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Making sense of the early-2000s global warming slowdown

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It has been claimed that the early-2000s slowdown or hiatus, characterized by a reduced rate of global surface warming, has been overstated, lacks sound scientific basis, or is unsupported by observations. The evidence presented here contradicts these claims.

A large body of scientific evidence – amassed before and since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5)[1] – indicates that the so-called surface warming "slowdown", also sometimes referred to in the literature as the "hiatus", was due to the combined effects of internal decadal variability and natural forcing (volcanic and solar) superimposed on human-caused warming[2]. Given the intense political and public scrutiny that global climate change now receives, it has been imperative for scientists to provide a timely explanation of the warming slowdown, and to place it in the context of ongoing anthropogenic warming. Despite recently voiced concerns we believe this has largely been accomplished.

Figure 1 shows annual average anomalies of global mean surface temperature (GMST) in three updated observational datasets[3-5], and averaged over 124 simulations from 41 climate models. The observed rate of global surface warming since the turn of this century has been considerably less than the average simulated rate[6]. This mismatch helped to initiate discussion of a warming slowdown in observations. We note that in the multi-model mean, averaging across models damps internal variability, thus providing a less-noisy estimate of the underlying climate response to combined natural (volcanic and solar) and anthropogenic forcing.

Serious scientific interest in the slowdown began around 2009 (e.g., Ref. 7) when decadal GMST variability was found to be a relatively common feature in 20th Century observations and climate model simulations. Initial attention was focused on the role of internal variability; this work built on an extensive body of research into the nature and causes of internal decadal climate variability – research that had been actively pursued since the 1990s. Subsequent slowdown studies examined contributions from external forcing and observational uncertainty, as we discuss below. This important historical perspective is missing in recent critiques of research into the slowdown (e.g., Refs 4, 8 and 9).

How unusual a period of slowing is depends strongly on its length[10]. Rates of warming remained slow into the early 2010s, but a warming in 2014 and the record warmth of 2015 illustrate the sensitivity of warming estimates to choice of trend length, starting point, and end point. To illustrate such issues, and to place the slowdown in the context of longer-term trends and variability, we compute overlapping trends using 15-year, 30-year and 50-year windows starting in 1900.

Using overlapping windows to characterize the slowdown is preferable to the practise of defining the slowdown based on arbitrary start and end dates (e.g., Refs 4and 9). Figures 2a-c compare observed overlapping trends against a measure of model uncertainty in simulated overlapping 15-year trends. In all three datasets the most recent 15-year trend (ending in 2014) is lower than both the latest 30-year and 50-year trends. This divergence occurs at a time of rapid increase in greenhouse gases (GHGs)[1]. A warming slowdown is thus clear in observations; it is also clear that it has been a "slowdown" not a "stop". The slowdown was more pronounced in earlier observational datasets, and in studies based on them. Note also that the most recent observed 15-year trend is lower than the majority of simulated trends; common peaks in the modelled and observed overlapping trends around 2000 reflect similar recovery from the Pinatubo eruption in 1991.

Scientific advances

The initial focus of post-AR5 slowdown research was on explaining why observed and modelled temperature changes differ in the early 21st Century[6]. One of the many valuable ancillary benefits of this scientific activity has been improved understanding of the role of ocean decadal variability in modulating human-caused global surface warming. For example, new research has shown that decadal timescale cooling of tropical Pacific sea surface temperature (SST) – which is linked to trade wind intensification associated with the negative phase of the Interdecadal Pacific Oscillation (IPO) – made a substantial contribution to the warming slowdown[11-14] (Fig. 2e). Since averaging over a large number of climate model simulations reduces the random noise of internal variability, and assuming a large contribution from internal variability in the slowdown, the mean of the multi-model ensemble (MME) could not be expected to reproduce the slowdown.

A different perspective on the role of internal variability is obtained through the analysis of the individual models and realizations comprising the MME. In ten out of 262 ensemble members, the simulations and observations had the same negative phase of the IPO during the slowdown period – i.e., there was a fortuitous “lining up” of internal decadal variability in the observed climate system and the ten simulations[15,16]. These ten ensemble members captured the muted early 21st century warming, thus illustrating the role of internal variability in the slowdown.

Related work has identified additional contributions to the slowdown from decadal variability arising in the Indian[17] and Atlantic Oceans[18]. However, the flows of heat in these and other ocean basins (including the tropical Pacific) remain poorly constrained by measurements. Other positive outcomes of this slowdown research include better understanding of the influence of uncertainty in ocean SSTs on decadal timescale GMST trends[4], and of the role of decadal changes in volcanic forcing in partially offsetting human-caused warming[19]. Research has also identified a systematic mismatch during the slowdown between observed volcanic forcing and that used in climate models[19].

It has been suggested[20] that the lack of Arctic surface measurements has resulted in an underestimate of the true rate of GMST increase in the early 21st Century. Independent satellite-based observations[21,22] of the temperature of the lower troposphere (TLT; Fig. 2f) have near-global, time-invariant coverage. Although satellite TLT datasets also have important uncertainties[21], they corroborate the slowdown of GMST increase[23] and provide independent evidence that the slowdown is a real phenomenon.

These examples have built upon earlier advances in our scientific understanding of the causes of fluctuations in GMST. For example, the cooling after the Pinatubo eruption in 1991 was predicted before it could be observed. The ability of climate models to simulate this cooling signal was reported in published papers and IPCC assessments. Previous work noted the importance of the “spring-back” from Pinatubo, which contributed to relatively rapid rates of global warming over the decade of the 1990s (e.g., Ref. 23); a similar “spring-back” occurred in the 1980s after El Chichón.

Understanding of the recent slowdown also built upon prior research into the causes of the so-called “big hiatus” from the 1950s to the 1970s. During this period, increased cooling from anthropogenic sulphate aerosols roughly offset the warming from increasing GHGs (which were markedly lower than today). This offsetting contributed to approximately constant GMST. Ice core sulphate data from Greenland support this interpretation of GMST behaviour in the 1950s to 1970s, and provide compelling evidence of large temporal increases in atmospheric loadings of anthropogenic sulphate aerosols. The IPO was another contributory factor to the big hiatus[13].

Research motivated by the warming slowdown has also led to a fuller understanding of ocean heat uptake[17,24] in the context of decadal timescale variability in GMST. Improved understanding was only possible after recent progress in identifying and accounting for errors in observed estimates of ocean heat content (OHC)[25], and by advances in isolating the signatures of different modes of variability in OHC changes. In summary, research into the causes of the slowdown has been enabled by a large body of prior research, and represents an important and continuing scientific effort to quantify the climate signals associated with internal decadal variability, natural external forcing, and anthropogenic factors.

Claims and counterclaims

Recent claims that scientists “turned a routine fluctuation into a problem for science” and that “there is no evidence that identifies the recent period as unique or particularly unusual”[26] were made in the context of an examination of whether warming has ceased, stopped, or paused. We do not believe that warming has ceased, but we consider the slowdown to be a recent and visible example of a basic science question that has been studied for at least twenty years: what are the signatures of (and the interactions between) internal decadal variability and the responses to external forcings, such as increasing GHGs or aerosols from volcanic eruptions?

The last notable decadal slowdown during the modern era occurred during the big hiatus. The recent decadal slowdown, on the other hand, is unique in having occurred during a time of strongly increasing anthropogenic radiative forcing of the climate system. This raises interesting science questions: are we living in world less sensitive to GHG forcing than previously thought[27], or are negative forcings playing a larger role than expected? Or is the recent slowdown a natural decadal modulation of the long-term GMST trend? If the latter is the case, we might expect a "surge" back to the forced trend when internal variability flips phase[13].

A point of agreement we have with Ref. 26 concerns the unfortunate way in which the recent changes have been framed in terms of GMST having "'stalled', 'stopped', 'paused', or entered a 'hiatus'". Just exactly how such changes should be referred to is open to debate. Possible choices include "reduced rate of warming", "decadal fluctuation" or "temporary slowdown" – all try to convey the primary mechanism involved, which in the recent example is likely internal decadal variability.

The warming slowdown as a statistically robust phenomenon has also been questioned. Recent studies have assessed whether or not trends during the slowdown are statistically different from trends over some earlier period. These investigations have led to statements such as "further evidence against the notion of a recent warming hiatus"[4] or "claims of a hiatus in global warming lack sound scientific basis"[9]. While these analyses are statistically sound, they benchmark the recent slowdown against a baseline period that includes times with a lower rate of increase in greenhouse forcing[1], as we discuss below. Our goal here is to move beyond purely statistical aspects of the slowdown, and to focus instead on improving process understanding and assessing whether the observed trends are consistent with our expectations based on climate models.

Baseline periods

The claim that the slowdown is not manifest in observations[4] is based on comparing recent trends in updated GMST against the GMST trend over a baseline period from 1950 to 1999. Given the variability evident in Fig. 1, it is obvious that the choice of start and end dates will determine the extent to which trends over one interval are larger or smaller than those over another interval (as shown in Ref. 7). A baseline period that includes the big hiatus, during which time positive anthropogenic GHG forcing was weaker than today (and negative forcing from anthropogenic sulphate aerosol emissions was increasing rapidly), will necessarily yield a relatively small baseline GMST trend. Similarly, comparisons can be strongly affected by computing decadal-scale trends over intervals with end dates influenced by large El Niño or La Niña events, or changes in volcanic aerosols. In our opinion, start and end dates should be selected based on physical understanding of the forcings and processes involved.

Our exploration of an alternative baseline period is motivated by ΔF, the estimate of anthropogenic radiative forcing[28]. This represents the perturbation to the radiative budget of the planet from the combined effects of human-caused increases in GHGs and aerosols. Since the Industrial Revolution, human activities have caused net positive forcing of the climate system, leading to overall warming of the surface. Superimposed on this forced anthropogenic response are internal variability, cooling and recovery from volcanic eruptions, and small signals of solar irradiance changes.

The role of these factors is illustrated in Fig. 3, which shows $R_{\{\Delta T/\Delta F\}}$, the anomalies in the ratio of trends in GMST and global-mean anthropogenic radiative forcing. Results are calculated over the big hiatus and warming slowdown periods, as well as over the intervening period. $R_{\{\Delta T/\Delta F\}}$ provides information on the change in GMST per unit change in anthropogenic forcing. A simple interpretation is that variations in $R_{\{\Delta T/\Delta F\}}$ reflect influences other than anthropogenic forcing, such as external forcing from volcanic eruptions and/or internal variability. Changes in the sign of $R_{\{\Delta T/\Delta F\}}$ indicate periods over which non-anthropogenic influences add to or subtract from the anthropogenically-forced warming response.

The big hiatus and slowdown periods show $R_{\{\Delta T/\Delta F\}}$ values that are noticeably lower than average, whereas $R_{\{\Delta T/\Delta F\}}$ is slightly above average during the intervening period (1972 to 2001). Use of current estimates of total (anthropogenic plus natural) external forcing for calculating $R_{\{\Delta T/\Delta F\}}$ yields qualitatively similar results. Although there are remaining uncertainties in both ΔT and ΔF, these are unlikely to explain the pronounced differences in the sign and size of $R_{\{\Delta T/\Delta F\}}$ between the 1972 to 2001 baseline and the recent slowdown period from 2001 to 2014. The most plausible interpretation of these differences is that the combined effects of internal variability and natural forcing enhanced warming over 1972 to 2001 and reduced warming in the early 21st Century. A different but complementary approach to ours reached the same conclusion[29].

The big hiatus and warming slowdown periods correspond to times during which the dominant mode of decadal variability in the Pacific – the IPO – was in its negative phase. In the intervening period the IPO was in its positive phase. Recent modelling[11-13,15,16,24] and observationally based studies[14,18] indicate an important role for Pacific decadal variability in modulating temporal changes in GMST. Based on both of these factors – the relatively steady increase in net anthropogenic forcing over 1972 to 2001, and the consistent sign of the IPO during this period – we argue that as a baseline for evaluating whether the surface warming rate is unchanged in the early 21st Century, 1972 to 2001 is a preferable choice to 1950 to 1999. Using this more physically interpretable 1972-2001 baseline, we find that the surface warming from 2001-2014 is significantly smaller than the baseline warming rate.

"during the early 2000's"
or
"during 2001-2014"

Concluding remarks

Our results support previous findings of a reduced rate of surface warming since the beginning of the 21st Century – a period in which anthropogenic forcing ~~has been~~ increas~~ing~~ at a relatively constant rate. Recent research that has identified and corrected errors and inhomogeneities in the surface air temperature record[4] is of high scientific value. Investigations have also identified non-climatic artifacts in tropospheric temperatures inferred from radiosondes[30] and satellites[31], and important errors in ocean heat uptake estimates (Ref. 25 and references contained therein). Newly-identified observational errors do not, however, negate the existence of a real reduction in the surface warming rate in the early 21st Century relative to the 1970s-1990s. This reduction arises through the combined effects of internal decadal variability[11-18], volcanic[19,23] and solar activity, and decadal changes in anthropogenic aerosol forcing[32]. The warming slowdown has motivated substantial research into decadal climate variability and uncertainties in key external forcings. As a result, the scientific community is now better able to explain temperature variations such as those experienced during the early 21st Century[33], and perhaps even to make skillful predictions of such fluctuations in the future. For example, climate model predictions initialized with recent observations indicate a transition to a positive phase of the IPO with increased rates of global surface temperature warming[34,35].

In summary, climate models did not (on average) reproduce the observed temperature trend over the early 21st Century[6], in spite of the continued increase in anthropogenic forcing. This mismatch focused attention on a compelling science problem – a problem deserving of scientific scrutiny. Based on our analysis, which relies on physical understanding of the key processes and forcings involved, we find that the rate of warming over the early 21st Century is slower than that of the previous few decades. This slowdown is evident in time series of GMST and in the global mean temperature of the lower troposphere. The magnitude and statistical significance of observed trends (and the magnitude and significance of their differences relative to model expectations) depends on the start and end dates of the intervals considered[23].

Research into the nature and causes of the slowdown has triggered improved understanding of observational biases, radiative forcing, and internal variability. This has led to widespread recognition that modulation by internal variability is large enough to produce a significantly reduced rate of surface temperature increase for a decade or even more – particularly if internal variability is augmented by the externally driven cooling caused by a succession of volcanic eruptions. The legacy of this new understanding will certainly outlive the current warming slowdown. This is particularly true in the embryonic field of decadal climate prediction, where the challenge is to simulate how the combined effects of external forcing and internal variability produce the time-evolving regional climate we will experience over the next ten years[36].

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Author Contributions

J.C.F. and G.A.M. conceived the study. J.C.F. undertook the calculations and wrote the initial draft of the paper. All the authors helped with the analysis and edited the manuscript.

Additional information

None.

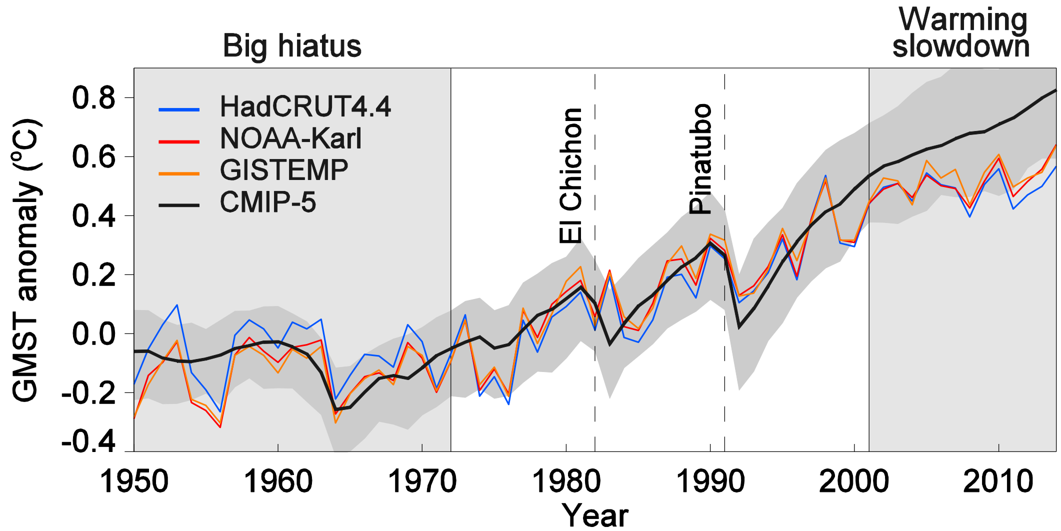

Figure 1 | Annual-mean and global-mean surface temperature anomaly. Anomalies are from three updated observational datasets[3-5] and the ensemble mean (black curve) and 10-90% range (darker grey shading) GMST of 124 simulations from 41 CMIP-5 models using rcp4.5 extensions from 2005[28]. Anomalies are relative 1961 to 1990 climatology. We obtain 1972 as the end year of the big hiatus (the period of near-zero trend in the mid-20th Century) by constructing an optimal piece-wise bilinear fit to the NOAA-Karl data over the period 1950 to 2001. We note that this baseline period is essentially the preceding WMO climate normal period (1971-2000) against which the early 21st Century records can be compared. Using this period rather than the baseline determined by a bilinear fit to the data (yielding a 1972 start date) does not materially change the result. Choice of the 2001 start year of the warming slowdown avoids possible end-point effects associated with large El Niño or La Niña events in 1998 and 2000 (respectively).

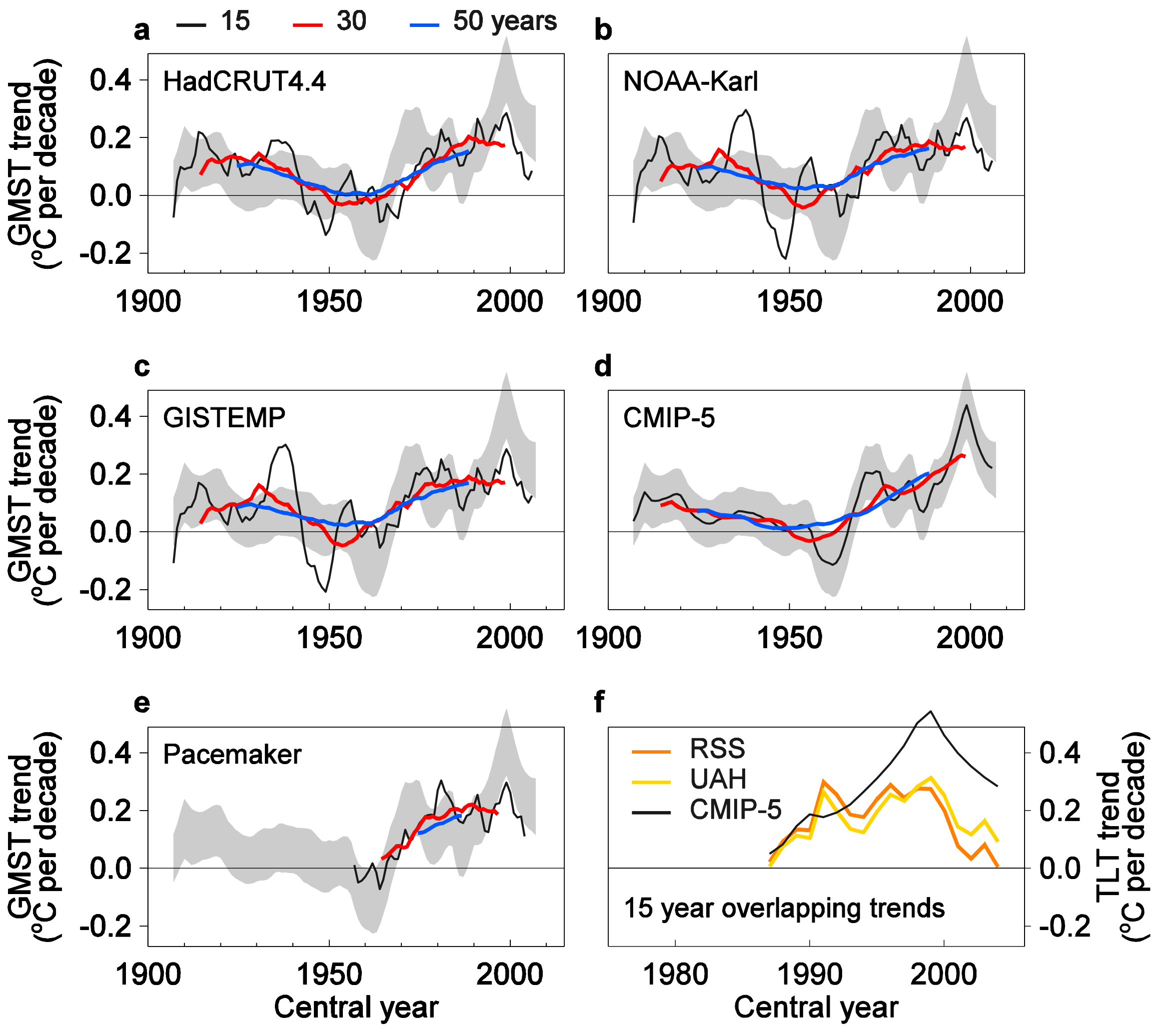

Figure 2 | Overlapping trend in annual mean temperature. a-d, Overlapping trend in global mean surface temperature (GMST) in three updated observational datasets[3-5] and ensemble mean GMST from 124 simulations from 41 CMIP-5 models using rcp4.5 extensions from 2005[28]. The shading is plus to minus one standard deviation of the 15-year overlapping trends from the CMIP-5 simulations. **e**, Overlapping trend in so-called "pacemaker"[12] experiments where a CMIP-5 climate model was forced with observed eastern tropical Pacific sea surface temperature variability and rcp4.5 extensions from 2005[28]. **f**, Overlapping trend in the temperature of the lower troposphere (TLT), spatially averaged over the near-global (82.5°N-70°S) coverage of two satellite-based datasets[21,22]; model results are from 41 simulations of historical climate change performed with 28 CMIP-5 models, with rcp8.5 extensions from 2005[28]. Peaks in the running 15-year trends around 2000 reflect recovery from the combined effects of the El Chichón eruption in 1982 and the Pinatubo eruption in 1991.

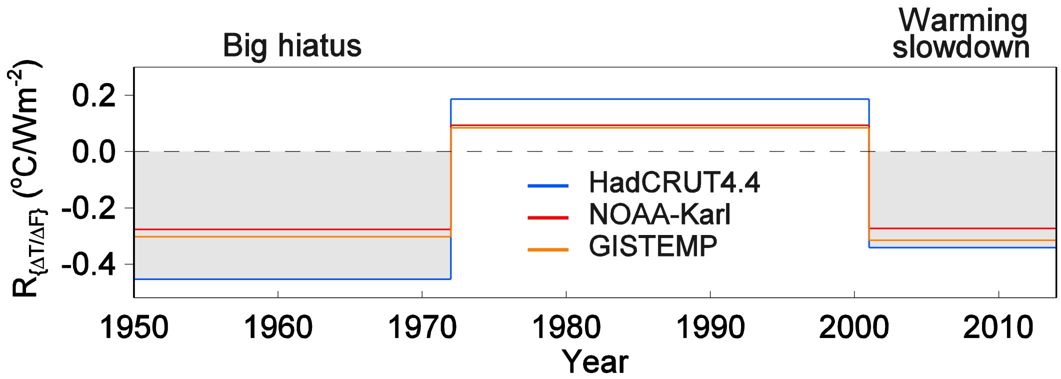

Figure 3 | Ratio of trend in annual-mean and global-mean surface temperature to trend in anthropogenic radiative forcing. The ratio of trends over each period shown in this figure (i.e., 1950-1972, 1972-2001 and 2001-2014) is expressed as an anomaly relative to the trend computed over the full period from 1950 to 2014. The caption to Fig. 1 explains the rationale for the end date and start date for the big hiatus and warming slowdown periods (respectively).