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LETTERS

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Quantifying the likelihood of a continued hiatus in global warming

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Since the end of the twentieth century, global mean surface temperature has not risen as rapidly as predicted by global climate models[1–3] (GCMs). This discrepancy has become known as the global warming 'hiatus' and a variety of mechanisms[1,4–17] have been proposed to explain the observed slowdown in warming. Focusing on internally generated variability, we use pre-industrial control simulations from an observationally constrained ensemble of GCMs and a statistical approach to evaluate the expected frequency and characteristics of variability-driven hiatus periods and their likelihood of future continuation. Given an expected forced warming trend of ~0.2 K per decade, our constrained ensemble of GCMs implies that the probability of a variability-driven 10-year hiatus is ~10%, but less than 1% for a 20-year hiatus. Although the absolute probability of a 20-year hiatus is small, the probability that an existing 15-year hiatus will continue another five years is much higher (up to 25%). Therefore, given the recognized contribution of internal climate variability to the reduced rate of global warming during the past 15 years, we should not be surprised if the current hiatus continues until the end of the decade. Following the termination of a variability-driven hiatus, we also show that there is an increased likelihood of accelerated global warming associated with release of heat from the sub-surface ocean and a reversal of the phase of decadal variability in the Pacific Ocean.

The unexpectedly modest rise in global mean surface temperature (GMST) over the past decade or so, often referred to as the global warming 'hiatus', has attracted considerable interest from the scientific community and wider public[1–3,8,18]. Although recent observational studies have shown that incomplete spatial sampling may play a role[19], this cannot account for the discrepancy between the observed trend (−0.04 to 0.04 K per decade, for the decade ending in 2013) and the central estimate from climate models (0.2 K per decade; Fig. 1). However, several studies have shown that hiatus decades are not inconsistent with our expectations of internal climate variability[1,8,10,11,20] and do not necessarily imply a reduction in the rate of energy accumulation in the Earth system[10,21,22].

The latest Intergovernmental Panel on Climate Change (IPCC) assessment report[2] attributed the hiatus to some combination of external climatic forcings that are not adequately represented in model simulations of the recent period and the internal climate variability that is intrinsic to individual model simulations but largely absent from the multi-model mean. Mechanisms proposed to explain the hiatus include aerosol emissions from modest volcanic eruptions[6,12,13,16,23], a delayed response to the Mount Pinatubo eruption[24], the unexpectedly prolonged solar minimum[7,14,24], stratospheric water vapour changes[15], increases in anthropogenic sulphate aerosol emissions[14,16,25], internal decadal variability in the Pacific and/or high-latitude oceans[9–11,26,27], and externally forced and/or internally generated wind-driven rearrangement of heat in the oceans[4,5]. Several studies have previously commented on the likelihood of a warming hiatus and the potential for a subsequent accelerated warming[5,8,17,20,27,28]; however, none has considered the likelihood of the present hiatus continuing into the future using the framework of conditional probabilities or evaluated the conditions following the termination of a hiatus.

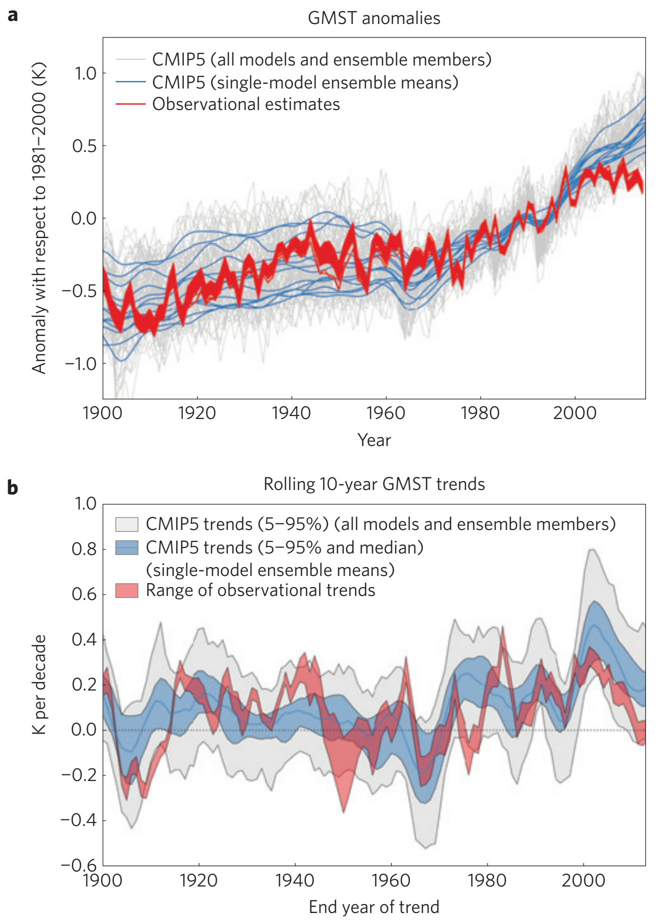

Figure 1 | Observed and simulated GMST. a, GMST anomalies in observational data sets (red; see Methods for details), CMIP5 historical and RCP4.5 scenario ensemble members (grey) and single-model ensemble means smoothed with a 10-year low-pass filter (blue). **b**, Range (observations) and 5th–95th percentiles (CMIP5 models) of rolling 10-year trends in GMST for the data sets plotted in **a**.

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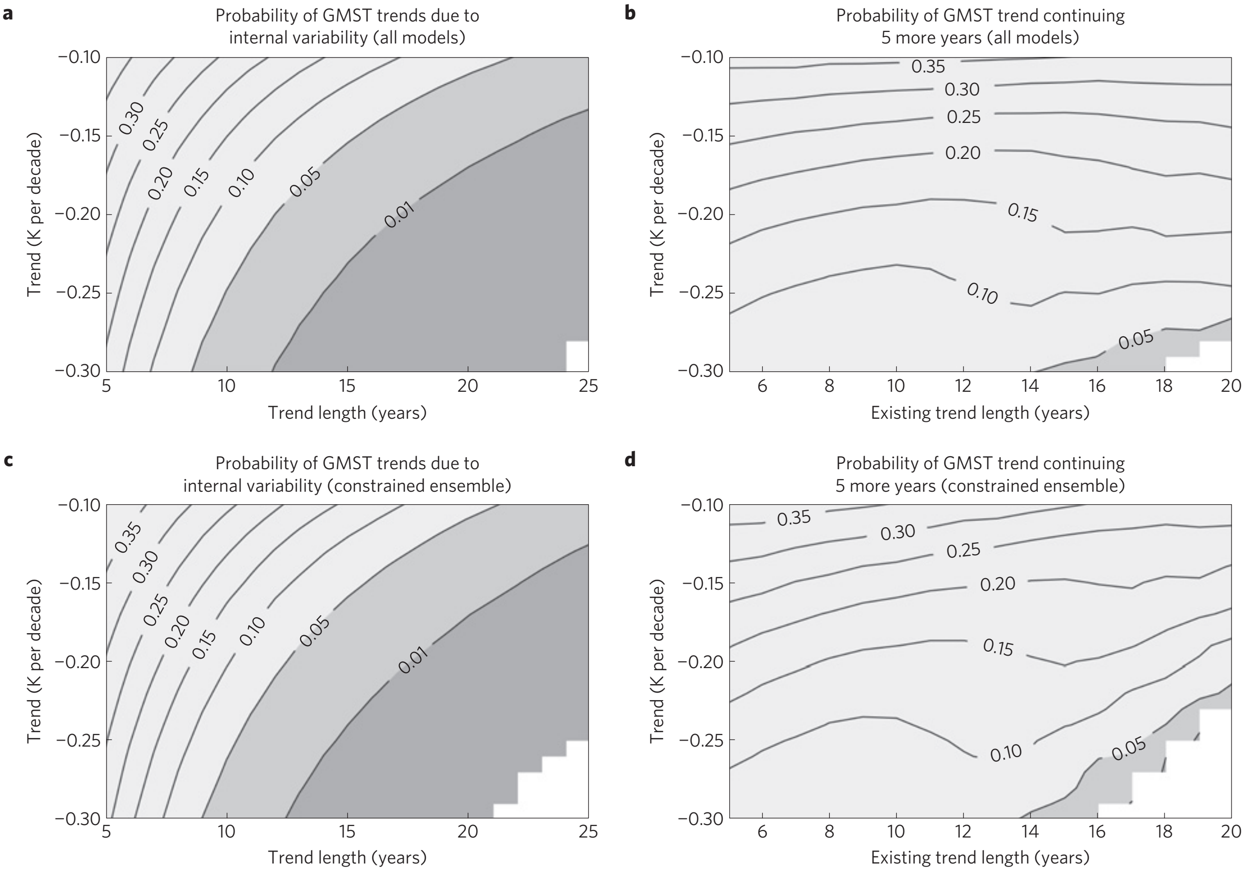

Figure 2 | Probability of GMST trends due to internal variability. a, Multi-model probability of GMST trends due to internal variability less than or equal to the specified values (all models). For example, the probability of a −0.25 K per decade trend lasting 10 years is about 0.05 (5%). This probability drops to about 0.01 (1%) for trend length of 14 years. **b**, Conditional probability of GMST trends continuing 5 more years, given the existence of a trend in the preceding *N* years. For example, if a −0.25 K per decade trend has been observed for 12 years, the probability of it continuing for another 5 years is about 0.10 (10%). **c**,**d**, The same as in **a**,**b**, but calculated using the observationally constrained subset of models identified in Supplementary Table 1 and Fig. 3.

Here, we consider how long the observed hiatus might last owing to internal variability alone and characterize both the spatial patterns of surface temperature change, and the likelihood of accelerated GMST rise, following the termination of a hiatus. The results of our study are based on 23 multi-century pre-industrial control simulations from Phase 5 of the Coupled Climate Model Intercomparison Project CMIP5 (see Methods). These physically based model simulations of climate variability are combined with statistical models (autoregressive moving-average (ARMA) models, see Methods) to quantify both absolute and conditional probabilities of a hiatus event continuing for a given number of years. In addition, we repeat our analysis with a subset of climate models that have the most realistic representation of Pacific variability—an area of the ocean that has played a key role in the observed hiatus[5,9].

We assume that the time evolution of GMST can be considered a linear combination of a 'signal' due to external climate forcings superimposed on 'noise' that is consistent with variability in pre-industrial control simulations. In addition, we assume that the rate of warming due to external forcings can be considered constant on decadal timescales. These assumptions are reasonable when considering the evolution of GMST during the early twenty-first century (see Supplementary Methods). In this paradigm, the probability that internal variability will offset a warming rate of, for example, 0.2 K per decade for the current climate, is the same as the probability that internal variability will cause a global temperature trend <-0.2 K per decade in a pre-industrial control experiment. We note that if greenhouse gas concentrations continue to increase during the twenty-first century, then periods of zero warming will become less likely in the future[28]. However, periods with anomalous rates of cooling/warming will continue to arise from internal variability and it is on these events that we focus our analysis. We use the following terminology. 'Hiatus' refers to a period of suppressed warming (GMST change), or even zero trend or cooling, when a forced warming trend is expected. Assuming linearity, it can be equated with an anomalous cooling in a pre-industrial control simulation that exceeds some threshold value, superimposed on a forced warming trend. 'Continued hiatus' refers to an existing hiatus that experiences continued muted GMST response of the same (or greater) magnitude. 'Accelerated warming' refers to a period of anomalous warming that exceeds that which would be expected from the forced signal. Such a period may be equated with a warming trend that exceeds the magnitude of cooling during a preceding hiatus in a pre-industrial control simulation as in our definition of a hiatus.

We estimate the multi-model mean probability (see Methods) of GMST cooling trends of −0.1 to −0.3 K per decade—sufficient to offset a long-term warming rate of the same magnitude—arising from internal variability as a function of trend length (Fig. 2a). This range of trend magnitudes is chosen to account for uncertainty in the transient climate response (TCR) to external forcings (see Methods). Given an expected warming rate of 0.2 K per decade, our multi-model probability for a 10-year warming hiatus due to internal variability is 9% with a range across models of 0–17% (Table 1 and Supplementary Fig. 1). For a 20-year hiatus (that is, a 20-year period with a trend <-0.2 K per decade) the multi-model probability is $<1\%$ (Fig. 2a) and the range across models is 0–2%

Table 1 | Selected absolute and conditional probabilities extracted from Fig. 2 for trends in GMST sufficient to offset a warming rate of 0.2 K per decade.

	All CMIP5 models	Constrained ensemble
5 years	28% (15–33%)	30% (27–33%)
10 years	9% (0–17%)	10% (5–17%)
20 years	<1% (0–2%)	<1% (0–2%)
5 years (following an existing 15-year hiatus)	16% (0–29%)	15% (0–25%)

Values are given as multi-model means with the range across models in parentheses.

(Table 1). The range of probabilities across models is a consequence of differences in the characteristics of simulated internal GMST variability (Supplementary Fig. 3). Notably, a 20-year hiatus due to internal variability alone is very unlikely, but is not outside the range of internal variability as simulated by GCMs (Supplementary Figs 1 and 2).

However, we argue that the expected frequency of a hiatus occurring in any given period is not the most useful quantity for communicating the chance that the current warming hiatus will extend into the future. To evaluate the fraction of hiatus events of a given length that will continue for a specified period, we propose the use of conditional probabilities (Fig. 2b). For example, if internal variability has offset warming of 0.2 K per decade for a period of 15 years, our multi-model mean estimate of the fraction of events that will continue to offset warming for another 5 years is 16%, with a multi-model range of 0–29% (Table 1). In addition, for trend lengths of 5 to 20 years, the probabilities in Fig. 2b are surprisingly insensitive to the existing trend length. This is a consequence of the year-to-year persistence of GMST anomalies associated with internal variability (Supplementary Fig. 3). If internal variability has been the dominant driver of the hiatus since 2000, and GCMs are representative of the real world, this ensemble of models indicates that there is a non-negligible probability (that is, between 0 and 29% for an expected warming rate of 0.2 K per decade) of the current hiatus continuing for 5 more years. Failure to adequately communicate this possibility could lead to allegations of overconfidence in GCM projections, especially if the existing hiatus continues until 2020 and beyond.

To investigate the spatial changes associated with hiatus events in models, we identify 128 decades with global cooling less than −0.2 K per decade from 23 CMIP5 pre-industrial control simulations. The mean characteristics of these events share many of the previously identified features of warming slow-downs in observations[4,5,9] and models[10,11], including a pattern of surface temperature change resembling the negative phase of the Pacific Decadal Oscillation (PDO), accelerated Pacific trade winds and spin-up of the sub-tropical gyres, sub-surface warming in regions of thermocline convergence (Supplementary Fig. 4), and increased ocean heat uptake beneath the ocean mixed layer (Fig. 4).

However, we emphasize that the composite mean is an inadequate description of any single model or event. Single-model composites and individual events show marked differences in the magnitude and patterns of near-surface temperature change (Supplementary Fig. 5), the locations and magnitude of heat convergence in the thermocline and regions of deep-water formation (Supplementary Figs 6 and 7), the relative importance of ocean heat redistribution and top-of-atmosphere radiation (TOA) imbalance (Supplementary Fig. 8), and the patterns and magnitudes of near-surface wind anomalies (Supplementary Fig. 5). For example, as previously reported[10], hiatus decades in the Community Climate System Model 4 are characterized by a PDO-like pattern of near-surface temperature change, increased deep-ocean heat uptake (and associated heat export from the near surface), and no significant changes in TOA. In contrast, hiatus decades in the Geophysical Fluid Dynamics Laboratory Climate Model 3 are characterized by strong surface cooling and accelerated westerly winds over the Southern Ocean, a large contribution to cooling from TOA imbalance, and no significant changes in deep-ocean heat uptake. These differences are a powerful motivator for the application of observational constraints that allow us to identify models that have the best representation of internal climate variability.

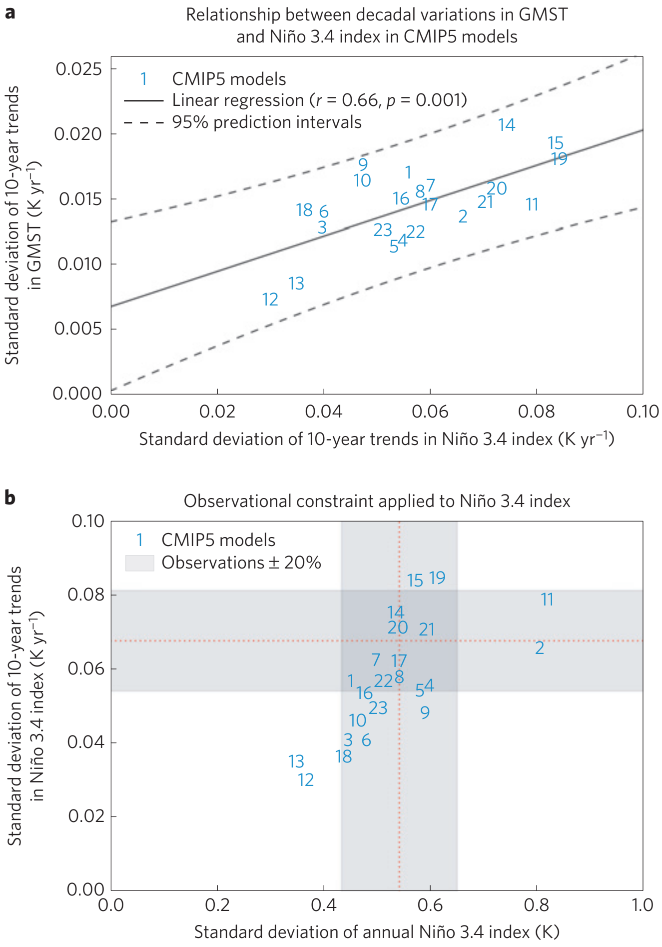

Figure 3 | Trends in GMST and Niño 3.4 index. a, Relationship between decadal SST trends in the Niño 3.4 region (120° W–170° W and 5° S–5° N) and decadal GMST trends in CMIP5 pre-industrial control simulations (labels correspond to models in Supplementary Table 1). **b**, The magnitude of Niño 3.4 SST variability on annual and decadal timescales in CMIP5 pre-industrial control simulations compared with observed values (see Methods). Our constrained ensemble corresponds to the nine models that simulate the magnitude of Niño 3.4 variability on interannual to decadal timescales to within ±20% of observed values.

The evaluation of internal GMST variability by comparison with historical observations is complicated by the confounding influence of uncertain climate forcings and variable model responses[2]. However, many studies have emphasized the importance of the tropical Pacific for the evolution of GMST (refs 5,9,29,30). To examine the sensitivity of our results to model deficiencies in simulated internal climate variability, we use a simple metric to identify a subset of models that most accurately simulate the magnitude of tropical Pacific sea surface temperature (SST) variability (Fig. 3; see Methods for details of the applied constraint). Following the application of our constraint, the absolute and conditional probabilities of a hiatus event continuing for a given

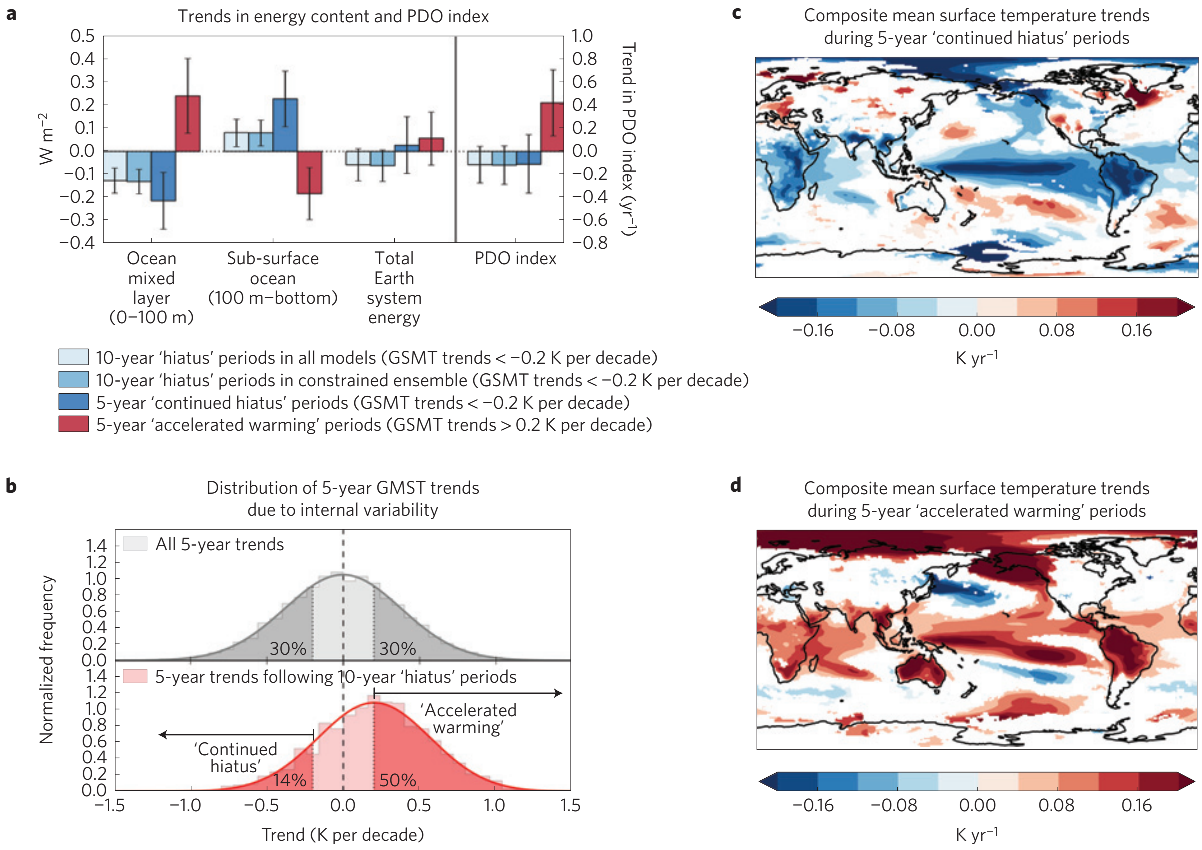

Figure 4 | Characteristics of hiatus and post-hiatus periods a, Trends in upper ocean heat content, deep-ocean heat content, total Earth system energy content (defined as time-integrated anomalies in TOA), and the PDO index for 'hiatus', 'continued hiatus', and 'accelerated warming' periods as defined in the main text. Error bars indicate ±1 s.d. across the composite. **b**, Distributions of 5-year trends in GMST due to internal variability estimated using ARMA models for all 5-year periods and for 5-year periods starting from the last year of a 10-year 'hiatus' period. Annotations indicate the probability of trends >0.2 K per decade and <-0.2 K per decade. **c**,**d**, Composite mean patterns of near-surface temperature change associated with 5-year 'continued hiatus' (<-0.2 K per decade, $N=10$) and 'accelerated warming' (>0.2 K per decade, $N=25$) periods following 'hiatus' decades (<-0.2 K per decade, $N=61$) in our constrained ensemble. To indicate consensus across composites, data are plotted only if more than two-thirds of trends are of the same sign. Further details are included as Supplementary Methods.

number of years are very similar (Fig. 2c,d and Table 1), although the probability of events lasting longer than 20 years is reduced owing to the exclusion of some models that have large-amplitude GMST variability on multi-decadal to centennial timescales. Using our constrained ensemble, the multi-model probability for a 15-year variability-driven hiatus continuing 5 more years (using an expected contemporary surface warming rate of 0.2 K per decade) is 15% with a multi-model range of 0–25%.

Finally, we use our constrained ensemble to evaluate the climatic impacts in the periods that follow hiatus decades. Although we have emphasized the possibility of an existing hiatus continuing into the future, there is also an increased risk of 'accelerated warming' following a hiatus (Fig. 4b). We find that a 5-year period of accelerated warming >0.2 K per decade is 1.7 (model range of 1.3–2.1) times more likely to occur when starting from the last year of a hiatus decade (<-0.2 K per decade; Fig. 4b) . Alternatively, a 5-year 'accelerated warming' period is 2.0 (model range of 1.6–2.4) times more likely to occur when we consider only trends starting the last year of 'terminated' hiatus decades (that is, those that do not continue another five years into the future).

Continued hiatus periods are associated with heat uptake by the sub-surface ocean (Fig. 4a) and a composite mean pattern of surface temperature change similar to that in hiatus decades (Fig. 4c). In contrast, accelerated warming periods are associated with the release of $\sim$0.2 W m^{-2} of heat from the sub-surface ocean (Fig. 4a), a pattern of warming that approximates a mirror image of surface temperature trends during hiatus periods (Fig. 4d), and a strong shift towards the positive phase of the PDO (Fig. 4a). In addition, there is some consensus ($>2/3$ events) that periods of accelerated warming following global cooling decades will be associated with warming across South America, Australia, Africa, South East Asia, and the Arctic.

One of the notable discrepancies between recently observed surface temperature trends and the features of 'hiatus' decades in model simulations[9–11] (Supplementary Fig. 4) is in the sign of temperature change over the Arctic. Hiatus decades associated with internal variability in models generally exhibit cooling over the Arctic whereas recent observations[19] indicate a strong warming. Our results indicate that, following the termination of the current global warming hiatus, internal climate variability may act to intensify rates of Arctic warming leading to increased climate stress on a region that is already particularly vulnerable to climate change.

Here, we have shown that, although rare, a global warming hiatus could last 20 years or more owing to internal variability alone. Although we found no systematic bias in the representation of tropical Pacific SST variability (Fig. 3), others have highlighted that a recent acceleration of equatorial Pacific trade winds is outside the range of variability simulated by CMIP5 models[5]. This difference was attributed to models systematically underestimating internal variability and/or a role for external forcings in the recent hiatus. If either of these factors are important, we expect hiatus periods in the real world to last longer and/or be more extreme (that is, offset more warming) than those due to internal variability in CMIP5 models. In addition, regardless of whether internal variability or external forcings have been the dominant driver of the observed warming hiatus, we emphasize that there is a substantial probability that internal variability of the climate system could offset warming until the end of the current decade.

Methods

Observed temperature trends. We use the following observational data sets to estimate GMST trends: 100 realizations of the Hadley Centre/Climate Research Unit temperature data set[31] (HadCRUT4) available from http://www.metoffice.gov.uk/hadobs/hadcrut4; two versions of HadCRUT4 in which unobserved grid boxes are filled using either optimal interpolation or a hybrid method that incorporates satellite temperature data[19] available from http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html; the Goddard Institute of Space Studies Surface Temperature Analysis[32] available from http://data.giss.nasa.gov/gistemp; The National Oceanic and Atmospheric Administration (NOAA) Merged Air Land and SST Anomalies data[33] available from http://www.esrl.noaa.gov/psd. Observed SST trends in the Niño 3.4 region are calculated using the Hadley Centre Sea Ice and Sea Surface Temperature gridded data set[34] available from http://www.metoffice.gov.uk/hadobs.

CMIP5 model data. We use data from simulations performed as part of CMIP5. CMIP5 is the primary modelling resource used in support of the Fifth Assessment Report (AR5) of the IPCC and the contributing models represent the state-of-the-art in coupled climate simulations. Each model provides an estimate of the evolving ocean and atmosphere state in response to any imposed climate forcings and includes representation of the intrinsic variability generated by the coupled climate system.

Estimation of warming due to external forcings. To estimate background warming rates over the historical period, we use historical (up to 2005) and Representative Concentration Pathway 4.5 (RCP4.5, post 2005) scenarios from available CMIP5 models. We estimate uncertainty in the forced component of climate change by calculating single-model ensemble means for CMIP5 models with three or more historical scenario ensemble members, and applying a low-pass Butterworth filter with a 10-year cutoff. From 2004 to 2013, our estimates of background warming rates due to external forcings range from 0.11 to 0.28 K per decade. The thirteen models with three or more historical ensemble members have a TCR (as estimated by ref. 35) to a doubling of CO_2 in the range 1.5–2.5 K (see the IPCC AR5 likely range of 1.0–2.5 K). TCR represents a measure of the sensitivity of GMST rise to imposed greenhouse gas concentrations in the models such that those with a larger TCR have a larger projected surface warming for a given climate change scenario; importantly, we find no significant relationship between model TCR and the characteristics of internal GMST variability (Supplementary Fig. 9). This means that the impact of uncertainties in TCR can be considered independently from the impact of uncertainties in the representation of GMST variability.

Calculation of internal variability. To estimate internal variability in GMST and Niño SST indices we use CMIP5 pre-industrial control simulations and calculate annual mean diagnostics using data from the 23 models listed in Supplementary Table 1 retrieved from the CMIP5 archive (http://cmip-pcmdi.llnl.gov/cmip5). All pre-industrial control time series are linearly detrended to limit the impact of model drift.

Estimation of trend probabilities. Long time series are necessary for the estimation of probabilities conditional on the existence of a preceding event. For this reason, we use generic ARMA models to generate 10,000-year-long synthetic realizations of GMST variability that have the same auto-correlation characteristics as data from CMIP5 pre-industrial control simulations. We fit ARMA models of the form

$$\left(1-\sum_{i=1}^{p}\varphi_i L^i\right) X_t = \left(1+\sum_{i=1}^{q}\theta_i L^i\right)\varepsilon_t \qquad (1)$$

to each detrended CMIP5 time series (X_t), where φ_i and θ_i are autoregression (AR) and moving-average (MA) coefficients at lag i, p and q are the order of AR and MA components, L^i is the lag operator (defined such that $L^i X_t = X_{t-i}$), and ε_t is Gaussian white noise with a variance of σ^2. Values of p and q are calculated by minimization of an Akaike information criterion as implemented in the forecast package of *R* (ref. 36). Trend probabilities are estimated by calculating linear least-squares trends for all overlapping trends of length N and then finding the fraction of trends with a slope coefficient less than or equal to a specified value.

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Author contributions

C.D.R., M.C. and M.D.P. conceived the study. C.D.R. and D.M. analysed the data and conducted statistical analyses. All authors contributed to the interpretation of the results and the preparation of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.D.R.

Competing financial interests

The authors declare no competing financial interests.