation trends. Therefore, an averaging interval of 29 years was chosen and Figure. 8(d) shows the trend for the annual precipitation in Germany (as a whole) from 1960 on. There is a (roughly) steady increase of precipitation from 770 mm in 1960 to around 815 mm in 1995 (around 6%). After 1995 there is a decrease for one decade, and forecasts for the time after 2005 are very risky. Again, there is a different behavior in the former GDR. This is illustrated in Figure. 8(c), were the ratio of precipitation in the state Brandenburg/Berlin and Germany is plotted vs. time. From 1960 to 1990 there is continuous decrease of this ratio from 0.73 to 0.695 (-5%). After 1990 there is a steep increase of this precipitation ratio till the original value of 1960 (0.73) is roughly reached again. A similar effect is seen in the federal state Sachsen-Anhalt. Overall, there is a consistent picture: During the "GDR-period" between 1960 and 1990 the weather became dryer and sunnier than in the rest of Germany. During the first decade after the German unification (1990) the weather in the former GDR became rainier and less sunny until a (rough) alignment to the rest of Germany was reached. This is consistent with the temperature behavior seen in Figure 7, showing a retardation of temperature increase between 1990 and 2000 (3rd and 4th point) where the weather became rainier and less sunny.



(a) ratio sunshine hours

(b) sunshine hours Germany (9-year average)



(c) ratio precipitation

(d) precipitation Germany (29-year average)

Figure 8: Comparison of Annual Sunshine Hours and Precipitation of Federal Countries Brandenb/Berlin and Germany
(a) Ratio of annual sunshine hours (9-year average) of Brandenburg/Berlin and Germany (total)
(b) Annual sunshine hours (annual plus 9-year average) of Germany (total). Points with line-connection: 9-year average
(c) Ratio of annual precipitation (29-year average) of Brandenburg/Berlin and Germany (total)
(d) Annual precipitation (29-year average) of Germany (total)

So, the overall effect of local air pollution (incl. SO_2) seems to be that there is only a small decrease of local temperature when the air becomes cleaner (while SO_2 is already decreasing). On a global scale, this effect should be negligible. This empirical finding is consistent with local measured data, i.e. temperature, sunshine duration and precipitation. What we see is just a combined effect of air pollution (SO_2, fine dust). The effect of SO_2 on temperature may be negative but it seems to be compensated to a large extent by other air pollution effects such as fine dust. The local data of DWD 2021 (including precipitation and sunshine hours) are very valuable since they provide consistent and plausible data in this respect.

Impact of Main Other Greenhouse Gases

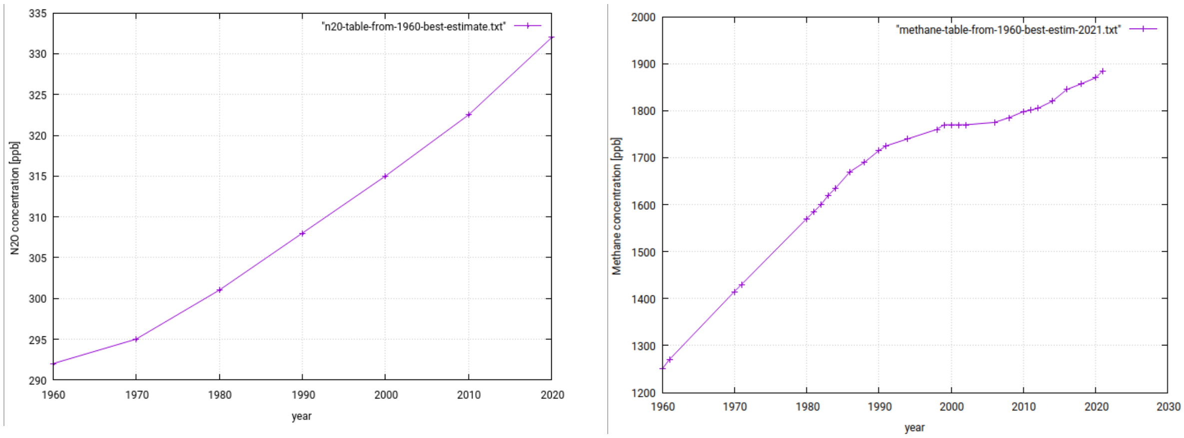
In order to give a simplified assessment of other greenhouse gases in comparison with CO_2 one may use the concept of the global warming potential (GWP), see EPA GWP 2021. Essentially the impact of 1 kg of a specific greenhouse gas is compared with the global warming potential (GWP) of 1 kg CO_2. For gases like Methane which are only rather short-lived in the atmosphere, there are long-term (100 years) GWP factors and also short term (20 year) GWPs which is quite confusing for non-experts (like the author). All of these GWP factors have rather large uncertainty intervals. It is also clear that a GWP factor for 1 kg release into the atmosphere is not identical with an equivalence factor for 1 kg present at a time in the atmosphere, so that only a rough estimate for this equivalence effect can be calculated if the mole fractions in the atmosphere are used approximately with the best-estimate GWPs.

Two greenhouse gases will be considered approximately in the following considerations: One is nitrous oxide (N_2O), the other is Methane. N_2O concentration is steadily increasing in the atmosphere, even slightly accelerated, so the effect of CO_2 plus (equivalent) N_2O is expected to show a similar (excellent) linearity as CO_2 alone. With Methane, this behavior is expected to be different: combining the Methane data of M. Meinshausen et al. (2017) and NOAA ESRL (Methane data 2021), there is a "kink" in the gradually increasing curve around the year 1990. Such a "kink" could have a distorting effect regarding the strict linearity of temperature vs CO_2 concentration.

The other climate-sensitive gases such as Methane and nitrous oxides are believed to be responsible for around 25-40% of the (historical) total greenhouse gas effect, see AR6 (IPCC 2021) and EPA (global greenhouse gas emissions 2022, based on AR5). Moreover, the influence of Methane is relatively complicated because the distribution over the earth's surface is not entirely homogeneous.

In the present evaluation only the main contributors Methane and nitrous oxides are considered. The fluorinated gases which are responsible only for around 2-3% of the present warming (according to EPA) will be neglected. In order to make a full assessment of the greenhouse gases one has to generate a table of the annual sum of all CO_2-equivalents in the atmosphere in the last 60 years. These data were taken partly from the NOAA server (most recent data till 2020) and from Meinshausen et al. [14]. For methane an equivalence factor of 31 is taken for one molecule (taking the short-term (20-year) GWP of 85 and multiplying it by the mass ratio 16/44), for N_2O a factor of 265 (GWP, no mass correction) is assumed. The respective concentrations have to be multiplied by these factors to obtain CO_2-equivalents. Uncertainties for these factors surely exist but will not be discussed here. The intention is to obtain just an order of magnitude for the contributions of these other greenhouse gases relative to CO_2. In consistency with the procedure above, only 20-year averages will be calculated for the five 20-year periods.

The historical data for the Methane and N2O concentrations are taken from the most recent NOAA (NOAA ESRL 2021) data for the period from around 1980 to 2020 and from Meinshausen et al. for the period before this [14]. This combination is shown in Figure 9(a) for N_2O and in Figure 9(b) for Methane. The data for N_2O seem to be overall convincing and consistent: there is a slightly accelerated increase over the whole time period, similar to CO_2. However, for Methane the visual impression is not really convincing: With the original NOAA data (which is essentially Methane concentration measured over sea area) there is some stagnation in the period between 1990 and 2010. Generally, the increase of Methane seems to slow down after 1980, but a convincing argument for this behavior is missing. The general dynamic behavior is a moderately accelerated growth of nitrous oxide and a slightly decelerated growth of Methane.



(a) Nitrous Oxide Concentrations since 1960

(b) Methane Concentrations since 1960

Figure 9: Evolution of Nitrous Oxide and Methane in the Atmosphere since 1960
(a) Nitrous Oxide (N2O), combination of (approx. graphically extracted) data from NOAA and Meinshausen et al.
(b) Methane, combination of (approx. graphically extracted) data from NOAA and Meinshausen et al.

Starting from the data in Fig. 9 the average values for the five time periods (20 years each) were evaluated in a very simple approximate manner: the values at the borders of the time intervals were added plus the value in the middle multiplied by two, and then divided by four (a "poor man's" integration method). In Table 10 these 20-year averages of the N_2O concentrations are compiled together with their contribution to the CO_2-equivalent concentrations. The ratio of the CO_2 concentration and the equivalent concentration including the N_2O effect (last column) shows that the CO_2 concentration grows relatively faster than the N_2O concentration during the last 60 years.

Table 10: N_2O concentrations (20-year averages) and their CO_2 equivalents (using equivalent factor of 265 for N_2O)

	N_2O conc.	CO_2 conc.	Equivalence conc.	Ratio equivalence conc.
Time Period	[ppb]	[ppm]	CO_2+N_2O [ppm]	CO_2 / (CO_2+N_2O)
1961-1980	295.8	326.66	405.05	0.806
1971-1990	301.3	339.63	419.47	0.810
1981-2000	308	354.54	436.16	0.813
1991-2010	315.1	371.3	454.80	0.816
2001-2020	323	391.62	477.22	0.821

The ratio of the CO_2 concentration relative to the equivalent concentration of CO_2 and NO_2 is gradually increasing over a period of 50 years, i.e. from 0.806 to 0.821. CO_2 increases faster in the atmosphere than SO_2: There is an increase of around 30% of CO_2 in the last 60 years whereas there is an increase of only around 14% for N_2O. The consideration of N_2O (as a greenhouse gas besides CO_2) leads to similarly excellent linearity for the global temperature as CO2 alone (less than 1% standard error compared to straight line). Eleven percent of the CO_2 effect have to be added to obtain the combined effect of CO_2 and N_2O for the period of the last 60 years. This is shown in Table 11:

Table 11: Determination of the GHG sensitivity (B) and standard errors for different temperature data sets and the combination of CO_2 and N_2O (equivalence concentration from Table 10)

Temperature data set	A [K]	stdev A (%)	B [°C/ppm]	stdev B (%)	Fraction of CO_2	ratio rel. to CO_2
GISTEMP 2020, $CO_2 + N_2O$	−3.981	0.78	0.00987	0.72	0.900	1.111
NOAA 2020, $CO_2 + N_2O$	−3.689	0.73	0.009248	0.66	0.900	1.112
HADCRUT5 2020 $CO_2 + N_2O$	−4.207	0.79	0.01020	0.74	0.899	1.112

With this simple approach, the integral warming effect of N_2O is 11% relative to the CO_2 effect in the last 60 years (average). This can be compared with the EPA data for 2010 (EPA global greenhouse gas emission data 2021): From this a ratio of 8% can be calculated (6%/76%) which is a reasonably good agreement, also keeping in mind that the present approach overestimates the effect of N_2O because it remains permanently in the atmosphere whereas CO_2 is taken up again by land/ocean to a considerable extent. Moreover, the relative influence of N_2O is gradually decreasing, EPA value is for 2010 and not the average of the last 60 years. Just looking on the "strictness of linearity", there is no difference between CO_2 and CO_2 plus N_2O.

A similar data compilation is given in Table 12 for Methane. Here, not only the "best-estimate" (BE) values are given, but also an approximate "linear concentration" trend for the last 40 years based solely on NOAA data and "best estimate" Methane land concentrations which are (roughly) assumed to be 15% higher than the "best estimate" sea data of NOAA (see NOAA ESRL Global Monitoring Laboratory 2021).

Table 12: Methane concentrations (20-year averages) and their CO_2 equivalents. (using equivalent factor of 31 for methane)

	Methane "best estimate"	Methane linear 1980-2020	CO_2	Equival. CO2+Meth.	Equival. CO_2+Meth. linear	Equival. CO_2+Meth. Land (+15%)	Ratio CO_2/ (CO_2+Meth) "best est."	Ratio CO_2/ (CO_2+Meth) linear Meth	Ratio CO_2/ (CO_2+Meth) land
Time period	[ppb]	[ppb]	[ppm]	[ppm]	[ppm]	[ppm]			
1961-1980	1413	1575	326.66	370.5	375.5	376.1	0.882	0.87	0.869
1971-1990	1568	1635	339.63	388.2	390.3	394.5	0.875	0.87	0.861
1981-2000	1693	1695	354.54	407	407.1	413.8	0.871	0.871	0.857
1991-2010	1763	1755	371.3	426	425.7	433	0.872	0.872	0.857
2001-2020	1809	1815	391.62	447.7	447.9	454.8	0.875	0.874	0.861

The assumed linear increase of methane concentration ρ (in ppb) which would be roughly representing the methane concentrations in the last 40 years is given by the following equation:

$\rho\ (\text{year}) = 1550 + 6*(\text{year}-1960)$

The main difference to the "best estimate" data compiled in Tables 12 (second row) are the significantly higher values for the time period 1960-1980. In Table 13, the mean differential quotient of the increase in temperature vs. the increase of GHG ("GHG sensitivity" B) is compiled for two temperature data sets (GISTEMP global and NOAA global land) and two different sets of Methane concentrations. This GHG sensitivity is the mean temperature increase divided by the CO_2-equivalent GHG concentration increase. If this is divided by the CO_2 sensitivity in Table 2, one obtains the fraction of the pure CO_2 effect relative to the combined effect of the respective GHG (last column but one in Table 13). This fraction is an average value over the last 60 years. The reciprocal value of this is shown in the last column of the table and shows to which extent the CO_2 contribution has to be multiplied to obtain the combined CO_2 plus Methane effect.

Table 13: Determination of the GHG sensitivity (B) of CO_2 plus Methane and standard errors for different temperature data sets and Methane concentrations (“BE” = best estimate, “lin.” = linear methane increase)

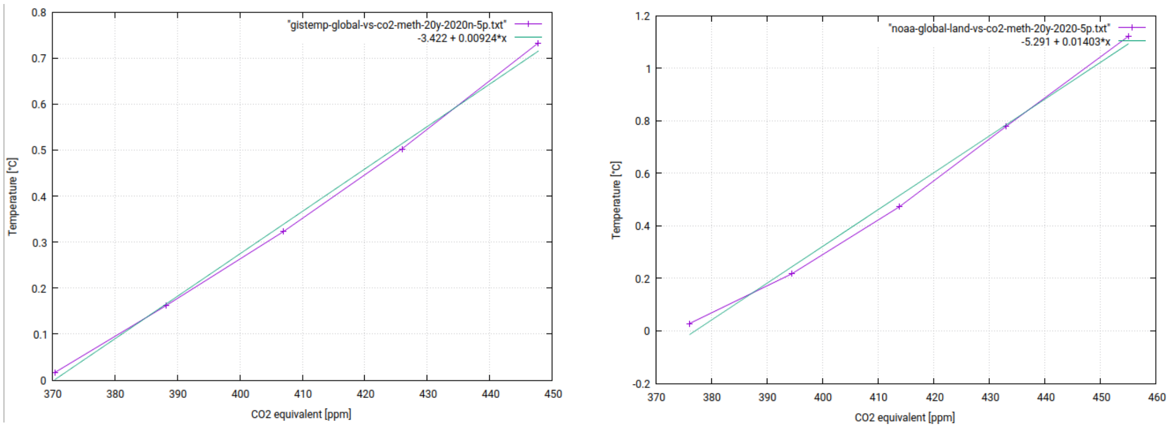
Temperature data set	A [°C]	stdev A (%)	B [°C/ppm]	stdev B (%)	Fraction of CO_2	ratio rel. to CO_2
GISTEMP 2020, CO2 + Methane BE	−3.42	3.5	0.00924	3.2	0.842	1.187
GISTEMP 2020, CO2 + Methane lin.	−3.68	0.91	0.00985	0.91	0.898	1.114
NOAA 2020 land, CO2 + Meth. BE	−5.29	5.2	0.0140	4.8	0.824	1.213
NOAA 2020 land, CO2 + Meth. lin.	−5.75	2.4	0.0151	2.2	0.885	1.129

Accordingly, around 19 % have to be added to obtain the combined effect of CO_2 and Methane for the period of the last 60 years, assuming “best-estimate” (BE) Methane concentrations. However, the linear behavior is significantly disturbed by considering this “best-estimate” Methane curve. A standard error of 3.2% is a significant deterioration of linearity, compared to excellent standard errors below 1% for CO_2 alone. The 19% effect of Methane relative to CO_2 of the present simple calculation can be compared with the EPA value of 21% (16%/76%), see EPA global greenhouse gas emission data 2021, which also seems to be a reasonably good agreement of this Methane effect. If we just assume a linear increase of Methane vs. time (roughly approximating Methane increase in the last 40 years and extrapolating it backwards to the last 60 years) there is no significant deterioration of the linear quality, a standard deviation of 0.91 % is really excellent. However, in that case also the Methane effect compared to CO_2 is significant lower (only 11 %). Similar effects are seen when considering the global land temperature data of NOAA (last two rows of Table 13). If “best estimate” Methane concentrations are considered, the deterioration of linearity is even larger (4.8% standard deviation of B), while assuming linear Methane increase vs. time yields almost the same standard deviation of B (2.2%) as with CO_2 alone as greenhouse gas (1.8%). These larger standard deviations are clearly not stochastic effects but have the character of systematic deviations from a linear behavior. This is illustrated in Fig.10, where the cases with “best estimate” Methane data are plotted. For the time 1960-1990 (first three points) the increase of temperature vs. equivalent CO_2 (CO_2 plus Methane) is significantly lower than for the time period 1990-2020 (last three points). This effect is even stronger for global land temperature. The simple reason for this behavior is that the increase of Methane in the atmosphere is much bigger for the time period before 1980 than after (see Meinshausen et al. 2017). In particular, in the last 60 years the increase of Methane was roughly 47% whereas the increase of CO_2 was just 31%. However, in the last 40 years the increase of Methane was just 19% whereas the increase of CO_2 is 21% which means that the relative influence of Methane compared to CO_2 became gradually weaker. There are several possible explanations for this behavior:

There may be some effect other than CO_2 and Methane which compensates the reduced increase of Methane after 1980. Looking at Fig. SPM.2 of the AR6 report the most probable candidate for this additional effect should be aerosols/SO_2. Fig. SMP.2 indicates a strong (“best estimate”) negative effect of SO_2. This could be compensating the Methane effect before 1980 to some extent. However, as the section above indicates such a large negative effect is not plausible when looking at the dynamic behavior of temperatures between 1960 and 2000.

The strong increase of Methane concentrations before 1980 is possibly not a real effect. However, it is hard to be believe that these measured data before 1980 should be totally wrong. The application of the GWP factor of Methane to atmospheric concentrations is overestimating the impact of Methane on global warming. Indeed, there is a “short-term“ (20-year) GWP which is roughly three times higher than the “long-term” (100-year) GWP. In the present (rather simple) investigation (Table 12) the 20-year GWP was used. On the other hand, the CO_2 in the atmosphere is partly also only “short-term” as more than half of this CO_2 is taken up by land/ocean, so the “real” Methane GWP for this sort of simple comparison could be lower.

Maybe there are additional possible explanations. In the view of the author the last item above appears to be most likely so that the impact of Methane is overestimated. The present simple calculations indicate that the Methane effect in the last 40 years (relative to CO_2) is probably only of the order of 10% or even lower. It is likely that there is also an overestimation of the total historical effect of Methane in the last 150 years which is supposed to be (according to Fig. SPM.2 of AR6) around 60% of CO_2 which would mean that it is by far the most important greenhouse gas besides CO_2.



(a) (b)

Figure 10: Global temperature (20-y ave) vs. equiv. CO_2 concentrations (CO_2 plus “best estimate” Methane)
(a): Global temperature (GISTEMP) vs. equivalent CO_2 concentrations and comparison with fitted line.
(b): Global land temperature (NOAA) vs. equivalent CO_2 concentrations and comparison with fitted line.

Some open questions remain with the treatment of Methane. The main trend seems to be that the impact of Methane in the last 40 years is gradually decreasing relative to CO_2 which is also expected for the next decades.

Linear Correlation between GHG Concentrations and Local Temperature Increase

In a similar manner not only the global (or global land) temperature increase can be correlated to CO_2, but also the local temperature behavior. In Timm W. 2021 (preprint) it is shown that in many regions of the world the temperature increase also correlates well linearly with the CO_2 increase (using the same simple averaging procedure), but with different sensitivity values and in most cases also with larger standard errors (i.e. larger deviations from linearity). An excellent linear correlation is obtained for the region of Germany where the temperature data of DWD 2021 correlate extremely well with CO_2 (standard error of fitted straight line around 1%), local temperature increase being roughly twice the global value. Some examples of regional CO_2 sensitivities (e.g. UK, USA, Alaska, various continents) are also given in Timm W. 2021, chapter 3.3 and 3.5. Also on a local scale, there are approximate temperature trend-lines which are linear as a function of CO_2. The annually averaged temperatures fluctuate around this trend-line with a specific local standard deviation. While this standard deviation is rather low for global temperatures (around 0.1 °C for global land/ocean and 0.17 °C for global land), this fluctuation is much larger for local areas, some examples are given in Table 4 of Timm W. 2021. They can vary between 0.2 °C (parts of South America) to more than 1 °C (parts of Siberia/Canada/Upper Midwest). Maritime influences will provide small deviations while Northern continental weather will lead to large deviations. Regions with “mixed” maritime/continental weather such as Germany typically have standard deviations of 0.6-0.8 °C. These weather characteristics seem to facilitate also linear behavior of local temperature vs. CO_2. As was demonstrated in the aerosol section above, the analysis of local weather data can give additional valuable hints on the impact of climate-sensitive gases/particles.

Summary and Discussion

The results of the present study can be summarized as follows: Apart from the “normal” fluctuations in the global temperatures, there is a very simple long-term trend in the rise in global (and in many cases also regional) temperatures, which correlates relatively strictly linearly with the increase in CO_2 in the atmosphere. This long-term trend is determined by 20-year averages of global (or local) temperatures. The local increases can be significantly higher than the global values. The “normal” fluctuations of the annually averaged global temperatures relative to this trend-line seem to remain practically unaffected by the increase in CO_2, see Figure 4.

The quotient of the increase of temperature and the increase of CO_2 content of the atmosphere (correlation coefficient) is here referred to as “CO_2 sensitivity”. This is a purely empirical (measured) parameter. It is not claimed that CO_2 is solely responsible for this temperature effect. The global value is around 0.011 °C / ppm CO_2 (mean value based on GISTEMP, NOAA and HADCRUT5 temperature data sets, with average being close to GISTEMP). The accuracy of this value seems to be clearly less than 10%. This includes the uncertainty of the temperature data set and the uncertainty of the empirical derivation of these values from averaging. The value is to be understood in such a way that it contains the influence of all climate-sensitive greenhouse gases, of which CO_2 is obviously dominant. The AR6 report (IPCC 2021) indicates that around 70-80% of the total global warming effect should be caused by CO_2 (best estimate with significant uncertainty). The present investigation is based on the dynamics of the global temperature in the last 60 years. There is no way to distinguish between CO_2 and other (minor important) greenhouse gases which behave dynamically similar as CO_2 (e.g. nitrous oxide, see section above about other GHG). However other climate sensitive gases such as Methane or SO_2 should disturb this linearity if their effect is as large as their “best estimate” contributions to global warming (according to AR6) indicate. However, such a distortion of linearity is not seen in the last 60 years. In the opinion of the author, their impact should be smaller than indicated by the "best estimate" values of the AR6 report. This is especially plausible for the negative effects of aerosols which does not even disturb the temperature increase of global land, although aerosols are mostly short-lived and concentrated on land. For the author it seems plausible that the influence of aerosols should be almost negligible on a global scale, if SO_2 is considered together with other "black" particles such as fine dust. Similarly, the impact of Methane is probably also overestimated. In the last 40 years its impact is probably only of the order of around 10% relative to CO_2 or even less.

The above-mentioned "CO_2 sensitivity" is calculated "transiently" from measured temperature data with growing (moderately accelerating) CO_2 emissions in the last 60 years. There is also a "CO_2 sensitivity" for the global land temperature which is around 0.0165 °C/ppm CO_2. This effect is higher than the ratio of global land to global (land/ocean) temperature which is cited in the AR6 report (around 1.45). This is not directly comparable as the AR6 report gives the ratio in the last 150 years whereas the present investigation with a ratio of around 1.55 just covers the last 60 years. When trying to make forecasts for the immediate future, i.e. one or two decades, it seems appropriate to use the higher ratio for the last 60 years.

Another important finding of the present investigation is that there is not just a strict linear relationship between global temperature (20-year average) and CO_2 in the atmosphere but also between global temperature and cumulative global CO_2 emissions. Such a relationship was already mentioned in the AR6 report but an empirical correlation coefficient was not given. Assuming that the anthropogenic CO_2 emissions are the sum of fossil fuel emission and the land-use exchange emissions then an extremely strict linear relationship is found between cumulative CO_2 emissions and CO_2 in the atmosphere. One Gt cumulative CO_2 emission will increase the atmospheric CO_2 concentration by 0.059 ppm. This linearity is roughly expected since the take-up of emitted CO_2 by land/ocean is constant (around 56%) in the last 60 years. Similarly, the global temperature will increase by 0.65 °C per 1000 Gt cumulative CO_2 emissions, based on GISTEMP data. Both linear correlations show very high accuracy (standard deviation of correlation coefficient <1%).

Due to the high accuracy of these correlation coefficients forecasts are quite easy for the next one or two decades. The statement in the AR6 report that the global temperature (20-year average) will reach the 1.5 °C level around 2030 (relative to the average of the years 1850-1900) is confirmed by the present simple correlations. It is very easy to test the quality of the correlations above for forecasts, both for global and for global land temperatures. We only have to wait for one or two decades.

Political Discussion

Strategies and discussions on how to mitigate global warming are omnipresent in the public and also subject to climate conferences. So the author also takes the opportunity to give his personal view on this issue, although this is clearly not part of the scientific investigation. A trivial and simple conclusion from the above findings would be to extract as much CO_2 from the atmosphere as possible, also as soon as possible. Forget aerosols, don't bother too much about Methane. Clearly this last point is not the view of the IPCC.

In the view of the author, probably the only realistic way to make decisive global progress in climate protection is, apart from international CO_2 emission trading, the CDR technique (anthropogenic CO_2 removal, e.g. CCS, BECCS, reforestrations etc.). Details to these techniques, also cost assessments, can be found in the Web. In the AR6 report (page SPM-39) there is a recommendation of utilizing CDR which is highly appreciated. Although CDR is not new and not really "rocket science" (e.g. BECCS) nothing happens in this respect. Its potential is largely ignored by politicians/journalists/activists etc.. Instead the main focus is on just reducing CO_2 emissions. The concept of CO_2 budgets in view of temperature targets is a bit misleading because it totally ignores the important potential of CDR. Just reducing CO_2 emissions will not solve the problem fast enough. The author thinks that the industrialized countries should extract even more CO_2 from the atmosphere than they emit themselves due to their historic responsibility. Abandoning the burning of fossil fuel as soon as possible should not have the highest priority if efficient CCS is used. There is nothing wrong with having internationally certified tender for CO_2 compensation (which could be financed e.g. by tax on gasoline and which would help to establish "market CDR prices"). One should remain technologically open to find the best solution to flatten the CO_2-curve as soon as possible.

Author

Wolf Timm is a retired physicist and previously worked in the field of nuclear technology / neutron physics.

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Conflicts of Interest

The author declares no conflict of interest.

Availability of data

Only open data from the WWW are used, Code availability: Only open software was used

Author's Contribution

The manuscript essentially deals with the statistical evaluation of existing climate/weather data, both on a global and regional scale. These are open (high quality) data from NASA(GISTEMP), NOAA, DWD, MET Office/CRU. Probably the most important contributions came from the NOAA server which cannot be praised enough. The main contribution of the author is the development of a specific statistical evaluation scheme and the consistency check of this scheme with the AR6 report of the IPCC and with EPA information.

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