Can climate models explain the recent stagnation in global warming?

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In recent years, the increase in near-surface global annual mean temperatures has emerged as considerably smaller than many had expected. We investigate whether this can be explained by contemporary climate change scenarios. In contrast to earlier analyses for a ten-year period that indicated consistency between models and observations at the 5% confidence level, we find that the continued warming stagnation over fifteen years, from 1998 -2012, is no longer consistent with model projections even at the 2% confidence level. Of the possible causes of the inconsistency, the underestimation of internal natural climate variability on decadal time scales is a plausible candidate, but the influence of unaccounted external forcing factors or an overestimation of the model sensitivity to elevated greenhouse gas concentrations cannot be ruled out. The first cause would have little impact of the expectations of longer term anthropogenic climate change, but the second and particularly the third would.

Estimates of the observed global warming for the recent 15-year period 1998-2012 vary between 0.0037 ^{0}C/year (NCDC)[(1)] , 0.0041^{0}C/year (HadCRUT4)[(2)] and 0.008^{0}C/year (GISS)[(3)] . These values are significantly lower than the average warming of 0.02^{0}C/year observed in the previous thirty years 1970-2000[(4)]. Can models explain the global warming stagnation?

We compare the recent global warming trend with an ensemble of global warming trends computed by 23 different models in the Climate Model Intercomparison Projects CMIP3[(5)] and CMIP5[(6)] (Supplementary Table S1). The simulations were carried out for two scenarios A1B (CMIP3) and RCP4.5 (CMIP5) that lie close to the recent emission history, with linear increases of the emissions beyond 2012 to the year 2060 (Figure 1).

A comparison of the ensemble of model-simulated trends for different segment lengths with the middle global warming estimate (0.0041^{0}C/year, HadCRUT4) is shown in Figure 2 (a more detailed statistical summary, including the two other estimates of the recent trend, is presented in Supplementary Table S2). For 10-year trend segments, 6% (CMIP3) or 8% (CMIP5) of the simulated trends are smaller than or equal to the observed trend over the period 1998-2012 - in agreement with a previous positive consistency test for the period 1998-2009[7]. However, for the 15-year trend interval corresponding to the latest observation period 1998-2012 , only 2% of the 62 CMIP5 and less than 1% of the 189 CMIP3 trend computations are as low as or lower than the observed trend. Applying the standard 5% statistical critical value[8], we conclude that the model projections are inconsistent with the recent observed global warming over the period 1998- 2012. (note, however, that the standard statistical-test terminology, although widely used, is not strictly appropriate in this case; see supplementary material [9]). The inconsistency increases rapidly with increasing trend length. A continuation of the current observed global warming rate for a period of twenty years or longer would lie outside the ensemble of all model-simulated trends.

What do these inconsistencies imply for the utility of climate projections of anthropogenic climate change? Three possible explanations of the inconsistencies can be suggested: 1) the models underestimate the internal natural climate variability; 2) the climate models fail to include important external forcing processes in addition to anthropogenic forcing, or 3) the climate model sensitivities to external anthropogenic forcing is too high,.

The first explanation is simple and plausible. Natural climate variability is an inevitable consequence of a slow system (climate) interacting with a fast system (weather) [10]. The forcing of the slow system by the (white noise) low-frequency components of the fast system produces a "Brownian motion" of the slow system, represented by a red variance spectrum - in qualitative agreement with observations. However, the details of the response depend strongly on the internal dynamics of the slow system in the time scale range of interest - in the present case, on decadal time scales. It is long known, from successive reports of the Intergovernmental Panel on Climate Change[4], that contemporary global climate models have only limited success in simulating many such processes, ranging from the variability of the ocean circulation, ENSO events, various coupled ocean-atmosphere oscillation regimes, to changes in sea ice, land surface, atmospheric chemistry and the biosphere. The inability to simulate the statistical internal climate variability may have been artificially compensated in the past by tuning the models to prescribed external forcings, such as volcanic eruptions and tropospheric aerosols. This would explain why simulations with historical forcing by different GCMs tend to be very similar and follow closely the observed record. This artificial "inflation"[11] of forced variability at the expense of unpredictable natural variability works, however, only in the period of tuning, and no longer in the post-tuning phase since about 2000. The net effect of such a procedure is an underestimation of natural variability and an overestimation of the response to forced variability. .

Nevertheless, the second explanation cannot be ruled out: in the spirit of traditional model tuning, the recent stagnation in global warming could be assigned to an external forcing that is not included, or not included satisfactorily, in contemporary models. Volcanic eruptions and variations in solar insolation are frequently proposed candidates. However, while both explanations have supporters, a significant increase in recent volcanic activity has not been recorded, while variations in solar insolation or activity still require rather speculative amplification mechanisms that could contribute to the observed recent decrease in global warming[(12,13)].

Finally, the model overestimation of the global warming in the period 1998-2012 could be partially corrected by a reduction in the assumed model sensitivity to radiative forcing. In principle, climate model sensitivities are calibrated by fitting the climate response to the known seasonal and latitudinal variations in solar forcing, as well as by the observed climate change to increased anthropogenic forcing over a longer period, mostly during the 20th century. It would be difficult to modify the model calibration significantly to reproduce the recent global warming slow down while still satisfying these other major constraints. While adjusting the effect of aerosols may help to reconcile differences between observed and simulated long term trends[14], and a recent study[(15)] argues that the true sensitivity may indeed lie at the lower range of the of the contemporary climate models, a recalibration reproducing the reduced warming of the last 15 years appears hardly feasible. Whether or not a later calibration of the CMIP5-models was undertaken is not known, but the CMIP3 models were run before the recent stagnation emerged.

We do not wish to suggest which of the three possible explanations is the most probable, leaving this for others to decide. Quite possibly, all three factors contribute to some extent. But we hope that the need to understand the origin of the recent stagnation in global warming will accelerate efforts to achieve a more reliable simulation of climate variability on decadal time scales, and the ability to disentangle the relative contributions of forced (deterministic) and internal (stochastic) variability.

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Figure 1: Anthropogenic carbon emissions according to the SRES scenario A1B (red) and RCP4.5 (blue) compared to estimated anthropogenic emissions (Martin Heimann, pers. comm.).

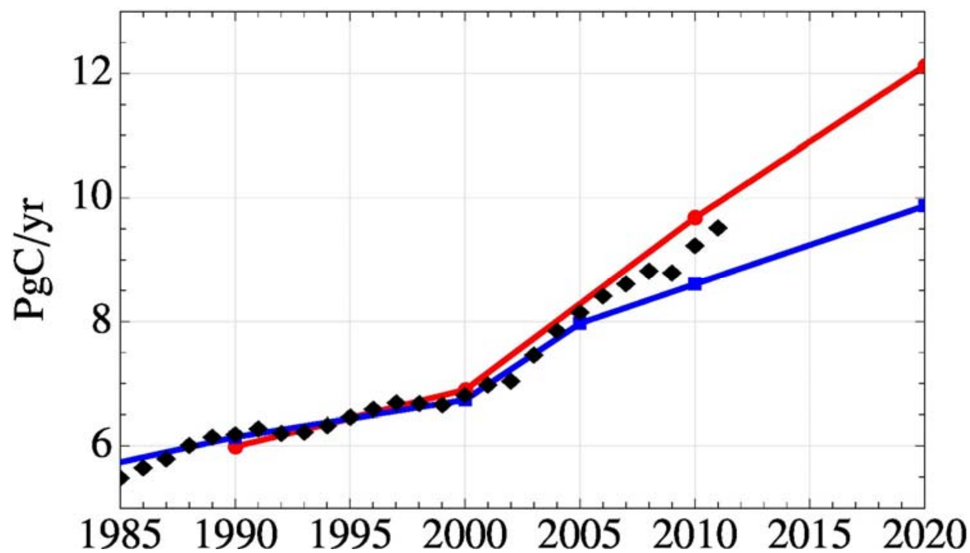
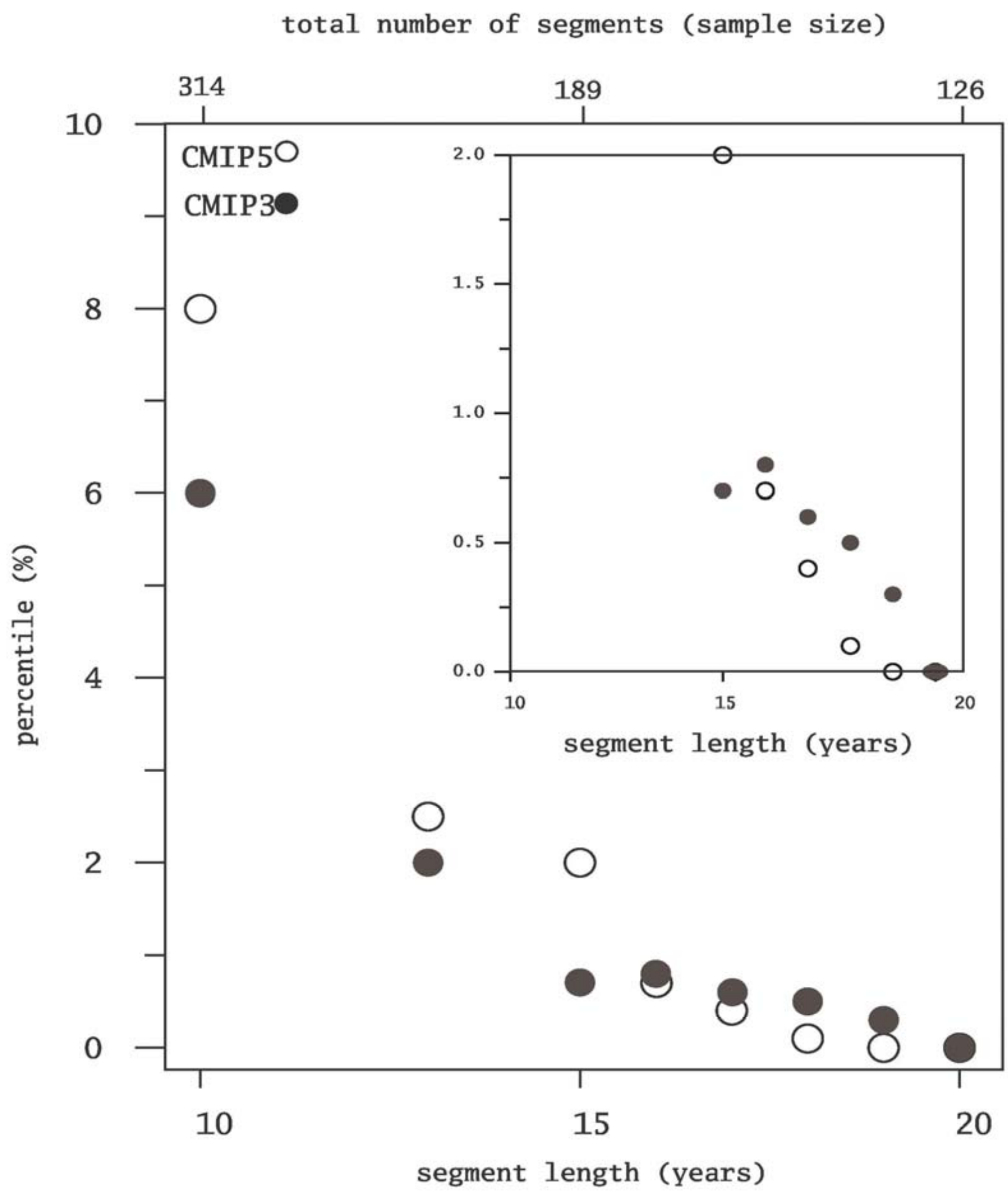


Figure 2. Consistency between the recent trend of the global mean annual temperature and simulations with climate models: the figure shows the proportion of simulated trends that are smaller or equal to the observed global annual trend in the period 1998-2012 in the HadCRUT4 data set, $R_{hadcrut15}$.= 0.0041 °C/year. The ensemble of simulated trends has been calculated from non-overlapping periods of length *n* in the period 2001-2060. The climate models were driven by the emission scenarios RCP4.5 (CMIP5) and A1B (CMIP3). The inset shows an expanded view of the range 0% to 2% .



Supplementary Information

	CMIP3	Number of simulations	CMIP5	Number of simulations
1	BCCR-BCM2-0	1	ACCESS1-0	1
2	CCCMA-CGCM3-1	5	ACCESS1-3	1
3	CCCMA-CGCM3-1-t63	1	BCC-CSM1-1-m	1
4	CNRM-CM3	1	BCC-CSM1-1	1
5	CSIRO-MK3-0	1	CCSM4	5
6	CSIRO-MK3-5	1	CESM1-CAM5	3
7	GFDL-CM2-0	1	CESM1-WACCM	1
8	GFDL-CM2-1	2	CMCC-CM	1
9	GISS-AOM	3	CMCC-CMS	1
10	GISS-MODEL-E-H	5	CSIRO-MK3-6-0	9
11	GISS-MODEL-E-R	1	GFDL-CM3	1
12	INGV-ECHAM4	1	GFDL-ESM2M	1
13	INMCM3-0	1	GISS-E2-H-CC	1
14	ISPL-CM4	1	GISS-E2-H	5
15	MIROC3-2-HIRES	1	GISS-E2-R	15
16	MIROC3-2-MEDRES	3	INMCM4	1
17	MIUB-ECHO-G	3	IPSL-CM5A-LR	4
18	MPI-ECHAM5	4	MIROC5	3
19	MRI-CGCM2-3-2A	5	MPI-ESM-MR	1
20	NCAR-CCSM3-0	7	NORESM1-M	1
21	NCAR-PCM1	4	HAHGEM2-CC	1
22	UKMO-HADCM3	1	HADGEM2-ES	4
23	UKMO-HADGEM1	1	HADGEM2-AO	1

Table S1: List of models, and number of simulations with each model, in the CMIP3 and CMIP5 ensembles used in this analysis

A Segment length (years)	B Number of non-overlapping segments		C 50% quantile (°C/year)		D 5% quantile (°C/year)		E quantile of R= 0.0041 °C/year (%)		F quantile of R= 0.0082 °C/year (%)		G quantile of R= 0.0037 °C/year (%)	
	CMIP 5	3	CMIP 5	3	CMIP 5	3	CMIP 5	3	CMIP 5	3	CMIP 5	3
10	314	314	0.20	0.26	0.0	0.0	8.0	6.0	16.0	9.0	6.7	5.3
13	251	216	0.22	0.24	0.07	0.08	2.5	2.0	6.4	4.5	2.1	1.7
15	189	162	0.21	0.26	**0.08**	**0.1**	**2**	0.7	4.7	3.0	0.5	0.6
16	189	162	0.20	0.25	0.1	0.1	0.7	0.8	5.2	2.0	0.4	0.8
17	189	162	0.21	0.25	0.1	0.1	0.4	0.6	0.8	1.8	0.3	0.4
18	189	162	0.22	0.25	0.1	0.1	0.1	0.5	3.0	1.9	0.0	0.6
19	126	162	0.22	0.25	0.1	0.1	0.0	0.3	0.3	1.2	0.0	0.1
20	126	162	0.21	0.25	0.1	0.2	0.0	0.0	0.3	0.9	0.0	0.0
25	126	108	0.22	0.24	0.1	0.2	0.0	0.0	0.3	0.9	0.0	0.0
30	63	108	0.21	0.25	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Table S2. A measure of consistency between the observed trend in the global mean annual temperature, should it continue for a total of n years (column A), and the trends simulated by the CMIP3 and CMIP5 climate model ensemble in the 21st century up to year 2060; column B indicates the number of non-overlapping trends; column C and D, the estimated 50% and 5%iles of the ensemble of simulated trends (the shaded cells indicate the 5%-til for 15 year segments; column E, the quantiles corresponding to the observed trend in 1998-2012 in the HadCRUT4 temperature data (R_{had15} =0.0041 **°C**/year). The grey-shaded cells highlight the data displayed in Fig1 in the main text; column F and G, as column E but for the values of the trends estimated from the GISSTEMP (Hansen et al., 2010) and NCDCD (Smith et al., 2008) data sets, respectively. The analysis have been conducted with the routines *quantile* and *ecdf* from the statistical software package R

Supplementary text

The standard concept of a statistical test is not really applicable in this context because some basic assumptions are not satisfied (von Storch and Zwiers, 2013).

First, the set of all A1B or RCP4.5 scenarios cannot be defined, as it cannot be decided which simulation would represent a valid scenario and which would not. Thus, a random variable "A1B scenario" or "RCP.4-5 scenario" cannot be defined, and conclusions on "A1B scenarios" or "RCP-scenarios" in general cannot be drawn. Thus, all statistical inference relates only to the finite sample, which is used to carry out the test, leaving some uncertainty.

Second, the hypothesis to be tested, namely that the observed trend is not drawn from the ensemble of scenario-trends, has been built with the data, which are used to test the null hypothesis, so that the fundamental sampling assumption needed to apply such tests is violated.

We must concede that violating such assumptions is common in climate science, but the problem should at least be stated.

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