An empirical approach to the analysis of local and global climate and weather data and to the determination of CO2 sensitivities

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Abstract: Some freely available global temperature data sets which document the weather for a period of over 100 years, e.g. from NASA, from NOAA, additionally also local data e.g. for Germany (DWD) were analyzed in order to derive meaningful empirical long-term trends with suitable multi-annual averages. This is first demonstrated using global climate data with different approaches, whereby the results are to a high degree consistent. Analyzes of the German temperature and weather data and of climate data from other continents are carried out in a similar manner. For reliable forecasts it is important to determine the CO2 sensitivity as precisely as possible. A very simple method is to smooth out temperatures over 20 years at a time. If these values are plotted at intervals of 10 years over the associated (also averaged) CO2 content, the temperature database (since 1961) is condensed to 5 data points and a statement can be made about the quality of the linearity for the respective database. Both the NASA data and the NOAA data show an unusually good linearity with almost identical CO2 sensitivity (approx. 0.0105 K/ppm CO2). This indicates that the long-term trend in global temperature since around 1960 has been largely determined solely by greenhouse gases. If the regional weather data is used as a basis, there is also in many cases strict linearity with increasing CO2 content. The analysis of the regional data allows the conclusion that there is approximately a specific CO2 sensitivity for every region on earth with specific statistical uncertainties: For mean global land, it is 0.017 K, for Germany it is 0.022 K, and for Alaska even 0.028 K per ppm CO2.

Keywords: CO2 sensitivity of global and regional temperatures, GISTEMP, NOAA, DWD

1. Introduction

For the assessment of climate change, it is essential to know as precisely as possible the relationship between global temperature increases and the rise in greenhouse gases. The term climate sensitivity (ECS) is often used in science (Hickman L. 2020). Strictly speaking, this is a value which is reached asymptotically in a state of equilibrium when the pre-industrial CO2 concentration is doubled (approx. 280 ppm). For the value of the climate sensitivity (ECS) a value of approx. 3 K is given in climate science. According to recent studies (Sherwood et al. (2020)), the uncertainty of this value lies between approx. 2.3 and 4.5 K (1σ). In the present study, the author calculates a purely empirically derived (transient) CO2 sensitivity for the last 60 years, covering an interval roughly between 300 and 400 ppm CO2, which is a differential quotient of temperature increase divided by CO2-density increase. This is done with a simple procedure using solely measured temperature data, both from global and regional temperature data bases. The empirical determination of these CO2 sensitivities and their uncertainty is described in detail below. Much emphasis is put on local sensitivities.

2. Materials and Methods

This study only uses publicly available temperature and CO2 data (GISTEMP 2020, NOAA 2020, DWD 2020, MET Office 2020, CRU 2020 and NOAA ESRL CO2 data 2020). The evaluation is carried out with simple tools such as Excel, gnuplot (gnuplot homepage 2020), awk etc.. The results are therefore very easily reproducible for everyone who is familiar with such methods.
3. Results

3.1. Investigations into the Global Temperature Anomaly Based on NASA Temperature Data and CO2 Sensitivity

The reference for the evaluation of the “global temperature anomaly” is probably the data set from the NASA website (GISTEMP 2020). These represent a global mean value of temperatures over the oceans and the mainland. The zero point of these data (on a degree Kelvin / Celsius scale) is roughly in the vicinity of 1960. The “normalization” of the temperature anomaly takes place in such a way that the mean value over the entire last century is zero. NASA data has the unpleasant property that as a whole it is changed almost every year, including the data for years that are long ago. An evaluation is always carried out for a data set that may be out of date next year. However, the temperature data sets do not change too much from year to year.

Fig.1(a) shows the mean global temperature from 1880 to the present day (single points without connecting lines). In addition, a smoothed temperature curve is shown in Fig.1(a) (data set with connecting lines), whereby a mean value over 9 years is used as a basis for smoothing. Figures like in Fig.1(a) can be found quite often on the Internet, often using a 5-year average. In the present case, an averaging over 9 years was used because the smoothing is optically even better and the averaging time interval is almost a decade. It is often argued by climate scientists that anything that happens under a decade is just "weather" and not "climate". If the GISTEMP raw data are compared with the mean values (Fig.1(a)), you can see a scatter of the individual annual values of approx. 0.1 to 0.2 K compared to the 9-year mean values. This spread remains fairly constant over the entire time interval considered. A disadvantage of the relatively wide averaging interval is that the mean values lag behind the current annual figures. The last exact 9-year mean was determined for 2015. However, a 7-year average for 2016 was also approximately calculated here (as a trend).

Between the years 1880 and 1970, i.e. for almost a whole century, there was only a very moderate increase in global temperature of about 0.2 degrees. During this period there are two anomalies: one down by about 0.2 degrees (around 1910) and one up by about 0.1 to 0.2 degrees (during WWII). For the temperature anomaly after 1940 it is shown by Schiermeier (2008) that the recording of the temperatures over the oceans during the Second World War was probably incorrect. For the period after 1970 a sharp rise in temperatures can be seen, which is accelerating more and more and is almost one degree up to now. If only the period from 1959 (from which the CO2 concentration in Hawaii was measured and documented at Mauna Loa) until today is taken, the result is a very steady increase in the 9-year mean. So there is justified hope that the 9-year mean used contains a great deal of “climate” and little annual “weather” fluctuation. The continuous, slightly accelerated rise in temperature from 1970 onwards says nothing about the cause of the rise. Compared to the years 1880 to 1960, the behavior is definitely extremely unusual.

![Figure 1](image1.png)

(a) Temperature anomaly of the mean global temperature (GISTEMP) and presentation of the 9-year mean

Individual points: GISTEMP (2020) annual mean values, points with connecting lines: 9-year mean values

(b) Development of CO2 concentrations in the atmosphere (NOAA 2020 Mauna Loa data) since 1959

Individual points: original data Mauna Loa, Line: fitting polynomial: F(y) = 309.2 + 0.5809*y + 0.01281*y**2
Since 1959, CO2 concentrations have been measured at Mauna Loa in Hawaii (NOAA ESRL 2020). In the present study only the mean annual values are considered. A concentration of around 280 ppm CO2 (0.28 per thousand) is considered a pre-industrial value. The starting value in 1959 is approx. 310 ppm, the current value is over 410 ppm. The course of the concentrations over time is shown in Figure 1(b). A very steady, slightly accelerated increase can be seen until today (points without line connection). Due to this steady behavior, the curve can be well approximated by a polynomial of the 2nd degree (solid line, formula is given in Fig.1(b)). The deviation between the individual values and the polynomial function is a maximum of approx. 1 ppm, the polynomial thus represents an excellent fit. If the derivative of the adaptation polynomial is calculated, the change in CO2 concentration per year (as a "smoothed" value) is obtained. In 1959 this value was 0.8 ppm/year, in 2020 it was already 2.4 ppm/year, i.e. about three times as much. All fits (curve adaptations) in this study were created with the freely available program gnuplot (gnuplot homepage 2020), as were the graphic representations.

In order to represent the dependence of the global temperature on the CO2 concentration in a meaningful way, the 9-year mean temperature derived above is plotted against the CO2 content of the atmosphere, which increases monotonically over time. This CO2 content is “smoothed” for each year on the basis of the above CO2 approximation function (polynomial). The relationship is shown in Fig. 2 (individual points, each corresponding to an individual year from left to right). From 1959 until today there is a clearly linear course. The slope is approx. 0.0106 K/ppm CO2. This slope can also be verified by calculating the difference quotient from the change in global temperature and the change in the CO2 content, always based on the year 1965 (the CO2 content here is approx. 320 ppm). In that way a very stable difference quotient can be seen, which averages 0.0106. From a purely empirical point of view, there is clear evidence for the linear relationship between CO2 in the atmosphere and mean global temperature, at least in the last 60 years.

Figure 2. Global temperature (9-year average, GISTEMP) as a function of global CO2 concentration

The term “climate sensitivity” (Hickmann 2020) is often found in the literature, i.e. the (asymptotic) change in temperature when the pre-industrial CO2 content in the atmosphere doubles. For this, an expected value of about 3 degrees with a (relatively large) uncertainty of about 1.5 degrees is calculated. Assuming the linearity of the above correlation, a purely empirical value of 0.0106 * 280 = 2.97 K is obtained for an extrapolated “climate sensitivity”, i.e. almost exactly the value that climate science also predicts. One should keep in mind that the sensitivity given above is an approximate differential quotient and an extrapolation from an interval of 100 ppm to a value of 280 ppm is by no means trivial. It must be emphasized at this point that the temperature increase is presumably the result of all climate-sensitive gases (not just CO2). Strictly speaking, one would have to specify the labeling in Fig. 2 on the X-axis scale as “CO2 concentration plus equivalent greenhouse gases”. A definition of “climate sensitivity” should also be specified (more precisely) in this sense.

At the beginning of the 2000s there was a certain stagnation or even decrease in global temperatures (also in Germany) for a few years, which led to great discussions about the models of climate researchers at that time. If one only looks at the 9-year mean values, one can hardly see any more of this brief stagnation, as
there were relatively strong “catch-up” effects afterwards. Because of the 9-year averaging, this effect can only be seen as a small downward dent in the years 2005 to 2010.

One often finds the argument that a correlation is not proof of a causal relationship. In fact, the previous change of 100 ppm CO2 (0.1 per thousand) in the atmosphere is very small. But the corresponding temperature change of about one Kelvin is also very small when viewed on the absolute temperature scale (0.3%). Due to the “smallness” of both quantities, the principle of linearity (basic principle of infinitesimal calculus) then should apply to a good approximation, so that the linear behavior in Fig. 2 could be a good indication of causality. For example, Figure 1(b) shows a nonlinear relationship and does not represent causality. Even the only slight increase in global temperature between 1880 and 1960 is roughly compatible with the above relationship between CO2 content and temperature.

Researchers who deal intensively with climate models for determining “climate sensitivity” (ECS) could argue that the present empirical approach (based on historical climate data from around 1960) is somewhat simple and justify this as follows:

- The forcing (external impact on the climate) of CO2 is logarithmic, not linear. That would lead to smaller ECS.
- The oceans absorb heat and therefore temporarily dampen surface warming. That would lead to bigger ECS.
- CO2 is not the only forcing. Above all, this would lead to greater uncertainty.
- It has recently been discussed that the surface patterns of warming may temporarily lead to more cloud formation. This effect is highly uncertain, but it is likely to lead to greater ECS.

Nevertheless, the relatively strict linearity in Fig. 2 is remarkable and not trivial. The above values are not ECS values, but rather, strictly speaking, empirically derived transient effects. It cannot be ruled out that there will be additional, time-delayed effects in the future which will influence “climate sensitivity”.

In principle, the results shown here are not totally new. Since Callendar (1938), similar analyses were performed before. The extensive review article by Sherwood et al. (2020) considers not only model-based estimates of ECS but also observational estimates (e.g. Gregory et al. 2002; Gregory and Forster 2008; Otto et al. 2013) as well as hybrid estimates (e.g. Jiménez-de-la-Cuesta and Mauritzen 2019; Nijsse et al. 2020).

Moreover, there exists the “transient climate response” (TCR), which is the short-term “climate sensitivity”. TCR is defined as the surface temperature change after an increase of the atmospheric carbon dioxide concentration in a one-percent-per year fashion from the pre-industrial concentration up to the doubling. The CO2 sensitivities discussed here are closely related to TCR, as Eq. (2) of the article of Otto et al. (2013) shows that the temperature increase is proportional to the radiative forcing change on a small scale. However, the aspect of doubling the pre-industrial CO2 concentration as in most of the articles above is not important here.

In the following it is shown that other weather/climate data (NOAA 2020, CRU 2020, DWD 2020) also show this strictly linear behavior over a period of approx. 60 years, also regionally, and that with a very simple procedure the “quality” of the linearity can be determined.

3.2. Comparison with Other Weather/Climate Data (NOAA and others) and Simplified Procedure for Determination of CO2 Sensitivities

A very large temperature database is made available by NOAA (2020), whereby not only global (land/ocean) data can be queried, but also individual continents and even individual regions (by entering latitude and longitude on the earth surface). The relevant data can be downloaded directly (as “temperature anomalies”) in the form of Excel files. If the GISTEMP data set is compared with the NOAA data (land/ocean global), each based on the 9-year mean and depending on the CO2 content, a very good consistency of the two data sets can be seen, whereby the slope of the GISTEMP curve with the CO2 is slightly larger. Using the same procedure as above (tendency of the difference quotient), a CO2 sensitivity of about 0.0099 K/ppm CO2 is obtained for the NOAA data, i.e. about 7% lower value compared to GISTEMP, which can be assessed as good consistency.

In the course of the present study it turned out that one can use an even simpler method for determining the CO2 sensitivity. This takes advantage of the fact that the temperature profile for a 20-year average appears to be much smoother than for a 9-year average. The physical reasoning for this procedure is that such a large averaging interval will wipe out “annual weather fluctuations” to a large extent and thus only long-term trends...
will become visible. Typical values for annual “temperature fluctuations” will be given at the end of chapter 3.3. 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 behavior. The choice of reference points and the associated CO2 values are summarized in the following table:

| Points | 20 y ave Mouna Loa |
|--------|-------------------|
| no.    | Time period for averaging | CO2 concentration [ppm] |
| 1      | 1961-1980          | 326.7                  |
| 2      | 1971-1990          | 339.6                  |
| 3      | 1981-2000          | 354.5                  |
| 4      | 1991-2010          | 371.3                  |
| 5      | 2000-2019          | 389.4                  |

A temperature straight line is then fitted for the 5 pairs of values, which has the lowest possible standard deviations. This is done with the program gnuplot (gnuplot homepage 2020). The straight line is represented by the following function:

\[ f(x) = A + B \times x \]

(x = CO2 concentration)

The values of A and B are calculated by gnuplot together with the associated standard deviations. For some important temperature data sets, the results are summarized in the following table:

| Temperature Data         | A     | Standard Error A (%) | B      | Standard Error B (%) |
|--------------------------|-------|---------------------|--------|----------------------|
| GISTEMP (1961 - 2019)    | -3.524| 0.41                | 0.01084| 0.38                 |
| NOAA global              | -3.282| 1.05                | 0.01023| 0.94                 |
| CRUTEM4 north. Hem. (Land)| -6.064| 3.5                 | 0.0182 | 3.3                  |
| CRUTEM4 north. H. (1971-2019) | -6.486| 3.3                 | 0.0193 | 3                    |
| Germany DWD              | 1.022 | 8.4                 | 0.02166| 1.1                  |

The slope B represents the more important variable and is from now on considered as a reference value for the CO2 sensitivity (in [K/ppm CO2]). B is simply an averaged differential quotient:

\[ B = \frac{dT}{d\rho(CO2)} \]

T being the measured temperature and \( \rho(CO2) \) being the concentration of CO2 in the atmosphere. This quantity B is not intended as a new “climate sensitivity index”. Compared to the above procedure based on the difference quotients of the 9-year mean, the CO2 sensitivity with this simplified procedure is approx. 2-3% higher. Standard deviations of one percent or even less are sensational good. In particular, the extremely low standard deviation of 0.38% for the GISTEMP data is hard to believe. In Fig. 3(a) the 5 GISTEMP points are compared with the fitted straight line. The points are practically all on this straight line. One can say benevolently that the permanent changes to the entire GISTEMP data set may have increased the consistency of this data and thus contributed to this unusual result. However, the quality of linearity for the NOAA global data is also outstanding. As both data sets show this outstanding linearity, a lucky random effect can be practically ruled out. A plausible explanation could be that both temperature data sets are of very high quality and that the strict linear behavior is an indication of a complex law of nature. If the sensitivity B is multiplied by 100 ppm, one roughly obtains the temperature increase in the last 60 years.
Figure 3. 20-year mean of different temperature data sets vs. CO2 content and comparison with fitted straight lines,

\[
(a) f(x) = -3.524 + 0.01084 \times x, \quad (b) f(x) = 1.022 + 0.02166 \times x
\]

If the data sets are temperature anomalies, the constants A have the following meaning: Since the zero point of the straight line is between 1960 and 1970 (with approx. 320 to 330 ppm CO2), the value of A is the negative value of the temperature equivalent of around 320 to 330 ppm CO2, either globally or in the respective region. This does not apply to the data from the German Weather Service (DWD 2020), which is real data in degrees Celsius. The annual mean temperatures in Germany are around 9 °C. The evaluation of the CRUTEM4 data (CRU 2020) for the northern hemisphere (land only) showed a slightly higher uncertainty (around 3%) which is still good. In particular, the first point (period 1961 to 1980) was a little too high compared to the later ones. If only the last 4 points are taken (i.e. the period from 1971 to 2019, shortly “4P”), the result is a better fit, which presumably makes the CO2 sensitivity more accurate. There is also excellent linearity for the German temperature data (DWD 2020), as can be seen in Fig. 3(b). This is all the more remarkable as Germany only covers a very small part of the earth’s surface and the weather here fluctuates much more than the global mean. The CO2 sensitivities for the northern hemisphere and for land are significantly higher than the global land/ocean value. For Germany it is approx. 0.022 K / ppm CO2. This is a good indication that the procedure defined by Table 1 will also be applicable to many regions of the earth surface.

3.3 Regional CO2 Sensitivities (Based on NOAA Data)

Based on the table above, it can be approximately assumed that every region on earth has a specific CO2 sensitivity. Not only global (land/ocean) data can be queried from the NOAA server, but also individual continents and even individual regions (by entering latitude and longitude). The data can be downloaded directly as an Excel table and then evaluated in a very simple process. A selection of such regions and their CO2 sensitivity (B) is summarized in the following Table 3.

The chosen latitudes and longitudes for two individual points on earth surface were chosen close to Moscow and New York. The following tendencies result from the data in Table 3, which are only a selection:

- The CO2 sensitivity in the northern hemisphere is significantly higher than in the southern hemisphere
- The CO2 sensitivity on land areas is significantly higher than over the oceans
- The CO2 sensitivity in Asia / Europe is significantly higher than in North America
- In a number of cases, the restriction to the years 1971 to 2019 (4P) yields significantly improved adjustments, especially for individual “point regions” (defined by degrees of longitude and latitude)

The averaging of the northern and southern hemispheres, as well as the proportional averaging of land (29%) and ocean (71%), yields a relatively accurate global CO2 sensitivity (0.01 K/ppm CO2), as it should be. It makes sense to map all regions of the world with their regional CO2 sensitivities, also in order to obtain forecasts for regional trends. It is remarkable that the CO2 sensitivity on land surface (0.017) is more than twice as high as on ocean surface (0.0077) and that their ratio remains constant over a time period of 60 years. The conclusion from Table 3 is that the global temperature increase is the surface average of all local temperature increases which are in their ratio local/global (at least approximately) constant in time. Thus there is approximately an earth-wide stationary “form factor function” of this increase distributed over the whole
earth surface. As a result of Table 3 (and also Table 2), this can be seen as a measured fact, at least for those many regions of the world where the standard error of B is sufficiently low (order of 5% or lower).

The reason for the different behavior land/ocean is quite simple: The thermal interaction between atmosphere and liquid ocean is different to the one between atmosphere and solid ground. The heat sink of the ocean is larger than of solid ground: The surface of the oceans warm up due to the very high heat storage capacity of water and the effective turbulent mixing. Therefore there will be a steady (very small) additional heat flux from land to ocean. This is illustrated in Fig.4 of the article of J. M. Stafford et al. (2000) about the temperature increase (and precipitation) in Alaska between the years 1949 and 1998. In this Fig.4 isothermal lines of temperature increase are given for an Alaska map. Highest increases are found in the interior region. The negative temperature gradients towards the ocean surfaces induce a small heat flux towards the ocean surfaces. These temperature gradients strongly depend on the geographic details which are rather complex. For instance, the temperature rise gradient (of Alaska) is small in the north direction where there is arctic ice vicinity (solid ground) in the winter. These temperature distributions could be probably described approximately by a heat diffusion equation.

In some regions of the world (e.g. Upper Midwest USA, West Siberian basin), the standard error of the CO2 sensitivity (defined by the procedure above) is of the order of 10% or more. In these cases, it is recommended to look closer at the data. It could be either a purely statistical effect (if the typical annual temperature deviation is large compared to the expected temperature increase) or it could be an indication of a long-term regional climate changeover leading to a more significant deviation from linearity. This seems to be the case for the Upper Midwest, where the increase of temperature is mitigated since around 1990, probably by an enhanced maritime influence of the North Atlantic. The weather/climate in North America is rather complex. A more detailed investigation which would also consider seasonal effects is beyond the scope of this article.

A major difference between individual regions on the one hand and entire continents or global data on the other hand are the deviations of the annual temperature values from the averaged long-term trends based on the 20-year mean values. The present study approximately assumes that these trends are influenced solely by the development of greenhouse gases. For the long-term trend (temperature as a function of the year y) the formula

$$T(y) = A + B \times p(CO2(y))$$
The results presented in Tab. 4 show, as expected, that the standard errors in temperature for the global data sets are comparatively low (<0.1 K), for individual continents (land only) the standard errors are in the range from 0.2 to 0.3 K, roughly twice as high. For individual regions on the earth's surface considered here, the standard error is approx. 0.6 to 0.8 K. The mean value of all positive and negative deviations is very close to zero in all of the cases considered, which suggests that the assumptions on the long-term temperature trend are highly plausible. Typically, the annual temperature fluctuations should be within twice the value of the standard deviation (2σ). This is also the case for 2011, 2016 and 2019. However, with one exception, namely for Oceania and the year 2011. Here the temperature deviation lies outside the 2σ range. If you look at the data from Oceania in detail, however, this is only the second value of the entire data series (60 points), which is outside the 2σ range. The relatively low temperature value for 2011 seems to be primarily an effect of the southern hemisphere. Conversely, the high global temperature value for 2016 does not seem to have any influence on parts of Europe. The year 2019 (taking into account the long-term CO2 trend in Table 3) has the character of a “normal”, somewhat warm year: 7 out of 8 values are within the 1σ range, the remaining is still within the 2σ range.

The question still remains whether the uncertainties might increase with the rise in greenhouse gases in the atmosphere. For this purpose, Fig. 4(a) shows the deviations of the GISTEMP data set from the 20-year long-term trend. The 2σ range is exceeded only once, namely in 1976. After all, the high value of 2016 scratches the 2σ range. In addition to the individual annual deviations, Fig. 4(a) also shows the 9-year mean of the absolute value of the deviations (upper curve with line connection). This value is usually a little below the 1σ value, there is no discernible tendency to increase this value. In addition, the 9-year mean value of the deviation from the long-term trend (taking into account the sign) is shown (lower curve with line connection).

As expected, this curve fluctuates around the value zero. A short-term effect in the direction of lower temperatures (order of magnitude up to -0.05 degrees) can be seen for a period between about 2007 and 2013.
A similar effect was already seen between 1967 and 1976. These are rather short-term weather / climate
effects that slow down the rise in temperature for a while. Conversely, there also seem to be effects that
accelerate the temperature increase for a while.

**Figure 4:** Deviations of the annual temperatures from the 20-year long-term trend (individual annual values
without line connection)
Upper point curve with line connection: 9-year mean of the absolute deviations,
Lower point curve with line connection: 9-year mean of the deviations
Horizontal straight line: mean of all deviations

A similar representation is shown in Fig. 4(b) with the corresponding deviations in German temperatures
(DWD). The deviations here are almost an order of magnitude higher than in the GISTEMP data. There are
two “outliers” downwards (1996 and 2010, outside the 2σ range) but none upwards. Here, too, the 9-year
mean of the absolute value of the deviations is mostly below the 1σ value and no tendency to increase this
value is discernible. Even with the 9-year mean value of the deviations from the long-term trend (taking into
account the sign), a “short-term” effect in the direction of lower temperatures (order of magnitude up to
-0.3 °C) can be seen for a period around 2010.

### 3.4 Simple Considerations on Methane

The linear behavior in Fig. 2 and Fig. 3 is also remarkable insofar as it is well known that the gas CO2 is
not the only greenhouse gas. There are also other climate-sensitive gases such as methane and nitrogen
oxides, which together are believed to be responsible for around 30 to 40% of the greenhouse gas effect. The
strictly linear behavior shown above suggests that the other greenhouse gases are either less effective than
expected or that they increase over time to about the same extent as the CO2 concentration (or not at all). The
increase in methane in the atmosphere over the past 10 years is about 5% (GOSAT 2020), while the increase
in CO2 over the same period is about 6%. This could actually indicate a certain “lock step”. The influence of
methane is relatively complicated because the distribution over the earth's surface is not entirely
homogeneous.

The historical data for the methane concentrations are (at least to the knowledge of the author) only
available for a small period of time. In addition to the GOSAT data, there is also NOAA data (NOAA
methane 2020) for the period from around 1980 to 2010, which, however, make an overall inaccurate visual
impression. For 1971 the author (as “non-expert”) extrapolated a rough value (1480 ppb) in order to have a
reasonably complete data set for the period under consideration. Methane is assumed to be around 25 times
more climate-effective than CO2. An “effective CO2 concentration” including the methane effect can then be
derived from this. Since the course of the methane concentration from NOAA 2020 is not entirely convincing,
a “linear” course was assumed as an alternative, in which the concentration increases by around 60 ppb per
decade (from 1540 ppb to 1755 ppb).

The overall result is an increase in the “effective CO2 concentration” of approx. 11 to 12% due to
methane, when assuming a 25-fold higher effectiveness compared to CO2. The differences in the “effective
CO2 concentrations” for the two methane models are not very significant. With these new “effective CO2
concentrations”, the CO2 sensitivities were recalculated. The results are shown in the table below, for both
GISTEMP and NOAA data:

Table 5. Global CO2 sensitivities (B, based on GISTEMP and NOAA data) with an approximate
consideration of methane
(Standard deviations below 2% are marked in bold (very good fit))

| Temperature Data                        | A    | Standard Error A (%) | B    | Standard Error B (%) |
|----------------------------------------|------|----------------------|------|----------------------|
| GISTEMP (only CO2)                     | -3.524 | 0.41                | 0.01084 | 0.38                |
| NOAA global (only CO2)                 | -3.282 | 1.05                | 0.01023 | 0.94                |
| GISTEMP w. factor 25 Methane           | -3.516 | 2.4                 | 0.009694 | 2.18                |
| GISTEMP w. factor 12.5 Methane        | -3.512 | 1.3                 | 0.01024 | 1.2                 |
| GISTEMP w. factor 40 Methane          | -3.507 | 3.6                 | 0.009106 | 3.3                 |
| GISTEMP w. factor 25 “linear” Methane | -3.602 | 0.62                | 0.009908 | 0.57                |
| NOAA w. factor 25 Methane             | -3.277 | 1.39                | 0.009154 | 1.25                |
| NOAA w. factor 25 “linear” Methane    | -3.322 | 1.6                 | 0.00929 | 1.46                |

In most of the cases considered with methane, the fit remains very good, especially when using NOAA
temperatures. With the GISTEMP data, the methane concentrations from NOAA methane 2020 show a slight
deterioration, while with the linear approach for methane the quality of the linear correlation is still
sensationally good. The CO2 sensitivity for the “effective CO2 concentrations” (i.e. including the methane
effect) decreases by about 10%. In addition, the “climate effectiveness” of methane compared to CO2 was
varied, once a factor of 12.5 was used instead of 25, and once a factor of 40. While the factor 12.5 has little
effect on the quality of the linear correlation, the factor 40 (at least with the GISTEMP temperatures) leads to
a significant deterioration.

The consideration of methane is still connected with some open questions. Overall, however, the above
parameter study shows that the very well-proven linearity between global temperature and CO2 cannot be
called into question even by “effective” consideration of methane.

Regarding the other greenhouse gases, it is believed that effectively around 20% of the present
greenhouse gas emissions is non-CO2. A more detailed composition of these emissions is given by EPA 2018.
This link gives the composition of the emission for 2018 in the form of CO2-equivalents. This roughly
Corresponds to the increase of the CO2-equivalents in the atmosphere, the methane part being around 10%
which is in good accordance with the calculations given above. In order to make a full assessment of all
greenhouse gases one should make a table of the annual sum of all CO2-equivalents in the atmosphere in the
last 60 years. It seems that CO2 increase is faster in relation to the other gases. So, assuming the net effect in
temperature rise will be proportional to the increase in the sum of all CO2-equivalent greenhouse gases, some
deviation from the linear behavior would be expected, in fact the temperature increase (as a function of CO2)
should then be moderately decelerating. However, such an effect is not seen. There are two possible
explanations: The other greenhouse gases are not as “effective” as expected, or this effect is so low that it
cannot be detected with the present statistics.

3.5 Evaluation of the German Temperature Data

The evaluation of the temperature development in Germany and in selected federal states is based on
weather data of DWD, which are documented from the year 1880 on (DWD 2020). The DWD database (in
ASCII format) includes monthly and annual data (also individually for all federal states) on temperatures,
precipitation and sunshine duration. In contrast to the global NASA data, the older annual data do not seem to
have been changed afterwards. Figure 5 shows the temperatures in Germany since 1880, once the original
DWD annual values (without line connection) and once in the form of 9-year mean values (data with line
connection).
The data for Germany naturally fluctuate much more from year to year than the global temperature data (Fig. 1), since Germany only represents a very small section of the world’s climate. The deviations of the individual values from the 9-year mean are often of the order of one degree Celsius. The course of the 9-year mean values is also not as “smooth” as in the case of the global temperature data. Here, too, there are fluctuations up and down. From 1880 to approx. 1980 there was a moderate increase in temperatures in Germany, with a clear anomaly (upwards) after 1945. The author suspects that one reason for this anomaly is the strong release of fine dust at the end of the Second World War, which probably vanished after a few years. After 1980 the temperature rises relatively sharply, from around 2005 there is a longer stagnation in the temperatures and then a sharp rise again. Individual federal states are also examined below.

In Fig. 3(b), the temperature development in Germany is correlated with the global CO2 content using the method shown above (20-year-long-term-trend). The slope of the “best-fit straight line” of 0.0217 K/ppm CO2 has a very low standard deviation of 1.1%. It is remarkable that the strongly fluctuating behavior in Fig.5 (since 1960) is dominated by a simple long-term trend (Fig. 3(b)). By the way, the same goes for the “Moscow”-NOAA-data, which can be easily plotted by the NOAA-server (NOAA NCEI 2020). The temperature rise in Germany vs. the CO2 content is roughly twice as large as on a global scale. Such behavior is to be expected qualitatively, since Germany is predominantly mainland and lies in the northern hemisphere, with less moderating sea influence compared to the southern hemisphere. Corresponding evaluations were also carried out for individual federal states and different seasons. The results are summarized in the following table

| Region                        | A [°C] | Standard Error A (%) | B        | Standard Error B (%) |
|-------------------------------|--------|----------------------|----------|----------------------|
| Germany DWD                   | 1.022  | 8.4                  | 0.02166  | 1.1                  |
| Germany Summer (May-Oct)      | 6.88   | 6.1                  | 0.02086  | 5.7                  |
| Germany Winter (Nov-Apr)      | -4.76  | 5.4                  | 0.02225  | 3.2                  |
| Baden-Württemberg             | 0.9067 | 26                   | 0.02158  | 3.1                  |
| Bayern                        | -0.2929| 86                   | 0.02329  | 3                    |
| Brandenburg / Berlin          | 2.066  | 11                   | 0.01987  | 3.3                  |
| Niedersachsen                 | 1.248  | 4                    | 0.02221  | 0.62                 |
| Nordrhein-Westfalen           | 2.164  | 5                    | 0.0204   | 1.5                  |
| Schleswig-Holstein            | 1.076  | 19                   | 0.02158  | 2.6                  |
| average of 6 federal countries|        |                      | 0.02149  | 2.4                  |
| NOAA lat.53°-long.9° (Bremen) | (-7.837)| (4.5)               | 0.02165  | 4.65                 |
| UK (for comparison)           | 2.713  | 11.7                 | 0.01687  | 5.25                 |
| England                       | 2.804  | 11.9                 | 0.01877  | 4.99                 |
| Scotland                      | 2.235  | 15                   | 0.01434  | 5.53                 |
Overall, the values of the CO2 sensitivity (B) for the various regions in Germany are quite close to one another, so that no significant regional differences can be identified. In terms of statistical uncertainties, there is also no difference between summer and winter. It is noteworthy that the uncertainties are relatively large for the half-years, while they are very small for the full year. The very good linearity for the federal states of Lower Saxony and North Rhine-Westphalia is remarkable.

The almost identical temperature behavior in the different regions of Germany is by no means trivial. The weather in the north (Schleswig-Holstein/partly Lower Saxony) is maritime, while in the south (Bavaria) it is much more continental. However, the maritime influence on the CO2 sensitivity in Germany does not seem to be very strong. For comparison, the corresponding data for the UK are given (temperature data taken from MET Office 2020) at the end of Table 6. Obviously, the maritime influence is much stronger in the UK, accordingly the CO2 sensitivity is roughly 20% lower than in Germany. There is also a significant difference between England and Scotland, England being much more in the vicinity of the West European continent.

There is also a comparison with the point data of NOAA (lat.53°, long.9°, roughly corresponding to Bremen/Lower Saxony). The agreement of the CO2 sensitivity is excellent, but the standard error is somewhat larger (4.6%) which is still good. The annual fluctuation (1σ) of the temperature is 0.6 K with the NOAA data, which also in good agreement with the German DWD data (0.63 K, see Table 4).

There are generally large regional differences in precipitation in Germany (much greater than with the mean temperatures): Southern Germany is rainy, while Eastern Germany is relatively dry. There are also clear differences in historical behavior. When calculating historical trends in precipitation, it makes sense to carry out time averages for approx. 3 decades or even more. Fig. 6 shows the development of precipitation in the Germany mean and, for comparison, Schleswig-Holstein as the northernmost federal state, in each case as a 29-year mean.

![Fig.6: Comparison of precipitation data for Germany and Schleswig-Holstein (29-year average)](image)

It can be seen that precipitation in Germany has increased significantly in the last century (almost 10%), although there has been a slight decrease in precipitation since 1995. In Schleswig-Holstein the increase is even stronger, especially in the last 50 years, and there has been no decrease since 1995, but rather roughly constant rainfall. Such a north-south difference is also predicted in studies such as European Commission 2020 for Europe as a whole as a result of climate change, but without the stagnation since 2000 shown in Fig.6.

A more detailed study of the local weather in Germany is beyond the scope of the present article, in particular the consideration of rain and the duration of sunshine. A very interesting aspect of the DWD data (concerning precipitation) is a “GDR effect”, probably caused by environmental effects such as fine dust, in the period between 1960 and 1990, in which precipitation even decreased slightly in contrast to the other German trend.
4 Discussion

4.1 Summary and forecasts for next decades

The results of the present study can be summarized as follows:

- Apart from the “normal” fluctuations in the weather, there is a long-term trend in the rise in global and regional temperatures, which correlates relatively strictly linearly with the increase in CO2 in the atmosphere. The regional increases can be significantly higher than the global values. The “normal” weather fluctuations in temperature seem to remain practically unaffected by the increase in CO2.

- The quotient of the increase of temperature and the increase of CO2 content of the atmosphere is referred to here as CO2 sensitivity. The global value is relatively exactly 0.0105 K / ppm CO2 (mean value GISTEMP and NOAA). 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 this value 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 CO2 is obviously dominant.

- The above-mentioned CO2 sensitivity is calculated “transiently” from measured temperature data. The results in Table 2 are values that are based on 20-year mean values. Furthermore, a temperature database over a period of approx. 60 years is used, with no indications of any major deviations from the linear behavior. A “transient” climate sensitivity (covering an interval of 280 ppm CO2) of 0.0105*280 = 2.94 °C could then be extrapolated from the above global CO2 sensitivity. Here too, the accuracy should be around 10%, if extrapolation errors are ignored. This value is also to be understood in such a way that it contains the influence of all climate-sensitive greenhouse gases, of which CO2 is obviously dominant.

- For forecasts for the next few decades, the author considers it sensible to use the CO2 sensitivity described above, which is empirically very well established. Regional forecasts/extrapolations can also be (approximately) made over a period of a few decades with good accuracy using the local CO2 sensitivities derived as above (Table 2/3/6). In the opinion of the author, this concept of local sensitivity is the main merit of this article.

In 1997, the year of the Kyoto Protocol, the annual increase in CO2 levels was 1.8 ppm CO2. Today it is around 2.4 ppm. This shows, just like the curve in Fig. 1(b), that global CO2 concentrations continue to rise at an accelerated rate, independent of climate conferences. The format of the current climate conferences is therefore practically ineffective for climate protection, at least in the short and medium term. Realistically, therefore, there is little reason for optimism.

Based on the trend in Fig. 1(b), the annual increase in CO2 in 2040, i.e. in 20 years, would be around 2.9 ppm CO2 / year, resulting in around 2.6 ppm on average between 2020 and 2040. If you multiply this by 20 and with the conversion factor of 0.0105 K/ppm, you get a temperature increase of approx. 0.55 K in 20 years. Even if one optimistically assumes that the average annual CO2 increase remains at the current level of 2.4 ppm (which requires considerable effort), one also obtains a temperature increase of approx. 0.5 degrees in 20 years. Therefore, the 1.5 degree increase in global temperature compared to pre-industrial times is practically inevitable in about 20 years if one does not believe in miracles.

Correspondingly, one would predict a temperature increase of approx. 1.1 °C for Germany in 20 years, 1.3 °C for Moscow and even almost 1.5 °C for Alaska. The corresponding regions must adapt to this, as these values are practically inevitable too. If one also assumes a behavior for the increase in the CO2 content as shown in Fig. 1(b) after 2040, the pre-industrial CO2 content would have doubled by around 2070. However, forecasts over a period of 50 years are not reliable. Yet there is no reason for optimism.

4.2 Open Issues

Some open questions remain:

- Both the NOAA and the GISTEMP temperature data sets seem to be of excellent quality. As for both data sets an extremely strict linear correlation with the CO2 content in the atmosphere was shown, a lucky random effect should be ruled out. In the opinion of the author, this is an indication of a
complex law of nature, which is quite surprising in this strictness. The same applies to the German 
(DWD) temperature data and the strict linearity of the local CO2 sensitivity. Maybe here also the 
quality of the data helps and the rather “predictable” continental European weather (not all local data 
show this strictness). However, this behavior is still a miracle. Maybe there are other explanations.

- CO2 is not the only greenhouse gas. It is believed that effectively around 20% of the present 
greenhouse gas emissions is non-CO2. It would be extremely unlikely that all relevant gases rise in 
the same proportional steps. In fact, it seems that CO2 increase is faster in relation to the other gases. 
So, assuming the net effect in temperature rise will be proportional to the increase in the sum of all 
CO2-equivalent greenhouse gases, some deviation from the linear behavior would be expected, in 
fact the increase (as a function of CO2) should be moderately decelerating. However, such an effect 
is not seen. There are at least two possible explanations: The other greenhouse gases are not as 
effective as expected, or this effect is so low that it cannot be detected with the present statistics.

- In the process of global warming, time delayed effects could play some role: For instance, the oceans 
absorb heat and therefore temporarily dampen surface warming. There could also be other feedback-
effects (e.g. cloud formation, release of gases from the ground), maybe even self-accelerating, that 
could influence the speed of warming. As I have analyzed a database for the last 60 years, some time 
delayed effects could show up, but this does not seem to be the case. This is confirmed by the fact 
that the (separate) increase of land and ocean is also strictly linear for both. From this it could be 
concluded that time delayed effects either are already contained in the 20-year-averaging procedure 
or they do not play an important role on this timescale. Maybe there are other explanations, forecasts 
for the future about possible time delayed effects are extremely difficult. On a local scale, such time 
effects can be seen in some regions of the world.

4.3 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 CO2 from the atmosphere as possible, also as soon as possible. An IPCC 
report (IPCC 2018) deals with the conditions under which the 1.5 degree target (as the end of global warming) 
could still be achieved. As the above consideration shows, this seems almost impossible from today’s 
perspective. In the IPCC report four different (“illustrative”) scenarios are developed. The following is 
noticeable in these scenarios:

- All scenarios seem “utopian” for the period of approx. 30 years, also in view of the increasing world 
population and the continued accelerated growth of CO2 in the atmosphere
- All scenarios assume strongly increasing contributions from nuclear energy and “renewable” energies to 
electricity generation, a scenario with 100% “renewables” is not listed
- Three of the four scenarios assume high contributions from CDR (Carbon Dioxide Removal = 
techniques for capturing CO2 and extracting CO2 from the atmosphere, a simple form of “geo-
engineering”)
- The more we want to stick to our habits, the more CDR techniques are required. In this sense, scenario 
P4 is the most “realistic” one. Scenario P4 is also the only one with an “overshoot”, in which 1.5 degrees 
are temporarily exceeded.

In the view of the author, probably the only realistic way to make decisive global progress in climate 
protection is, apart from international CO2 emissions tradings, the CDR technique described above, i.e.: CCS, 
BECCS, reforestations etc.. Details to these techniques, also cost assessments, can be found in articles by 
Herzog H, et al. 2018, EASAC 2019 and Bauer C. et al. 2020. It would be a last resort if the industrialized 
countries extract more CO2 from the atmosphere than they emit themselves. There is a strong narrative in the 
public that we should abandon burning of fossil fuel as soon as possible. In the opinion of the author, this 
view is wrong. There is nothing wrong with operating gas power stations with CCS or having internationally 
certified tender for CO2 compensation (which could be financed e.g. by tax on gasoline). One should remain 
technologically open to find the best solution to flatten the CO2-curve as soon as possible. Due to the 
relationships described above, the effectiveness of climate policy measures can only be seen with a time lag of 
a few years, since a reliable temperature value can only be determined by averaging over about a decade.
Author: Wolf Timm is a retired physicist and previously worked in the field of nuclear technology / neutron physics

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Code availability: only open software was used

Author's Contribution: The manuscript essentially deals with the statistical evaluation of existing weather data, both on a regional and a global scale. These are open data from NASA, NOAA, DWD, MET Office and CRU. 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 concept of the local CO2 sensitivity which is described in detail in the chapters 3.2 and 3.3.

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