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GLOBAL AND HEMISPHERIC TEMPERATURE RISE – PROGNOSES FOR THE NEAR FUTURE

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Abstract

Mean temperature anomalies were described by a regression model. Using the data from 1900 – 2012, a temperature forecast was presented. A forecast of the main influences on the temperature anomalies, the atmospheric CO2 concentration, and the Atlantic Multidecadal Oscillation Index was prepared for the temperature prediction. The known temperature anomalies from 2013 to 2022 allow us to analyze the forecast. Two reasons for the deviation of the forecasted temperatures from the observed ones were established. On the one hand, the newer temperature sets show greater linear trends. On the other hand, the prognosis used for atmospheric CO_2 concentration for longer time intervals is not realistic. The prognosis of the CO_2 concentration was improved. A forecast of the temperature anomalies was calculated, and the achievements of temperature limits of 1.5°C and 2°C, as called by the Climate Conference in Paris in 2015, were determined. The 20-year average of temperature anomalies exceeding the 1.5-degree limit is expected around 2040.

1. Introduction

The global temperature continues to rise. Limiting its growth is one of the most important challenges of the 21st century. At the 2015 climate conference in Paris, one of the climate targets was defined as follows: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [1]. The limits of 1.5°C and 2°C are related to climate tipping elements with their expected tipping points [2,3]. The IPCC has developed scenarios for further development of greenhouse gas emissions and the corresponding atmospheric concentrations. This type of prediction is extremely difficult, as socio-economic developments are predicted over long periods of time, and the limitation of emissions is heavily dependent on political decisions. These have been continuously updated and further developed in subsequent IPCC reports. Another option for predicting temperature trends is the use of statistical methods.

In 2015, the authors published a statistical forecast of temperature trends for the coming decades [4]. In this paper, the forecast for the period after 2011 is discussed, deviations from the observable temperature development from 2012 to 2022 are pointed out, their causes are highlighted, and the limits of the used statistical models are shown. Finally, a new forecast for the time period after 2022 is created using the current temperature records.

2. Data

In the authors' 2015 publication [4], forecasts of global and hemispheric temperature trends were presented. The temperature sets are the global and hemisphere temperature anomalies from GISS[1] [5], the Hadcrut3 temperature[2] anomalies [6], and the NCDC temperatures[3] [7]. This data set is called here the older data set. The data sets of the basic version downloaded at different times are very close, but not identical, because they are continuously updated, homogenised, and more advanced methods are applied. The data sets were used to evaluate and visualise the forecast results for the period after 2011. For the period after 2011, more recent data sets of the temperature anomalies were used, as the older ones were replaced by new ones. HadCRUT3[4] was replaced by HadCRUT4 and later by HadCRUT5 [8], version 3 of the GISS dataset was replaced by version 4[5] [9], and the NCDC temperature dataset was replaced by version 5.1[6] [10]. The last sets are called the current temperature anomaly sets. All calculated temperature anomalies here are related to the mean temperatures observed during the preindustrial time interval from 1850 to 1900 based on the data set available for HadCRUT3 and HadCRUT5.

It is well known that the long-term global temperature driver is mainly the concentration of carbon dioxide (CO_2) in the atmosphere. In the present paper, we use the Hansen CO_2 data compilation[7,8] [11]. The data cover the period 1850-2006. The series has been extended to 2011 by adding the annual CO_2 concentration obtained by regressing the Hansen data against CO_2 measurements from the Mauna Loa observatory[9]. A quasi-decadal oscillation of about 70 years is described by the Atlantic Multidecadal Oscillation [12], a dominant mode of decadal climate variability [13], also called Atlantic Multidecadal Variation. We have used the simple (unsmoothed) AO index (AOI)[10], calculated by linearly detrended Sea Surface Temperature (SST) anomalies in the North Atlantic (0º-70ºN) based on the Kaplan SST V2[11] gridded global SST anomalies [14]. The Pacific Decadal Oscillation (PDO) was characterised by the updated standardised values of the PDO index[12] [15]. As in [4], El Niño events were described by the standardised version [16] of the Southern Oscillation index (SOI)[13]. The solar activity was characterised by the total solar irradiance (TSI)[14] reconstruction from Wang et al., [17], see also Kopp and Lean (2011) [18], and for the stratospheric aerosol loading from volcanic eruptions, the 2012 update of the Atmospheric Optical Depth

(AOD)[15] at 550 nm from Sato (1993) [19] was used. For more details about the indexes used, see the descriptions in [4].

3. Regression model

Temperature anomalies are statistically modelled using linear regressions, which are detailed in [4] and are, therefore, only briefly described here. The annual global and hemisphere temperature anomalies are estimated by additive linear regression models without interaction terms:

(1) $$\hat{T} = const. + \beta_1 * ln(CO_2/280\ ppmv) + \beta_2 * AOI + \beta_3 * PDO + + \beta_4 * TSI + + \beta_5 * SOI + \beta_6 * AOD + \varepsilon ,$$

where $\hat{T}$ are the estimations of the corresponding observed temperature anomalies. An autoregressive model of first-order AR(1) is applied for the residuals ε (e.g., Torrence and Combo, 1998, [20])

(2) $$\varepsilon_t = \varphi \varepsilon_{t-1} + u_t , \quad where \quad t = 1, \dots T ,$$

and φ represents the auto-regression coefficient estimated by the auto-correlation coefficient at lag 1, and it is assumed that u_t is normally distributed. (We must note that the t-test is valid only if the residuals are normally distributed.) The standard deviation of the modelled from the observed temperature anomalies was estimated by the effective value of the standard variance [21]:

(3) $$\hat{\sigma}_{eff} = \sigma \sqrt{\frac{1+\varphi}{1-\varphi}} = \sigma * f_{ampl.}$$

The quantity f_{ampl}. is referred to as the amplification factor [22]. Importantly, to avoid collinearity, as in [4], we do not include greenhouse gases other than CO_2 in the regression. Instead of CO_2 as the impact factor, the logarithm of CO_2 relative to its pre-industrial level of 280 ppmv was used [23]. CO_2 stands here for the effective impact of greenhouse gases on temperature anomalies. In contrast to [4], the temperature datasets HadCRUT, GISS, and NCDC are not analyzed separately, but only together as their mean values from 1880 onwards. Starting from the full model, the regression was performed stepwise backward, excluding the least significant model term in each step. The procedure was repeated until a model with only significant terms remained. To calculate the prognosis and determine the confidence interval, we computed the adjusted temperature anomalies related to CO_2 and AO variations:

(4) $$\hat{T}_{ad} = const. + \beta_1 * ln(CO_2/280\ ppmv) + \beta_2 * AOI$$

using the regression coefficients of the found significant model.

4. Regression results

The problem of collinearity was discussed in detail by the authors in [4]. Here, we limit ourselves to explaining the multiple regression results. The modelling approach to determine the main influences on hemispheric and global temperature anomalies is based on adequate models. By the stepwise regression, we found that only the CO_2 term and the terms describing the impact of the Atlantic multidecadal oscillation and the Southern oscillation term are statistically significant. The regression results obtained by the older data set are described in detail in [4]. The influence of Atlantic oscillation on the observed anomalies decreases about fourfold from north to south. In contrast, the influence of the Southern Oscillation is strongest in the South. With this simple linear statistical model, the temperature anomalies were explained down to about 12% compared to pre-industrial times. Thus, the explained variance in the Northern hemisphere

Table 1. Summary of the results of statistical modelling of hemispheric and global temperature anomalies. βi are the regression coefficients of the regressors written in the first row. Their statistical one-sigma errors are inserted below them. R^2 is the coefficient of determination, φ is the coefficient of autocorrelation, and ss2 is the squared sum of deviations of the observed and modelled temperature anomalies.

Current data set (HadCRUT5, GISS v4, NDCD v5.1), time interval 1900 - 2011						
	R^2	φ	ss^2	β_1	β_2	β_3
Northern hem.	***0.922***	***0.530***	***0.00370***	***3.510*** *0.120*	***0.725*** *0.050*	***-0.0217*** *0.0081*
global	***0.930***	***0.446***	***0.00254***	***3.337*** *0.099*	***0.421*** *0.041*	***-0.0315*** *0.0067*
Southern hem.	***0.874***	***0.521***	***0.00603***	***3.218*** *0.120*	***n.s.***	***-0.427*** *0.083*

is about 0.92, and in the Southern hemisphere is about 0.88. The time developments of the temperature anomalies of the averaged three data sets considered here are illustrated in the upper part of Fig. 1 as thick lines. The regression results for the same time period but with the current data set are summarized in Table 1. The regression coefficients for the CO_2 influence on the global temperature anomalies based on the current data set are about 3.34, and they are somewhat greater than for the older data set, where the obtained coefficient was 2.80. The regression coefficients for AOI and SOI don’t differ significantly. But for the Southern hemisphere, the AOI impact is not significant.

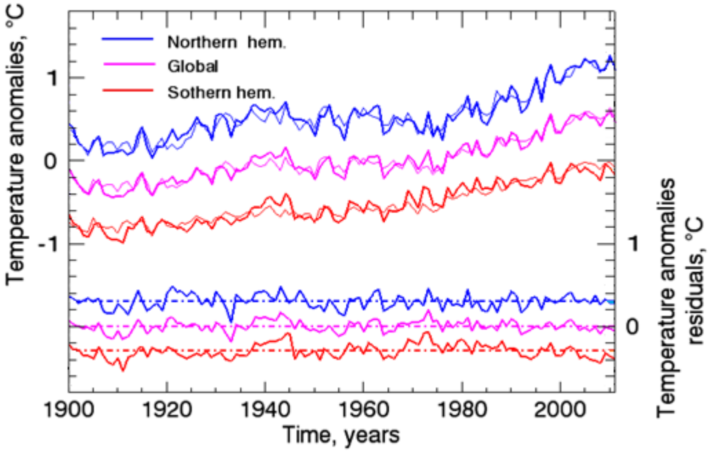

Fig. 1. Temperature anomalies developments in the Northern hemisphere (thick blue line, shifted by 0.5°C), the Southern hemisphere (thick red lines, shifted by -0.5°C), and the global development (magenta thick lines) are shown in the upper part of the graphic. Temperatures calculated by linear regression models for the older data set are shown by thin lines. The lower part represents the residuals (thick lines), and their corresponding null lines are shown as dashed dot lines.

The results of the same regression provided for the new data set but for the whole interval from 1900 to 2022 are close to those in Table 1 and, therefore, are not presented here. It is evident that the model describes the temperature anomalies very well. Using the current data set, the explained variations are greater than for the older data, especially for the regression provided over the whole-time interval, where the explained variations for regression for the Northern hemisphere and for the global data are better than 95%. Probably, after additional homogenization and including or excluding stations, the newer data will give better results.

5. Method to forecast the temperature development

5.1. Regressors with long-term variability used for the predictions

Predicting the development of the climate worldwide and on a regional scale is extremely important in order to take timely measures to limit negative impacts on human civilization. The prerequisite for a valid prediction of temperature development on the basis of regressions is the stable temporal development of the regressors. This applies to the temperature development only for continuing the Atlantic Oscillation and conditionally for an increase in the atmospheric CO_2 concentration, as explained in more detail below. The variations in solar irradiance caused by the 11-year cycle influence the temperature only to a small extent and are not significant at the level of $\alpha = 0.05$, taking into account the residual autocorrelation. Some factors, such as the SOI, describe only short-term temperature variations (shorter than decades); other influences are not significant in the context of the model used here. The AOD is mainly determined by strong, sudden volcanic eruptions leading to short-term cooling of the temperature near the Earth's surface and is not predictable. Other factors, such as the PDO, directly affect the temperatures only regionally, and their temperature influence is not significant within the framework of the model used here. During the 30 years from 1982 to 2011, the CO_2 concentration in the atmosphere grew almost linearly. It was assumed that this growth would continue in the near future after 2011. In order to determine the AOI period precisely to one year, the AOI time series was described based on the model of a simple harmonic oscillator with an absolute term. This corresponds to the procedure for determining a Lomb periodogram, but here, with equidistant time points. The spectrum can be determined for T starting with T_{start}, and then, at every step, the period is increased by one year. The periods are not limited to the corresponding Fourier frequencies. For the AOI, we found a period of 64 years, where the amplitude of the oscillations is 0.208. For the time interval from 1900 to 2022, a period of 66 years was found with approximately the same amplitude.

5.2. Determination of the confidence interval for the predicted adjusted temperature anomalies

The predictions for CO_2 and AOI allow the forecast of the adjusted temperature anomalies (see equ. 4). The predicted value T_{ad}^0 of the vector x^0 and its confidence intervals were calculated by

$$(5) \qquad T_{ad}^0 = \hat{T}_{ad}^0 \pm t_{n-k-1,1-\alpha} * s * f_{ampl.} \sqrt{1 + {x^0}^T (X^T X)^{-1} x^0} \, ,$$

where the matrix $X = (1, x_1, x_2, \ldots . x_k)^T$ is composed of the vectors x_i [24]. (In our case, k=2, and for mean-adjusted vectors, the first column consisting of units is omitted.) $t_{n-k-1,1-\alpha}$ is the value for the student's distribution with the degree of freedom *n-k-1* at the significance level α. (X^T is the transposed matrix X, and the exponent -1 stands for the matrix inversion.) x^0 is the matrix of vectors of the data values of CO_2 and AOI. The standard deviation s^2 was estimated by $\sum_1^n \left(T_i - T_{ad_i}\right)^2 / (n - k - 1)$, where *n* is the data points of T_i and *k* is the number of coefficients of the model to determine T_{ad}. To compute the confidence band in the forecast interval, the values of the vector components x_i for the time in the forecast interval are used. These vectors are also used to determine the prognosis temperature values by equation (4).

5.3. Analysis of the forecast results for the period 1900 – 2011

The forecasts were calculated to 2060 based on the older data sets. For the Southern hemisphere, the observed anomalies lie within the obtained confidence band; however, for the Northern hemisphere, observations (from 2012 to 2022) exceed the upper limit of the confidence band by about 0.3°C (in 2020). One reason for the difference is that, evidently, the current temperature sets differ from the older ones. The current temperature series show larger linear trends. For the current data set, the impact of AOI temperature on the Southern hemisphere is not significant. This leads to a higher quadratic deviation between the observed and modelled values and, thus, to a slightly wider confidence interval. The predicted temperatures in the Northern hemisphere now exceed the confidence limit only by 0.2°C (in 2020). A second reason for the observed higher temperatures is the underestimation of the CO_2 growth during the forecast period. As a result, the temperature growth was estimated to be lower by about 0.08°C in 2022. The linear development of the CO_2 concentration in the atmosphere, which implies a constant CO2 emission rate, is a scenario that is not real in the near future.

5.4. Improvement of the CO_2 prognosis and new AOI prognosis

As it became clear from the above results, our CO_2 prognosis, using a linear continuation of the CO_2 concentration in the atmosphere, needs improvement. The starting point is the well-known fact that atmospheric CO_2 grows by a value *p* of about 0.5% related to the prior year. Thus, the CO_2 increases exponentially related to the starting value $CO_2(t_0)$:

(6) $$CO_2(t_i) = CO_2(t_j) * (1 + \frac{p}{100\%})^n \text{ , } j < i,$$

where n is the number of years between t_i and t_j, related to the starting value of $CO_2(t_0)$. During the period from 1940 to 1960, this relationship was disturbed. We have, therefore, limited ourselves to using the interval from 1960 to 2022 for the approximation of atmospheric CO_2. By logarithmizing equ. (6) we obtain a linear relation between $\ln[CO_2(t_i)/CO_2(t_j)]$ and the year number n, allowing the determination of the regression constants. The resulting approximation in the interval from 1960 to 2011 is excellent, and the deviations of the observed CO_2 values from the extrapolated ones in the forecast interval 2012 – 2022 are only about 2 ppmv. To do a new temperature forecast, it is necessary to forecast the AOI with the full data from 1900 to 2022. We have done this using the regression based on a harmonic oscillator as before for the interval 1900 – 2011. The new period is 66 years with almost the same amplitudes as before. This proves once again the relative stability of the Atlantic Oscillation.

6. Temperature anomalies prediction based on the data from 1900 to 1922

With the new, improved CO_2 prognosis and the AOI approximation extrapolated in the interval from 2023 to 2060, we have determined the current prediction of the temperature anomalies from 2023 to the near future (see Fig. 2a).

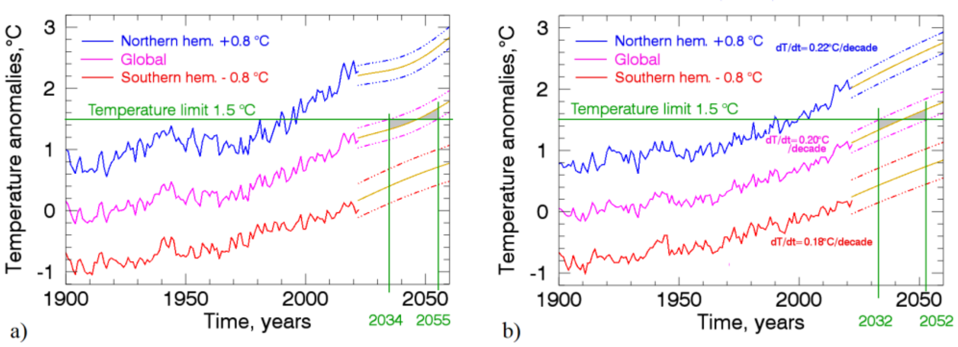

Fig. 2a) The climate forecast is based on the newer data sets with improved atmospheric CO_2 concentration forecast (see text) and the new AOI forecast with a period of T=66 years. b) the same as a) but with subtracted AOI influence.

This new prediction exceeds the upper confidence limit only by about 0.1°C. For the Southern hemisphere and the global temperature prediction, they are in the confidence band. In Fig. 2b, the same as in Fig. 2a, the AOI influences were subtracted from the temperature anomalies, so only the anomalies caused by human activities since the preindustrial period are presented. The global temperature anomalies limit of 1.5°C is drawn by horizontal green lines in Fig. 2a and 2b. The two vertical green lines in both panels of Fig. 2 mark an approximately twenty-year interval in which a mean temperature anomaly of about 1.5°C is to be expected. In both panels of Fig.2, the marked grey areas of the two triangles on both sides of the interval midpoint have to be approximately equal areas. Individual temperature values can already exceed the limit beforehand. The temperature average over 20 years is expected to exceed the 1.5°C limit between 2032 and 2055. The warming rates caused by human activity are 0.22°C/decade, 0.20°C/decade and 0.18°C/decade for the Northern hemisphere, the global anomalies, and the Southern hemisphere, respectively, for the interval approximately from 2000 to 2040 and would increase by about 0.04°C/decade in the next 40 years if the temperature development continues as it does now. Under the assumption of business as usual and no actions are being taken to limit atmospheric CO_2, the 2°C limit will be achieved around 2060.

Summary and Discussion

It was shown that a significant impact on the temperature anomalies has only the atmospheric CO_2 concentration, the AOI, and the SOI. However, only the CO_2 concentration and AOI have predictable long-term variations. Future temperature anomalies were estimated based on the regression model and the prognosis of the development of the CO_2 concentration and the AOI in the near future. The analysis of the obtained regression results shows that differences between performed forecasts are caused partially by differences in older and current temperature data sets and by the used method to forecast the atmospheric CO_2 concentration, which was based on the assumption of a linear growth of the CO_2 concentration. This method was replaced using the well-known fact of the exponential growth rate of the atmospheric CO_2 concentration. The CO_2 data extrapolated for the time interval 2012–2022 show deviations of only 2ppmv from the observations. It was established that the AOI oscillations were very stable over the investigated time interval. Therefore, the prognosis of the atmospheric CO_2 concentration and of the AOI oscillations allow the forecast of the temperature anomalies in the near future. It was found out that the called by Paris climate conference in 2015 temperature anomalies limit of 1.5°C will be exceeded between the mid-thirties and the fifties of our century. Because we are very close to this limit, it seems very unlikely that this limit can be maintained. Under the assumption that no actions are being taken to limit atmospheric CO_2, it is expected that the 20-year average of temperature anomalies will reach the 2°C limit around the 60s of the 21st century.

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ГЛОБАЛНО И ХЕМИСФЕРНОТО ПОВИШАВАНЕ НА ТЕМПЕРАТУРАТА – ПРОГНОЗИ ЗА БЛИЗКО БЪДЕЩЕ

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Резюме

Средните температурни аномалии са описани чрез регресионен модел. На базата на данните от 1900 – 2012 г. е представена температурна прогноза. За прогнозирането на температурата беше изготвена прогноза за основните влияния върху температурните аномалии: концентрацията на CO_2 в атмосферата и индекса на атлантическата мултидекадална осцилация.

Известните температурни аномалии от 2013 г. до 2022 г. позволяват да се анализира прогнозата. Установени са две причини за отклонението на прогнозните температури от наблюдаваните. От една страна, по-новите температурни набори показват по-големи линейни тенденции, а от друга, използваната прогноза за концентрацията на CO_2 в атмосферата за по-дълги интервали от време не е реалистична. Прогнозата за концентрацията на CO_2 е подобрена. Изчислена е прогноза за температурните аномалии и е определено времето на достигане на температурните граници от 1.5°C и 2°C, за които призова конференцията за климата в Париж през 2015 г. Очаква се стойността на температурните аномалии, осреднени за двадесет години, да надхвърли границата от 1.5 °C около 2040 г.