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Reconciling controversies about the 'global warming hiatus'

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Between about 1998 and 2012, a time that coincided with political negotiations for preventing climate change, the surface of Earth seemed hardly to warm. This phenomenon, often termed the 'global warming hiatus', caused doubt in the public mind about how well anthropogenic climate change and natural variability are understood. Here we show that apparently contradictory conclusions stem from different definitions of 'hiatus' and from different datasets. A combination of changes in forcing, uptake of heat by the oceans, natural variability and incomplete observational coverage reconciles models and data. Combined with stronger recent warming trends in newer datasets, we are now more confident than ever that human influence is dominant in long-term warming.

Some years after the record warm global-mean surface air temperatures (GMSTs) in 1998, claims were put forward by voices outside the scientific community that "[global warming] stopped in 1998"[1], arguing on the basis of the HadCRUT3[2] dataset that was available then that GMST had not increased over the period 1998–2005. This was later called the 'global warming hiatus', 'pause' or 'slowdown'. The topic circulated as a sceptical argument in the blogosphere for a few years[3], but until about 2013 only a few scientists[4–12] published on the observed short-term GMST trends being unusually low (Fig. 1a) and deviating from the ensemble of climate models[13]. We hereafter refer to the GMSTs in the 10–15 years after 1998 as the 'hiatus', and discuss whether there was in fact a hiatus, depending on the period and definition. Some had predicted a temporary slowdown of the warming[14,15], but confidence in this new field of initialized decadal predictions was low. In leaked drafts of the Intergovernmental Panel on Climate Change (IPCC) Working Group I (WG1) Fifth Assessment Report (AR5), the global warming hiatus was considered to be consistent with natural variability, and hence not in need of a detailed explanation. At the time of the first draft, there was almost no literature on the hiatus to be assessed anyway (Fig. 1b, bars). Scientists knew from observations and models that global temperatures fluctuate on timescales of years to decades[16,17], producing longer periods of reduced warming rates[18]. On Christmas Eve 2012, the UK Met Office published an updated decadal forecast stating that the temperatures may not increase for another five years, downgrading the warming from the previous forecast. Some media pitched this as scientists trying to hide the truth by releasing it at a time when few news channels would pick it up[19]. The interest of the media and public grew[20] (Fig. 1b, lines), and groups with particular interests used the case to question the trust in both climate science and the use of climate models[21]. In November 2009, the climate community was put under scrutiny after the leak of emails stolen from the Climate Research Unit (CRU)—later known as 'Climategate'—in which the integrity of some scientists was put into question. Even though the scientists were exonerated for scientific wrongdoing by several independent inquiries, with past events in mind, scientists felt like they needed to respond to the public's distrust. Consequently, several of the early scientific studies related to the hiatus were motivated by the increased focus in the media and blogosphere, and focused on natural variations in the climate system as an explanation. Other reasons might also have had important roles in bringing the hiatus into public focus, and in making it not only a scientifically driven research topic, but also a publicly driven one, such as the argued lack of clear communication from scientists[22–24] and the misleading wording of a 'pause' in global warming[24,25].

This ultimately led to the inclusion of a section dedicated to the hiatus in the IPCC AR5 WG1 report[26]. At the press conference when the report was released, there were more questions by journalists about the hiatus than about any other topic addressed in the report. Now, in 2017, almost four years later, after a wave of scientific publications and public debate (Fig. 1b), and with GMSTs setting new records again, it is time to take stock of what can be learned from the hiatus.

Elements of such a synthesis have been discussed elsewhere[25,27–31], but have not been put together into a broader perspective. Here we reconcile the diverging views on the existence of the hiatus and demonstrate that most of the seemingly contradictory statements relate to different definitions and periods used, and datasets analysed. We further review the proposed underlying mechanisms and quantify their effect. We argue that a combination of several mechanisms contributed to the hiatus. When we take these into consideration, what we are left with from the apparent hiatus is not inconsistent with the understanding of human influence on global climate. In fact, it increases the confidence in the dominant role of humans in long-term warming.

Hiatus characteristics and definitions

The 'global warming hiatus' often refers to the period starting around 1998 and ending around 2012, during which the annual-mean area-weighted GMST did not seem to increase as much as was expected from increasing atmospheric greenhouse gas concentrations. In the literature, three main definitions are used to characterize a hiatus (Fig. 2a): (i) the trend in GMST is zero, negative or not significantly positive (at the 5% level); (ii) the estimated trend from observations is lower than the preceding long-term warming trend; and (iii) the trend is lower than projected from model simulations. Sometimes the definitions are not even clearly stated. In addition to different definitions, studies also use different start and end years, and different datasets in their analyses (see ref. 30 for an overview).

The hiatus period started with an unusually strong El Niño in 1997/1998 that caused GMSTs to increase to 0.2 °C above the temperatures expected from the long-term warming trend[32], a GMST not seen before in the observational record. By defining the hiatus as the period 1998–2012, negative temperature trends over both ocean and land are found mainly in

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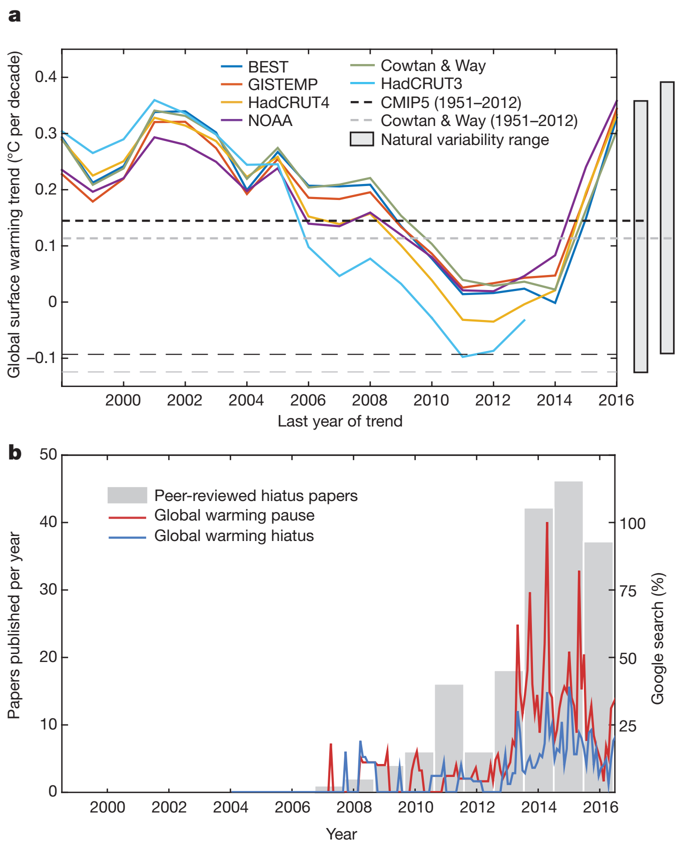

Figure 1 | Magnitude of and interest in the hiatus. a, Running 10-yr global-mean temperature trends for different observational datasets (coloured lines), where the time indicates the last year of the trend. The natural variability (5th–95th percentile of 10-yr trends) from control simulations of 42 CMIP5 models around the long-term (1951–2012) trend in the observational estimate from Cowtan & Way (thick grey dashed line) and the ensemble mean of the CMIP5 models (thick black dashed line) is given a grey shaded bar (right). Thin dashed lines illustrate the lower bounds on the natural variability around the long-term trends. **b**, Peer-reviewed studies published annually (histogram) by the end of 2016 that contributed to the understanding of the hiatus (178 papers in total excluding 'news and views' and commentaries) and monthly output from 'Google trends' for the search criteria "global warming pause" and "global warming hiatus", normalized to the maximum number of monthly searches for "global warming pause".

boreal winter[11] (Fig. 3a), but local negative trends are also evident in the annual temperatures (Fig. 3b). The tropical Pacific dominates the reduced warming trend in the global-mean sea surface temperatures (SSTs)[33], and North America and Eurasia dominate the land temperature trend[11].

Surface air temperatures are relatively easy to understand, their observational record is longer than for other variables, and in their global average they are arguably the best aggregate measure for global climate effects[34]. However, even for surface air temperature measurements, substantial uncertainties related to instrument calibration, homogeneity and the absence of complete data coverage remain when calculating a global mean (see Methods). Different perspectives on the hiatus relate to the use of different observational datasets, which are changing through updates and adjustments as more information about homogenization of different measurements becomes available. In 2009, the trend in the HadCRUT3 global temperature estimate since 1998 was slightly negative (−0.01 °C over 1998–2008; Fig. 2b). Hence, this (definition (i) above) was the original definition of the hiatus that was often used in the literature[4]. Several of the early hiatus papers used HadCRUT3[3,5,7,10]. Since then, this and other observational datasets underwent substantial, well-documented improvements, resulting in a positive temperature trend over the same period. As a result, some argued that the hiatus was not as substantial as first reported after gaps in the spatial coverage of HadCRUT4 were filled[35] and after correcting for inhomogeneities in the observational estimates caused by changes in the network of SST observations[36].

None of the five current observational datasets for GMST shows a negative linear trend for any duration of more than five years starting in 1998 (Fig. 2c and Extended Data Fig. 1). This supports the finding that there was no decadal-scale hiatus when the hiatus is defined as a period having zero or negative trends and starting in 1998 (ref. 37). HadCRUT4, on the other hand, has a negative decadal trend, but only for periods starting in 2001 or later, and lasting for up to 12 years (Extended Data Fig. 1). Differences across datasets are caused by different data sources, calibration of different instruments, homogenization and interpolation in areas without data[38] (see Methods). This makes interpreting and understanding the reasons for the differences in the observational datasets more difficult.

The definition of the hiatus as a trend smaller than the observed long-term trend (definition (ii)) involves some arbitrary choices in the different studies. Depending on the dataset and period from which the long-term trend is calculated, different periods are found to have a smaller than long-term trend. For example, by using 1951–2012, as in IPCC AR5, all of the current datasets have 15-yr periods starting after 1997 (and ending by 2015 the latest) over which the trend is less than the respective long-term trend (see Extended Data Fig. 1). By choosing the long-term period as the second half of the twentieth century (1951–2000), only GISS, NOAA and HadCRUT4 have 15-yr trends smaller than the long-term trend (not shown). However, the difference in long-term and short-term trends is not statistically significant[36,37]. This long-term period includes part of the mid-twentieth-century period of slight cooling, when radiative forcing was much lower than present-day[25].

The differences in conclusions on whether the hiatus occurred depend on the period investigated, and which dataset and definition are used. Consequently, there is no obvious contradiction between some studies that claim that the hiatus did not occur[36] and others that claim that it did[25], although some controversies remain. For example, recent studies have argued for using change-point analysis rather than fitting trends to separate periods in a staircase-like fashion[39,40]. These studies do not indicate a statistically significant reduction in the rate of global warming[39,41], but do indicate a change-point in boreal winter land air temperatures[42].

A system with variability will always show a range of trends on various timescales (Extended Data Fig. 2a). Not every year will be warmer than the previous year, so depending on the climate scenario there is no reason why future trends could not be different from those in the past. Choosing a threshold value (definitions (i) and (ii)) is arbitrary without underlying physical reasoning. The relevant question (definition (iii)) is therefore whether, and if so, why, the observations differ from what was expected or projected for that period, making the comparison of models and observations the most informative.

To do this comparison, the internal variability of the climate system needs to be taken into account[43]. The large thermal inertia causes the ocean to be a strong driver of internal variability of global temperatures on up to multidecadal timescales. Decadal-scale internal variability can produce GMST trends of about ±0.25 °C (Extended Data Fig. 2a), and sustain positive or negative temperature deviations for decades[7]. Control simulations with global climate models show that internal variability in ocean temperatures and heat uptake can mask the long-term anthropogenic warming in GMST signal over a decade[44].

The spatial pattern in all of the observational datasets shows, to a varying degree, a cooling over the Pacific Ocean and over North America towards Eurasia during the hiatus period. This is consistent with several known modes of natural variability in SST that have an imprint on GMST (Fig. 4) and with the distribution of heat between the ocean and the atmosphere. The Atlantic Multidecadal Oscillation/Variability (AMO/AMV)[45], and the El Niño and Pacific Decadal Oscillation (PDO)/Interdecadal Pacific Oscillation (IPO)[46] influence the climate on

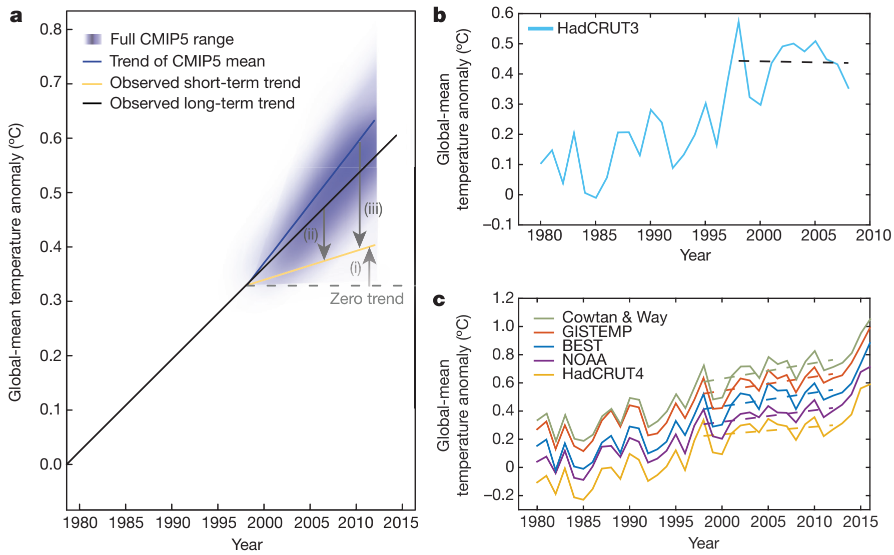

Figure 2 | Hiatus definitions and representation in different datasets. **a**, Different definitions of the hiatus from literature: (i) the short-term global-mean surface temperature trend from observations (yellow line) relative to a zero trend (grey dashed line); (ii) difference between the short-term trend and that expected from persistence of the long-term trend from observations (black line); and (iii) difference between short-term projected CMIP5 (blue line and shading) and trend from observations. The blue shading illustrates the range of individual trends in the CMIP5 models. **b**, Global surface temperature from HadCRUT3 until the end of 2008 (light blue line) together with the 1998–2008 linear trend (black dashed line). **c**, Global surface temperature (solid lines) from Cowtan & Way (green), GISTEMP (orange), BEST (blue), NOAA (purple) and HadCRUT4 (yellow) relative to 1961–1990. The time series have been shifted by 0.1 °C (from −0.2 to 0.2) relative to each other (no offset for BEST) for clarity. The dashed lines indicate the linear trend for 1998–2012 for the different datasets.

interannual to multidecadal timescales. The strong El Niño events are well reflected in the global temperature anomalies, superimposed on the low-frequency variability of the other indices (Fig. 4a). At times of El Niño occurrences, the SSTs in the tropical Pacific increase (Fig. 4c), leading to increased heat loss from the ocean to the atmosphere[47]. This leads to heat being transported to higher latitudes by the atmosphere, thus leaving a large portion of the globe warmer than normal. This strongly affects the GMST[48] (see Methods).

Although the GMST is comparatively well observed, it is not the most appropriate measure for tracking the whole Earth's net energy response to greenhouse gases. When considering only the surface of Earth, a large part of the climate system goes unnoticed[49], in particular the heat being taken up by the oceans, but also the upper atmosphere[50], and the heat used for melting ice. The ocean is by far the largest reservoir of heat in the global climate system and, owing to its large heat capacity, a layer of about 3.5 m of the global oceans holds the same amount of energy as the entire atmosphere[51]. Therefore, it is important to take into account the total heat uptake of the climate system.

Over the hiatus period, more heat has entered than has left the climate system at the top of the atmosphere (Extended Data Fig. 3a). This implies that the climate system as a whole warmed, and did not level off or cool like the hiatus (definition (i)) may suggest. Integrated ocean properties are more representative of the net energy imbalance of the climate system than are surface temperatures[44]. Both sea level and ocean heat content increased during the hiatus[47,52–57] (Extended Data Fig. 3b). During the period 1993–2003, around 90% of the excess energy put into the climate system as a result of greenhouse gas forcing was stored in the ocean[58]. Around half of the accumulation of ocean heat content since 1865 occurred after the mid-1990s, with 35% at a depth of greater than 700 m (ref. 59). Observational estimates show an increase in the ocean heat content of the upper 700 m throughout the hiatus, starting already in the 1970s[56]. The increase was largest in the beginning of the hiatus period and decreased but remained positive after 2005[56]. However, substantial uncertainties in the datasets and methods remain, which prevent the energy budget from being closed. When taking into account the heat used for melting sea ice, the uncertainties in the net top-of-atmosphere radiation and in the ocean heat uptake overlap, indicating that we cannot justify claims of inconsistencies or heat missing from the system (see Methods).

Proposed reasons for the hiatus

The proposed reasons for the global warming hiatus can broadly be categorized into four classes: external drivers, the Earth's climate response to CO_2 and other radiative forcings, and internal variability, which all affect the actual global temperature, and observational coverage, which affects only the observational estimate of global temperature. A combination of factors, possibly with interaction terms between them, is needed to explain both the spatial pattern and the magnitude of the GMST signal relative to what was projected from model simulations (definition (iii)).

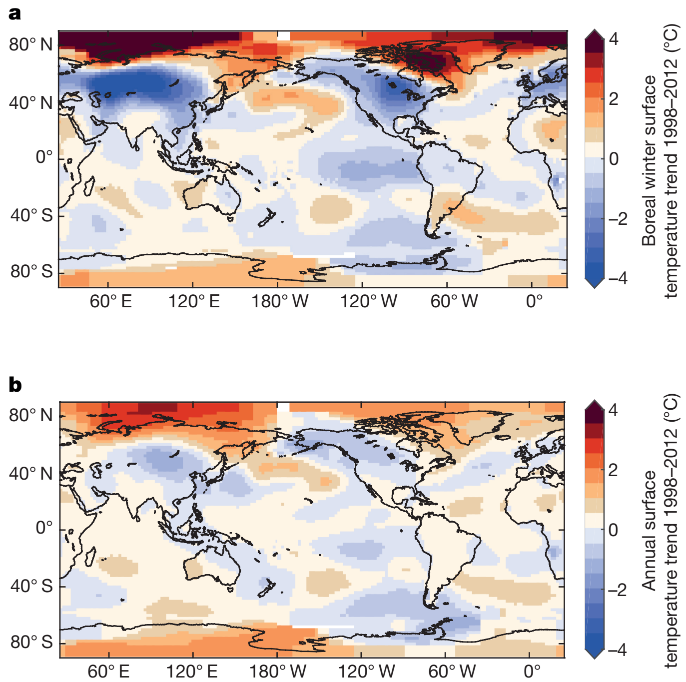

Figure 3 | Surface temperature trends for the period 1998–2012. **a**, **b**, Boreal winter (December–February; **a**) and annual-mean (**b**) surface temperature trends from observations using the GISTEMP dataset with 1,200-km smoothing.

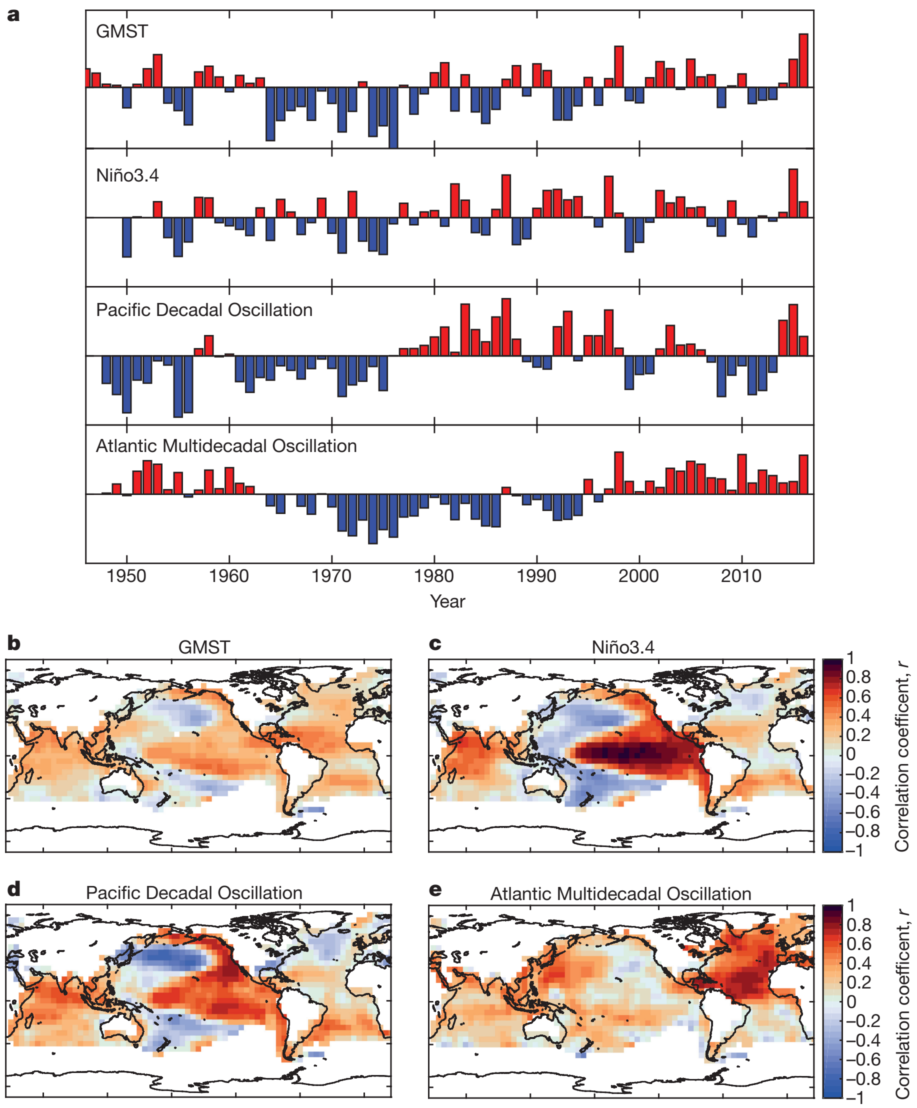

Figure 4 | Climate indices and global temperature. a, Global-mean surface air temperatures (GMSTs) from GISTEMP minus a second-order fit, and indices of Niño3.4, Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) relative to their mean states. **b**–**e**, Map of correlation coefficients (*r*) between GMST (**b**), Niño3.4 (**c**), PDO (**d**) or AMO (**e**) and the linearly detrended observed sea surface temperatures (SSTs) from Kaplan Extended SST V2 for the period 1948–2016. White regions indicate no available data. The indices are taken from NOAA ESRL (http://www.esrl.noaa.gov/psd/data/climateindices/list/).

Radiative forcing

During the hiatus, weaker solar forcing, increased tropospheric and stratospheric aerosol loadings and increased water vapour were all proposed as reasons for the reduced temperature increase or for discrepancies between models and observations. Tropospheric aerosols might have had a regional effect on the pattern of warming and cooling during the hiatus, but their negative and positive contributions cancelled on a global scale (see Methods). Owing to the large natural variability of stratospheric water vapour content, the importance of the effect on the surface temperature has been questioned. Several of these aspects are not taken fully into account in the models, and after 2005 the forcing used in the models starts to diverge from the current best estimate of the radiative forcing (see Methods for details and references).

Internal variability

The North Atlantic, Pacific, Indian and Southern oceans have all been mentioned as playing a part in the hiatus[60]. The Pacific has received the most attention because of the powerful El Niño in 1997/1998 and the relatively cold SSTs in the subsequent hiatus years. The main difference between the hiatus period and the preceding warming period is the cooler Southern Ocean and eastern tropical Pacific, while the rest of the globe was warmer during the hiatus[27]. The Pacific pattern is similar to a decadal-scale La Niña, or negative PDO/IPO[61]. The observed strengthening of the trade winds led to increased heat uptake by the ocean through the wind-driven ocean circulation in the Pacific[62] (see Methods for details).

The global warming hiatus over the oceans to a large extent reflects a competition between the cooling effect of a strongly negative PDO, a slight warming (or cooling) effect of the AMO and the anthropogenic warming signal[63]. Depending on how the forced signal is accounted for, different studies come to different conclusions about the role of the AMO in the hiatus. Some studies find that the AMO decreased during the hiatus, or hiatus-like periods, and hence had a cooling rather than a warming effect on the global temperatures[64,65].

Several studies suggested that the hiatus could have persisted for another few years as a result of natural variability[66,67] such as a weakening of the decadal-scale North Atlantic Oscillation (NAO) and its delayed effect on North Atlantic SSTs[68], an expected cooling of the North Atlantic as the AMO was heading into a negative phase[69], or a persistent La Niña phase. In any case, this prolonged hiatus would eventually have ceased to exist, either because the warm water that was subducted through the shallow overturning cells would have eventually re-emerged and made its way back to the surface in the western Pacific[70], or as a result of an El Niño episode[71], as was the case in 2015. On the basis of a surface-wind-initialized forecast, 2015 was predicted to be the hottest year on record—which observations confirm—and to be followed by a period of accelerated warming compared to the previous decade, resulting in an end to the hiatus in this climate model experiment[72].

Transient climate response

Regarding definition (iii), one suggestion for the larger-than-observed temperature trend in the CMIP5 models during the hiatus was that their equilibrium climate sensitivity or transient climate response (TCR)—the magnitude of the temperature response to CO_2—was too high compared to values inferred from radiative forcing and observed warming[73]. This conclusion assumes that global feedbacks are constant over time and across forcing agents; however, these assumptions are probably too simple (see ref. 74 and Methods). In addition, the discrepancy between model-based and observational estimates might be due to an underestimate of TCR inferred from observations. Accounting for these factors largely reconciles the TCR estimates from CMIP5 and those inferred from observations (see Methods for details).

Reconciling models and observations

The ensemble mean of all CMIP5 models shows a larger warming trend than does the HadCRUT4 observational estimate (Fig. 5, light blue versus light orange lines; see Methods for description). Whether the observation-based trend is inconsistent with the CMIP5 range has been debated in the literature. An earlier study found that they were statistically significantly different[13], but this was later disputed by using linear trends in combination with a fixed intercept, which produce more robust trend estimates[40]. The multi-model mean represents the forced temperature response to radiative forcing and is therefore not expected to coincide with observations. Meanwhile, the observations (based on recent datasets) are within the spread of the models (blue shading), although at the low end[29] (Fig. 5). Consistency with the observed warming can never prove that the underlying forcings and feedbacks—such as those due to compensating biases, for example between climate sensitivity and aerosol forcing[75]—are correct, so the fact that the ensemble encompasses the observations provides support, but does not prove that the models are correct[76].

For the period after 2005, the forcing used in the CMIP5 models differs from the current best estimate of the forcing. Consequently, models are expected to diverge to some degree from observations[10,13,77,78]. The two main forcings that are missing or biased in the simulations are small but prolonged volcanic eruptions and solar forcing (see Methods). By accounting for updated forcing[28], the CMIP5 ensemble mean is closer to the observations[29] (Fig. 5, intermediate blue line).

The frequency of simulated hiatus periods of different durations, both when defined as zero trends and as trends that are smaller than the long-term global warming, is similar to that in the observations for the multi-model mean, but varies across models[79,80]. Consistency is expected if the natural variability of the climate system is the main cause of the hiatus, but not necessarily if the forcing is biased. If the forcing imposed on models is biased towards additional warming, while the natural internal variability stays the same, then the frequency of simulated hiatus periods would be lower than in the observations.

In contrast to initialized decadal climate predictions, we do not expect the natural variability in the climate model projections to be in phase with the observed variability[43]. Natural internal variability is difficult to estimate from observations owing to the short record and the underlying forced signal. For the CMIP5 models, we estimate it for different timescales from the preindustrial control simulations (see Extended Data Fig. 2a). These show a 5% probability for internal variability to completely mask a 15-yr forced trend (the same duration as the hiatus) of about 0.25 °C, but with a substantial range of 0.1–0.4 °C across models (see Extended Data Fig. 2c and ref. 66). This range includes the largest 15-yr trends from observations (Extended Data Fig. 2b).

The differences in decadal SST variability between models and observations are largest in the low latitudes, for which many CMIP5 models underestimate interdecadal internal variability[81]. The spatial pattern of the ensemble-mean surface temperatures looks similar to observations when defining a hiatus as a decadal period having a trend smaller than the long-term warming trend[79,80], but individual models differ. Likewise, the simulated relationship between surface temperature and ocean heat storage during hiatus periods varies in the models. Some models show deep ocean heat uptake associated with a negative phase of the PDO during hiatus periods, whereas other models show a surface response in only the Southern Ocean and no marked increase in deep-ocean heat uptake during such periods[66].

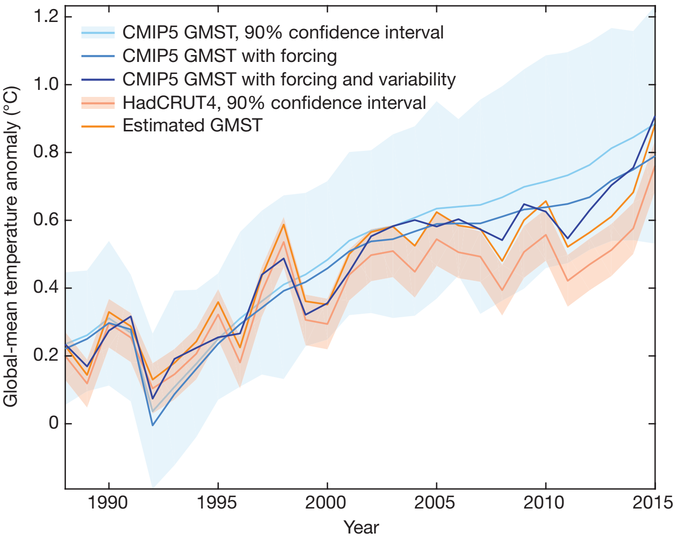

Figure 5 | Reconciling observed and modelled temperatures. Ensemble-mean global-mean surface air temperatures (GMSTs) taken from 84 simulations by 36 CMIP5 models (historical plus Representative Concentration Pathway (RCP) 8.5 after 2005) is shown (light blue line) with the 90% confidence interval (shading). The CMIP5 ensemble mean when adjusted with updated forcings (see text; intermediate blue line), and with updated forcings and corrected for Pacific variability using the analogue method described in Methods (dark blue line), are also shown. The observed surface air temperature in HadCRUT4 is shown as the light orange line, together with the 90% confidence interval (shading). The uncertainty is based on a 100-member ensemble of the HadCRUT4 dataset. The estimated true GMST based on HadCRUT4, but accounting for incomplete coverage and adjusted for blending of surface air temperature with sea surface temperature (SST) from the CMIP5 models, is shown as the dark orange line. The values are given relative to the mean of 1961–1990.

Taking into account the updated forcing from ref. 28 and the state of the internal variability by matching segments of observed with modelled unforced climate variability in the Pacific (see Methods) results in a similar variability in the CMIP5 ensemble mean and in observations[28,29] (Fig. 5, dark blue versus light orange lines).

Previous studies have shown that when also taking into account the state of the natural variability, the modelled results are closer to both the trend and the variability in the observations[43,60,61,82,83]. The remaining discrepancy, after accounting for internal variability and incorrect forcing, is eliminated when additionally taking into account an incomplete observational spatial coverage and the effect of blending SSTs with air temperatures in the observations[84] (Fig. 5, dark orange line). We estimate this effect from the models and add it to the observations to obtain an estimate of how much warming a truly global air temperature network would have experienced. Doing so increases the warming trend in the observational time series, resulting in excellent agreement between models and observations (Fig. 5, dark blue versus dark orange lines).

Most discrepancies between models and observations can therefore be explained by the state of the natural variability[43,60,61], incomplete or biased forcings[29,85], and observational limitations[36,84]; a complete explanation requires a combination of all of these[28,29] (Fig. 5). When the effects of short-term temperature variations such as the El Niño Southern Oscillation (ENSO), of volcanic aerosols and of solar variability are removed, the anthropogenically forced global warming signal has not decreased substantially[8,86]. This supports the current scientific understanding that long-term global warming is extremely likely to be of anthropogenic origin.

The controversy surrounding the global warming hiatus is reminiscent of the scientific discussion on an earlier phenomenon, the "moratorium"[87], which occurred between the 1940s and 1970s. A study from 1993 states, "[…] plotted from the year 1900 to present, there seems to be an increasing trend which apparently disappears between 1940 and 1970. This deviation from the expected trend has been the focus of debate for many years"[88]. Then, as now, the deep ocean was proposed to store the heat[18,87,88]. It was already recognized in 1959[89] that the ocean could store large amounts of heat in the subsurface, but that this would be only temporary[90], although other factors such as aerosol forcing probably played a part[91] in the halted warming.

Conclusions and implications

The hiatus no doubt was, and still is, an exciting opportunity to learn for many research fields. Social sciences might find this an interesting period for studying how science interacts with the public, media and policy. In a time coinciding with high-level political negotiations on preventing climate change, sceptical media and politicians were using the apparent lack of warming to downplay the importance of climate change. It is easy to paint a controversial picture, but as often the devil is in the detail. A few years of additional data are unlikely to overturn the vast body of evidence that supports anthropogenic climate change. But science requires time to analyse, test hypotheses and publish results, and engaging in fast-paced communication is challenging for scientists in such situations. This will not be the last time that weather and climate will surprise us, so maybe there are lessons to be learned from the hiatus about communication on all sides.

From a climate point of view, with 2015 and 2016 being the two warmest years on record, the question of whether "global warming has stopped" that climate scientists had been facing for many years in the public has largely disappeared. Whether there was a hiatus or slowdown at some point is still debated, with some arguing strongly for it[25,31] and others saying it lacks scientific basis[30,36,37,39]. The conclusions unsurprisingly depend on the time period considered, the dataset and the hypothesis tested, so the diverging conclusions do not need to be inconsistent.

Natural climate variability has long been known to be important for short-term trends[18,89,90], but the observed temperature during the hiatus differed enough from that projected by climate models to challenge at least some elements of the scientific basis for anthropogenic climate change (for example, how sensitive the climate system is to an increase in CO_2; see Methods section 'Transient climate response'). As a consequence, after a surge of scientific studies on the topic (see Fig. 1), we have learned more about the ways in which the climate system works in several areas.

Uncertainties in observational records continue to be a challenge. Even for surface temperature, the lack of data and the combination of data from different instruments is non-trivial[36]. For ocean data, the combined uncertainties from instrument calibration and limited sampling (in particular in the early decades) are even larger[92,93]. As a consequence, reconciling models and observations (Fig. 5) requires that the user understands the strengths, weaknesses and uncertainties in the datasets, and the differences between them. There are other instances where observations were as much a limiting factor as the climate models[94], and methods to compare models and observations continue to be challenging.

The other limiting factor for both the comparison of models and observations and for projections is that natural temperature variability is large on interannual to decadal timescales[7]. Although some studies have highlighted that[95,96], long-term projections were mostly presented as model averages with little variability. Decadal prediction might address some of the variability aspects, but their interpretation remains challenging[97]. The hiatus and the extreme El Niño events of 1998 and 2015 are now useful test beds for hindcasts. The relevance of variability to the hiatus was mentioned in a few early studies[4,6], but by 2013 it had become unlikely that variability would be the only explanation, as shown in Fig. 5. But, importantly, selecting only CMIP5 models that capture the global warming hiatus at the right time does not quantitatively change projections for the end of the twenty-first century[98], indicating that the hiatus has not changed our projections of the overall magnitude of climate change or the emission reductions that are required to address it.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

Estimating global temperature. To estimate the spatial distribution of temperatures, thousands of surface observations are taken around the world each day. These observations come from land-based weather stations, ships, buoys, and different types of autonomous observing systems. The surface temperature is used as the climate indicator of interest on the basis of a trade-off between integrated information and having records far back in time of a quantity that is accessible. However, the global-average surface temperature anomaly is still not straightforward to compute or interpret, owing to incomplete spatial and temporal coverage, different instruments causing inhomogeneities in the temperature record[99], urban heat islands[100], and different measuring methods that are assumed to give the same result being combined[101,102].

Differences across datasets. The estimated global temperature trend is sensitive to whether or not, and how, the lack of full observational coverage is accounted for. HadCRUT3[2] and HadCRUT4[103] do not include any spatial infilling of these regions, whereas NOAA[36], BEST[104], Cowtan & Way[35], and GISTEMP[38] do. Through spatial infilling of under sampled regions in HadCRUT4 (Extended Data Fig. 4), the hiatus trend gets closer to the long-term warming trend[35,36,105]. Also, when going the other way and comparing GISTEMP with HadCRUT3 using the spatial coverage from the latter, the GISTEMP trend is reduced and the trends in the two datasets are similar[38].

The observational datasets combine different land air and sea surface temperature estimates, which are produced using different assumptions and methods to correct for the aforementioned issues mentioned and form the basis of the uncertainties associated with the dataset[106–111]. By adjusting for a systematic difference between buoy data and ship-based temperatures and adjusting the ship data for changes in measuring methods, the observed warming trend between 1998 and 2014 increases in the dataset of ref. 36 and is significant ($P < 0.1\%$)[37]. Whether the trend over the hiatus differs from the long-term warming trend depends on the chosen periods for the pre-hiatus and the hiatus itself, because especially short-term trends are highly sensitive to adding or removing single years, or shifting the period slightly[40] (Extended Data Fig. 1).

Modes of variability. Global temperatures do not rise continuously with increasing greenhouse gas emissions to the atmosphere[112,113]. Shifts in global temperatures have occurred several times within the last century[114]. On relatively short timescales, natural variability can be larger than the global warming over the same period[115–118]. This is why a 30-yr average is often used as a baseline in climate science. Several hiatus-like periods of varying duration are found in models and observations for the historical record[4,9,79,80,119–121], so this hiatus period is not unique.

The dominant mode of variability affecting GMST on interannual timescales is the El Niño Southern Oscillation (ENSO). The average SST anomaly in the Niño3.4 region (5° N–5° S, 120°–170° W) is often used as an index for that variability pattern. The cold temperature anomalies of the La Niña events observed during the hiatus project onto the global temperatures and hence are key to the global warming hiatus[9,61,63,122]. By prescribing observed SSTs in the central and eastern tropical Pacific in a climate model, the seasonal and regional characteristics of the hiatus are largely reproduced[61].

On longer timescales, the ocean variability is also important. The PDO is commonly defined as the leading mode of North Pacific monthly SST variability limited by 20° N and 70° N, and 110° W and 100° E, with the global-mean SST removed[46]. The decadal-scale variability arises from a combination of ocean memory, air–sea interaction relating to the Aleutian low, and decadal changes in ocean circulation[123]. The spatial pattern consists of a horseshoe-shaped positive anomaly in the east and a negative anomaly in the central and western part in a positive phase (Fig. 4d). The PDO is highly correlated with the IPO[124], the decadal-scale ENSO component, which is the Pacific-wide manifestation of the pattern. Whereas on interannual timescales the temperature fluctuations arise from interactions with the Aleutian low in the atmosphere, variability on decadal timescales is due to air–sea heat fluxes and to changes in the North Pacific gyre circulation[125].

Another prominent mode of long term variability is the Atlantic Multidecadal Oscillation (AMO). AMO-like variability with a period of around 60–80 yr in North Atlantic SSTs is found in instrumental records, model studies and in palaeo proxies dating back to before the industrialization[126–130]. This indicates that these variations may be internal to the climate system, and not externally forced. But the phasing of the variability might still be influenced by external forcing and volcanic aerosols[131,132]. Some studies suggest that internal variability is not needed to explain the AMO variations over the past decades, and aerosols are suggested to explain a large part of the observed North Atlantic SST variability since 1860[133], but this has been disputed[134]. The AMO is mainly defined as the low-pass-filtered, basin-wide, area-averaged SST anomaly over 0°–60° N, 75°–7.5° W (ref. 135). For the historical record, a linear trend is normally subtracted to remove the global warming signal[136]. However, this approach has been questioned because there is no reason why the forced signal should be linear, and so could cause artefacts in the data when trying to attribute changes in climate due to different states of the natural variability[137,138].

Changes in the AMO are mainly assumed to be driven by large-scale changes in the Atlantic Meridional Overturning Circulation (AMOC) (see, for example, refs 139, 140 and references therein), where a stronger-than-normal AMOC is associated with warmer North Atlantic SSTs. Historical simulations seem to disagree on the relationship between the two variables[141,142], but better agreement between models is obtained when accounting for the effect of external forcing[143]. For a stronger-than-normal AMOC, North Atlantic surface temperatures increase, but the total heat storage in the North Atlantic decreases[144]. For reduced deep or bottom water formation in the North Atlantic or Southern oceans, respectively, less heat is lost from the surface ocean to the atmosphere through air–sea fluxes, which would imply warmer water sinking and leaving a positive heat anomaly at depth[9].

Radiative forcing. Since 1987 the solar forcing has resulted in a slight cooling of the GMST[145]. Solar cycle 23, lasting from 1996 to 2008, was unusual compared to previous cycles in the observational record: it lasted longer and the minimum was the lowest since 1924[146]. The peak of solar cycle 24 (in 2014) was also far lower than previous maxima[147]. This probably contributed a small part to the hiatus[5,28,29,122,145].

Another potential factor is tropospheric aerosols concentrations, which increased during the late 1990s and early 2000s as a result of the rapid growth of short-lived tropospheric sulfur dioxide emissions. These emissions came mostly from coal combustions in Asia, and they partly compensated for the greenhouse gas warming during the hiatus[10]. At the same time, the sulfur dioxide emissions in the rest of the world decreased. The combined tropospheric aerosol forcing, acting mainly through indirect aerosol effects, was nearly zero, with positive and negative contributions cancelling globally[148–151]. If accounting for the effects of black carbon, then the net tropospheric aerosol effect potentially contributed to a warming[152]. Black carbon may further affect clouds, an effect that could be amplified by a feedback from SSTs on clouds[153]. However, the effect of clouds on the observed variations in global-mean surface temperature is small[154]. The estimated magnitude of the total tropospheric aerosol contribution to the hiatus varies across studies, because the estimates are dependent on the model used, on the aerosol species considered and on whether indirect aerosol effects are accounted for. However, with updated emissions for the period 1990–2015, models show that aerosols, black carbon and ozone together had a net warming effect on the global surface temperatures, although large uncertainties remain[155].

In addition to tropospheric aerosols, the volcanic aerosol content in the lower stratosphere increased by around 4%–10% per year between 2000 and 2009, even though there were no major eruptions[156,157]. Moderate, but relatively frequent, eruptions in the tropics[158] lead to an increase in stratospheric aerosols. These spread out to higher latitudes[157] and contributed to more solar radiation being reflected back to space and hence to a surface cooling[159]. This is not taken into account in most climate model simulations; instead, a near-zero stratospheric aerosol content is usually assumed after year 2000[160–163].

Along with increased stratospheric aerosol concentrations, water vapour concentrations in the stratosphere decreased abruptly between 2000 and 2004[164,165]. An intermediate complexity model suggests that this decrease could reduce the total radiative forcing and contribute a small amount to the hiatus over this period[164]. In a more complex model with prescribed stratospheric water vapour, this effect does not exceed natural variability[165]. However, the stratospheric water vapour content is very variable, and increased again between 2005 and 2011[165,166]. In addition, the overall contribution of stratospheric water vapour to the hiatus is reduced when including data until 2013[167]. In a statistical model, no statistically significant effect of stratospheric water vapour on surface temperature was found[10]. In most global climate models, this effect is not accounted for, owing to the limited vertical resolution of the stratosphere.

Transient climate response. In some studies, models show a TCR that is indeed inconsistent with observational estimates, or the observational estimates are located at the low end of the model range[168–171]. Recent work, however, points to limitations in simple energy-balance models that assume a single constant feedback (see ref. 74 for a review). Feedbacks change over time[74,153,172] and may differ for different forcing agents[173]. Accounting for this partly closes the gap between climate sensitivity or TCR estimates from energy budget considerations (that do not account for inhomogeneous forcing distributions) and from global climate models[174,175].

Discrepancies between observations and models also arise from an underestimation of the TCR determined from the observed warming. Reasons for this underestimation include observed temperature biases resulting from limited coverage[35] and from blending SSTs rather than air temperature over the oceans with air temperatures over land[84,176], the forcing efficacies used (the combined effect of forcings is larger than the sum of the effect of individual forcings)[174,177,178], overestimated and underestimated forcing[29,179], and how efficient the ocean heat uptake is in models[180–183]. Other studies do not find evidence for overestimated climate sensitivity or TCR in the models when natural variability and updated forcings are taken into account[28,115,122,176,179].

Surface wind changes. The Pacific SST anomalies during the hiatus are responding to an increased seasonal cycle in the zonal winds, producing an enhanced seasonal cycle in the surface currents and hence zonal temperature advection. The Pacific cooling trend is most pronounced from December to May, owing to upwelling of cold subsurface water[184,185], which occurs when the climatological easterly winds are strongest. During the other months, there is only a weak cooling or a slight warming trend[184].

The Northern Hemisphere mid-latitude cold land anomalies are connected to a negative North Atlantic Oscillation (NAO) or Arctic Oscillation in the 2000s[11,27,105] or to a weakened stratospheric polar vortex[186]. For the other seasons, the land surface temperatures continue to warm[11,42,187,188].

The land and ocean hiatus may be physically connected. The negative latent heat anomaly that occurred as a result of a shift in the central tropical Pacific rainfall during a negative PDO phase caused an upper tropospheric wave pattern, resulting in increased likelihood of cold winters over North America and Europe[33].

The surface winds in the Pacific increased during the hiatus and sustained the longer-term cold anomaly in the Pacific Ocean[62]. This is consistent with the increased Walker circulation during the period. The increased wind is a robust feature across several different observational datasets and reanalysis products, in addition to global atmospheric model integrations forced by observed SSTs[189,190]. The magnitude of the increasing trend in the strength of the Pacific trade winds is larger than in any global climate model[62,191]; however, the models suggest that trade winds are stronger during hiatus-like periods than during non-hiatus-like periods[9,80]. By prescribing the anomalous surface winds in the tropical Pacific[70,73,189,192], or by running ocean hindcasts forced with atmospheric reanalysis[193], the decreased surface temperatures and the observed prolonged drought over North America can both be explained. However, some studies find that not everything about the spatial pattern can be explained by this[73,185].

The intensified winds might be partly driven by changes in other basins, such as temperature variations in the Indian Ocean[194,195] and a warmer Atlantic[196–201]. The intensification of the Pacific trade winds is suggested to be a response to warming in the Atlantic causing the pressure systems to be displaced, and hence changing the Walker circulation[198]. This causes an upward motion of air over the whole tropical Atlantic, leaving a negative sea-level pressure trend, and a descending motion over the equatorial Pacific from the central to the eastern part, giving a surface high-pressure trend. In addition, the Pacific SST trend feeds back on the temperatures in the North Atlantic Ocean. Warmer-than-normal temperatures in the Indian Ocean are also suggested to strengthen the easterly winds in the western equatorial Pacific[194]. This warming also induces easterly anomalies in the North Pacific, contributing to the strengthening of the shallow overturning cells in the western Pacific. Alternatively, a shift in the anthropogenic aerosol loading from the USA and Europe to Asia is also suggested to have contributed to a weakening of the Aleutian low, and hence to changes in the PDO and Walker circulation[202].

The observed strengthening of the trade winds led to increased ocean heat uptake through the wind-driven ocean circulation in the Pacific[9,47,56,62] and in the tropical Atlantic[9]. The winds drive an increase in equatorial upwelling from below the thermocline in the eastern and central parts of the basin, cooling the surface, and cause a convergence of the warm water in the west. This pushes the thermocline deeper[192]. The warm water spreads out in the west and sets up shallow overturning cells towards the subtropics in both hemispheres, where the warm water is subducted. This subduction leads to increased ocean heat storage below the surface[62,203]. This is the same mechanism proposed for the seasonal signal[184], indicating that December–May dominates the trends in the annual analysis.

Closing the energy budget. Closing the energy budget of the climate system has proved to be difficult, at least during the hiatus[204], even though it was done for the preceding period[205].

The absolute energy imbalance at the top of the atmosphere (TOA) cannot be measured directly by satellite instruments[206]. However, the relative energy imbalance can be inferred by referencing the satellite observations to other observations, by estimating the imbalance using climate models constrained by observations, or through calculated changes of inventory in the different parts of the climate system. Although estimates differ for the various sub-periods of the hiatus, from the radiative balance at the TOA, more heat has entered than has left during the hiatus. The estimated imbalance ranges from $0.07\,\mathrm{W\,m^{-2}}$ to $1.57\,\mathrm{W\,m^{-2}}$, with the most likely value around 0.75–$0.93\,\mathrm{W\,m^{-2}}$, where all of the estimates overlap (Extended Data Fig. 3a).

Before the full deployment of Argo-floats from 2005, ocean heat content calculations are reliant on sparse and unevenly spaced observations. This results in higher uncertainty in how much heat was taken up by the ocean in the first part of the hiatus. For the latter part, however, temperatures in nearly the whole global subsurface ocean are well sampled down to 2,000 m (ref. 54), giving more confidence in the values. This still leaves around 50% of the total ocean volume poorly sampled. The main differences in ocean heat content estimates come from quality control of input data, treatment of uncertainties, gaps and differences in the observations, and spatial interpolation when calculating volume-weighted averages. Also, air–sea heat flux products estimating the net heat flux into the ocean during the hiatus period differ widely in magnitude[207].

Several studies have pointed to an error in the early Argo-float data and in the Expendable Bathythermograph (XBT) data, which prevailed in the data before, as the reason for not being able to close the energy budget[54,85]. In a revised energy budget of the climate system, it was found[208] that the rate of ocean heat uptake during the hiatus does not necessarily have to be larger than otherwise. The TOA radiation and ocean heat uptake reacts differently depending on whether the changes come from greenhouse gas warming or from natural variability. The TOA radiation is a response in the natural variability (for example, increased radiation back to space as a result of higher surface temperatures) whereas it is a driver in the greenhouse warming case (increased surface temperatures as a response to increased trapping of radiation).

After an initial decrease in connection to the 1997/1998 El Niño[47,56], the total ocean heat content from ocean reanalysis increased by 0.69–$0.93\,\mathrm{W\,m^{-2}}$ between 1992 and 2010[47,209] when adjusted to the total surface of Earth (Extended Data Fig. 3b). About 60%–85% of this occurred below the surface layer in the upper 700 m (refs 47, 93, 210–212) and the remaining in the deep ocean below 700 m. The negative heat content anomalies in the upper 100 m were largely cancelled by a positive anomaly in layers below (down to around 300–500 m)[192,213,214]. The deep ocean below 1,500–2,000 m did not contribute considerably to the sea-level rise in the period 2003–2012, indicating little change in heat storage at this depth[215,216]. However, contributions to sea-level changes from the layer between 700 m and 1,500 m are found. This indicates that this intermediate layer has warmed, thus suggesting that heat is sequestered in the intermediate ocean.

During the period 1993–2012, the upper 700 m of the global ocean warmed by 0.16–$0.74\,\mathrm{W\,m^{-2}}$ when adjusted for the total surface of Earth[54,85,92,217–220], with a larger range during the period 1993–2008 (0.25–$0.74\,\mathrm{W\,m^{-2}}$) than during 2005–2012 (0.16–$0.39\,\mathrm{W\,m^{-2}}$) (Extended Data Fig. 3b, brown shading). In the 300–1,500-m depth range, the accumulated heat was 0.69×10^{23} J (about $0.31\,\mathrm{W\,m^{-2}}$ when adjusted for the total surface of Earth) during the period 1999–2012[71]. The estimates of the change in heat content in the upper 2,000 m range from $0.2\,\mathrm{W\,m^{-2}}$ to $1.0\,\mathrm{W\,m^{-2}}$ (refs 53, 54, 85, 213, 214, 219; Extended Data Fig. 3b, blue shading), with a slight contribution of 0.018–$0.036\,\mathrm{W\,m^{-2}}$ from the abyss, below 4,000 m, for the period 2005–2010[221] (Extended Data Fig. 3b, grey shading).

Owing to the general lack of observations of the subsurface for an extended period, most of the studies that suggest that the heat has been stored in different parts of the depth column come from model data, with differing conclusions about which part of the column warms and cools. This indicates that the mechanisms following the increased wind stress on the surface ocean or changes in air–sea fluxes contributing to the deep convections are model dependent, but also ocean-basin dependent[203]. Some model studies suggest that the heat is stored in the upper ocean, but below the surface mixed layer (below about 100–300 m), and some find that the heat is stored in the deep ocean (700–2,000 m or 700–3,000 m). Ocean reanalysis constrained by observations are free to evolve where there are no observations—that is, in the deep ocean. The various reanalysis products produce different heating and cooling signals in the deep even though the same data has been used in the assimilation of observations in the products[222].

The Pacific and Indian oceans warmed below 700 m (refs 47, 56, 223). Heat was transported in the subsurface through the Indonesian Throughflow from the Pacific to the Indian Ocean, which acted as a heat storage during the hiatus period[212,222,224]. This is also supported by satellite observations of sea surface height[225]. It was found[222,224] that the cooling in the top 100 m of the Pacific Ocean since 2003 was mainly compensated by warming in the 100–300-m-deep layer of the Indian and Pacific oceans, and that the Southern Ocean plays a secondary part, with a warming between 100 m and 300 m. Using *in situ* data, it was found[212] that 70% of the global heat anomaly in the upper 700 m could be accounted for by the changes in the Indian Ocean between 2003 and 2012. It is not necessarily a contradiction that some find that the heat has accumulated in the Pacific Ocean and others the Indian Ocean, owing to heat transport between the basins.

Even though the SSTs in the North Atlantic and the Southern oceans do not reflect a hiatus, these regions contribute to storing the excess heat. A positive heat anomaly is found down to below 700 m (ref. 27), whereas for at least the north-eastern Atlantic others find a decrease in the upper-ocean heat content (0–450 m) and a warming below (1,000–3,000 m)[226]. Yet others find that only the Southern Ocean (during the period 1993–2008) shows increased heat content at these depths

(1,000–4,000 m)[221]. Around 75%–99% of the global 0–2,000-m-depth warming for the Argo period (2006–2015) is found in the Southern Hemisphere, predominately between 30° S and 50° S (ref. 227). Increased heat content is sequestered in the deep ocean owing to a weakened deep convection; hence, less cold water is produced by decreasing the heat loss to the atmosphere[9,71,193,203,223]. By relating sea-level observations with ocean circulation and heat transport, the upper North Atlantic Ocean (down to around 1,000 m) is found to accumulate heat during the hiatus[228]. Others find that increased heat uptake in the deep North Atlantic and Southern Ocean, in the Antarctic Circumpolar Current, was initiated by a salinity anomaly in the subpolar North Atlantic[71]. The ocean heat content anomaly first occurred in the North Atlantic below 700 m at the end of the previous century. This was related to a weakening of the AMOC[71]. This slowdown may also have resulted in a slight contribution from the Atlantic to the global surface warming trend in the period 2000–2006[47,56]. And yet others suggest that the subpolar gyres in the Southern Hemisphere determine the heat uptake through subduction of heat by the mean circulation and a wind-induced strengthening of the South Pacific gyre[213].

The relative contribution from the different basins varies in different studies. In a modelling study, the tropical Atlantic and Pacific oceans dominate the anomalous heat storage, with a slightly smaller contribution by the North Atlantic[211]. In an ensemble of the CMIP5 models, the heat anomaly in the Pacific is almost double that of the Atlantic for the upper 700 m for hiatus-like periods[80]. Using *in situ* data, the anomalous heat during 1999 and 2012 was found in the Atlantic and in the Southern Ocean, where each contributed slightly less than half of the global value below 300 m (ref. 71). Historical observational estimates probably underestimate the Southern Ocean contribution, owing to data sparseness and the infilling methods used to fill in the missing data[229].

From all of these studies it is not possible to determine exactly where the heat went, but it seems likely that there was a redistribution of heat[31], and that the ocean warmed during the hiatus[59].

Reconciling observed and modelled temperature trends. To reconcile the observed and modelled global air temperature trends during the hiatus, we start with the full suite of CMIP5 climate models (36 models and 84 simulations) using the RCP8.5 forcing scenario from 2006 onwards. The observed HadCRUT4 temperature increase falls at the lower end of modelled CMIP5 (Fig. 5). There are, however, several factors that hinder the direct comparison of simulated and observed temperatures, which need to be accounted for.

First, we update the modelled response to solar and stratospheric radiative forcing with estimates until 2012 from ref. 28. Here we use the solar-radiation correction from the Physikalisch–Meterologisches Observatorium Davos (PMOD), which is assumed to be the most accurate[230]. For the years from 2013 until 2015, we repeat the forcing correction of year 2012. This leads to a reduction in the simulated warming during the past two decades. A similar result is obtained with the forcing adjustment from ref. 29. Internal variability is averaged out in the multi-model mean, but variability, especially in the Pacific, played a key part in modulating air temperatures during the hiatus. We search within 35 CMIP5 pre-industrial control integrations, one from each model (consisting of more than 19,000 model years in total), for variability analogues for which the simulated and observed variability in the Pacific agrees best (this method was introduced in ref. 28). We select the 40 closest analogues, determined through the root-mean-square difference between observed and modelled variability, for each overlapping 6-yr-long period. We describe the Pacific wide variability with the IPO index of ref. 124. With these variability analogues, we estimate the imprint of Pacific variability on global air temperatures and update the CMIP5 ensemble accordingly. The year-to-year variability of the CMIP5 ensemble and of HadCRUT4 then agrees much better.

There is evidence that HadCRUT4 underestimates the twentieth-century global near-surface air temperature increase, first because the observed regions are not representative of unobserved regions, but slower-warming regions are overrepresented[35,36], and second because sea water instead of air temperatures are used over open oceans (this is the case for all of the observational time series). The sea water tends to warm more slowly than the air temperature above in climate models and reanalyses[84,231,232]. Observational inhomogeneities and diurnal range effects impede detecting such an effect in the observational records[84]. We assume that the models correctly capture the residual warming between sea water and air temperatures above and the warming in regions with missing observations. To account for these two effects, we use data from ref. 84, in which the temperature increase of the CMIP5 multi-model mean is calculated once with global coverage and with air temperatures everywhere and once by emulating the HadCRUT4 methodology and coverage exactly. The effects of blending and coverage depend on whether they are estimated in re-analysis, observations or models, and open questions about the details remain[84]. By adding this difference to HadCRUT4 we obtain a new dataset with increased warming that is more representative of the true global-mean warming.

An apples-to-apples comparison between observed and modelled temperatures now shows very close agreement, further reinforcing that there is no systematic disagreement and that the models do not overestimate the TCR.

Data availability. The data used in this study were provided by Berkley Earth (http://berkeleyearth.lbl.gov/auto/Global/Land_and_Ocean_complete.txt), the Climatic Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/cru/data/temperature/HadCRUT4-gl.dat), the NOAA National Centers for Environmental Information, Climate at a Glance: Global Time Series (http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/p12/12/1880-2016.csv), Cowtan & Way (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/had4_krig_v2_0_0.txt), and the GISTEMP Team, 2016: GISS Surface Temperature Analysis (GISTEMP), NASA Goddard Institute for Space Studies (http://data.giss.nasa.gov/gistemp/).

The climate indices for Nino3.4, PDO and AMO were downloaded from NOAA ESRL (http://www.esrl.noaa.gov/psd/data/climateindices/list/) the and Kaplan SST V2 data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/).

CMIP5 GMST data emulated to match the HadCRUT4 methodology was provided by K. Cowtan and M. Richardson, and downloaded from http://www-users.york.ac.uk/~kdc3/papers/reconciled2016/methods.html.

All datasets were accessed on 18 January 2017.

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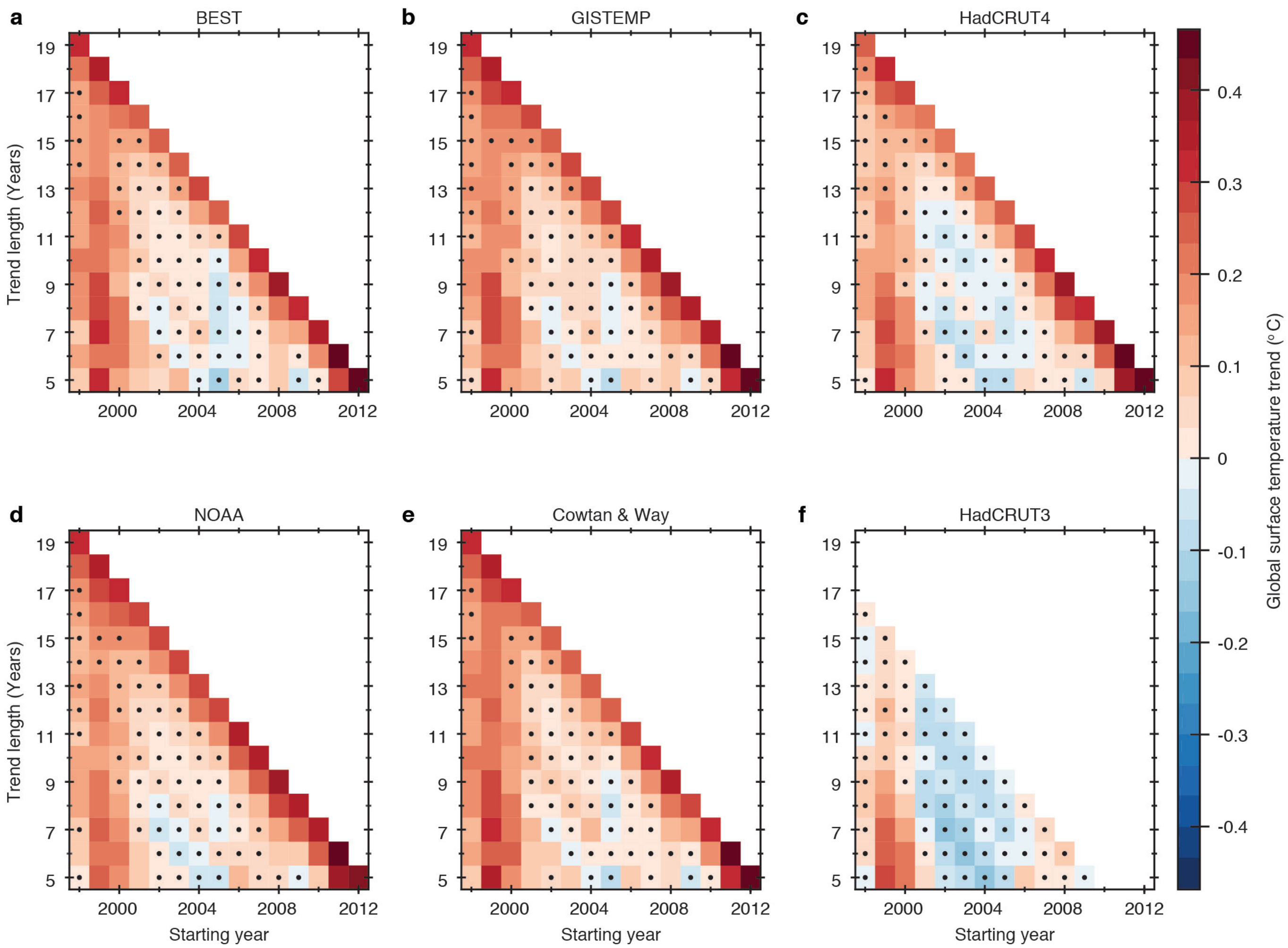
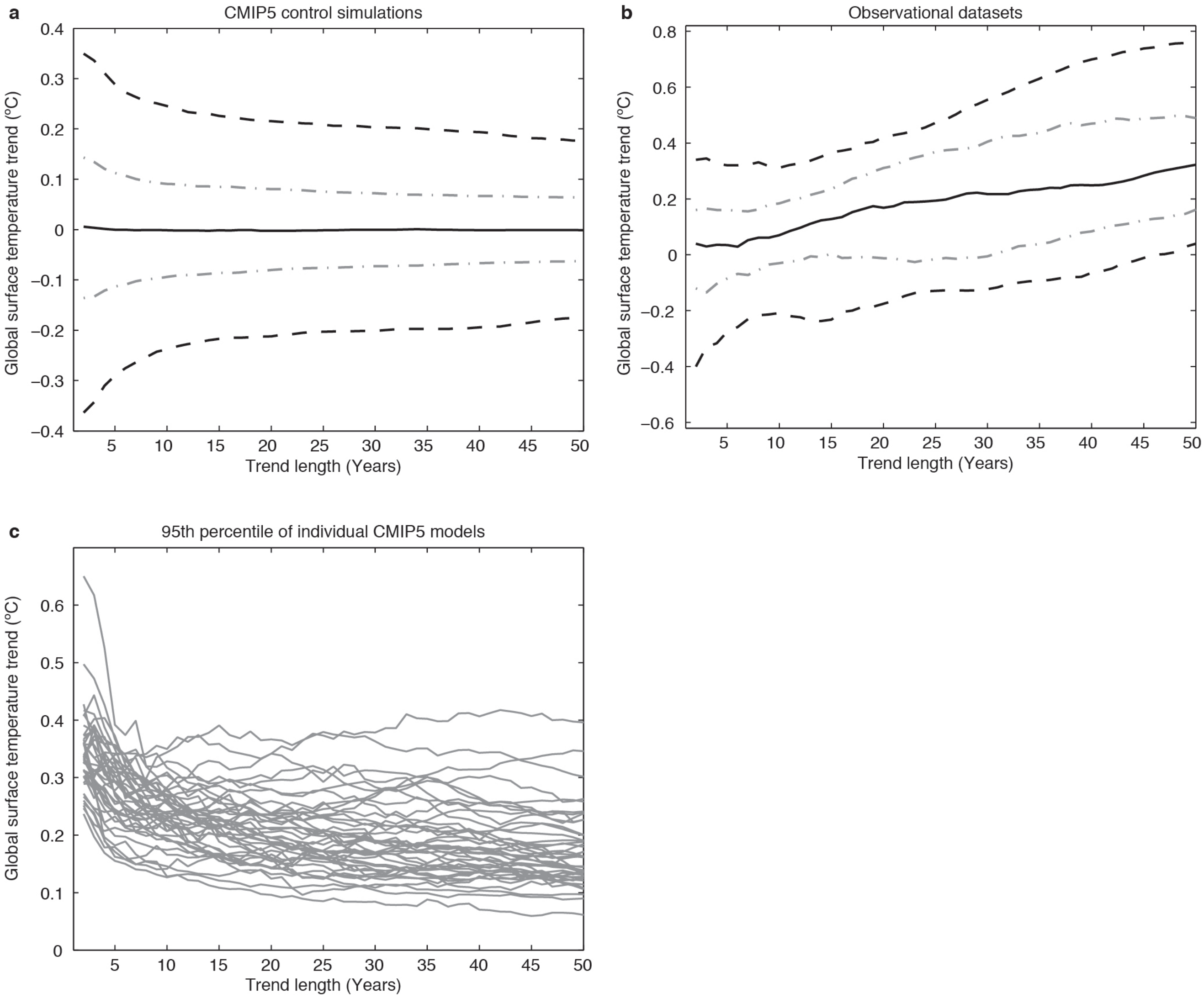
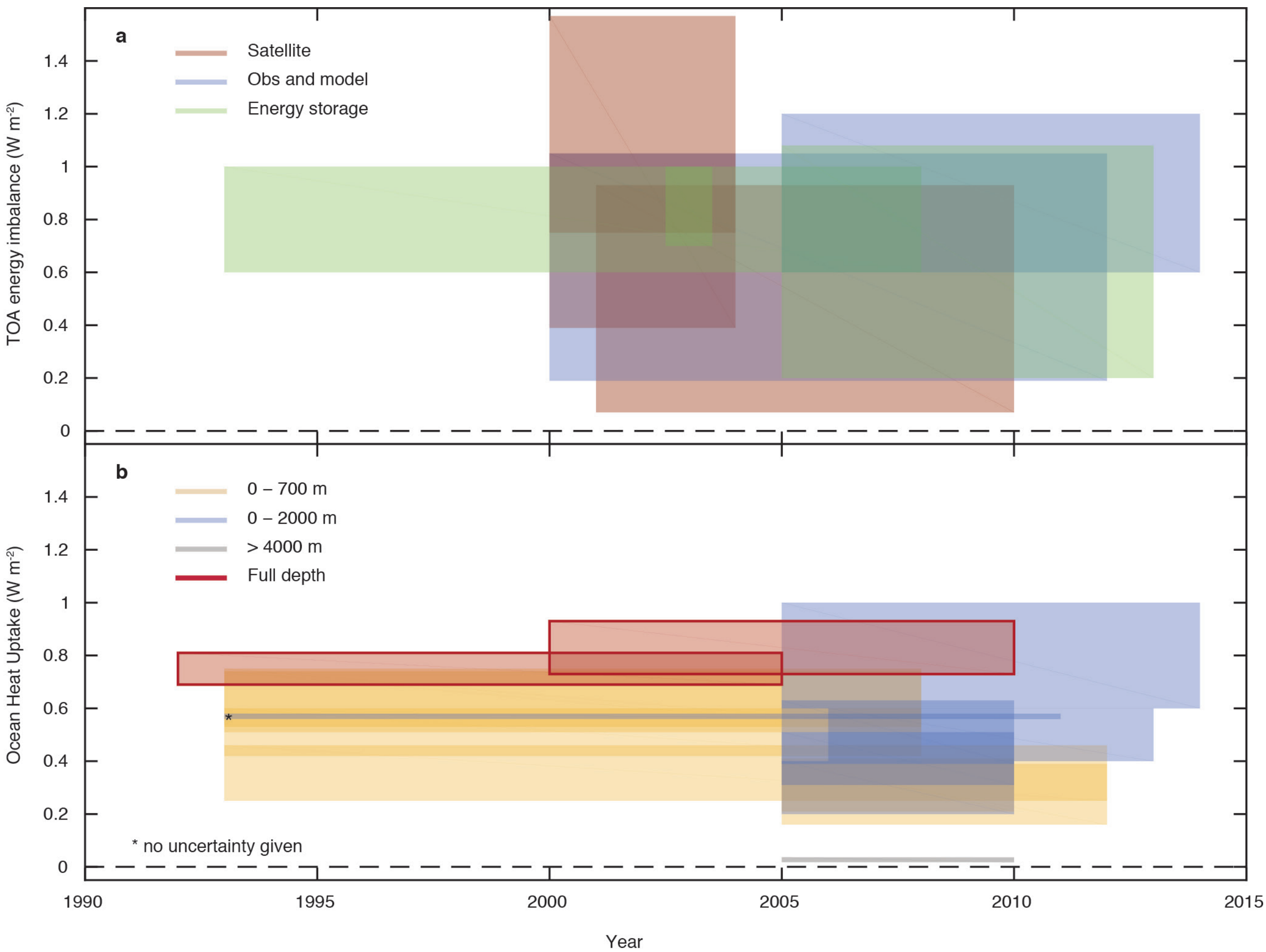


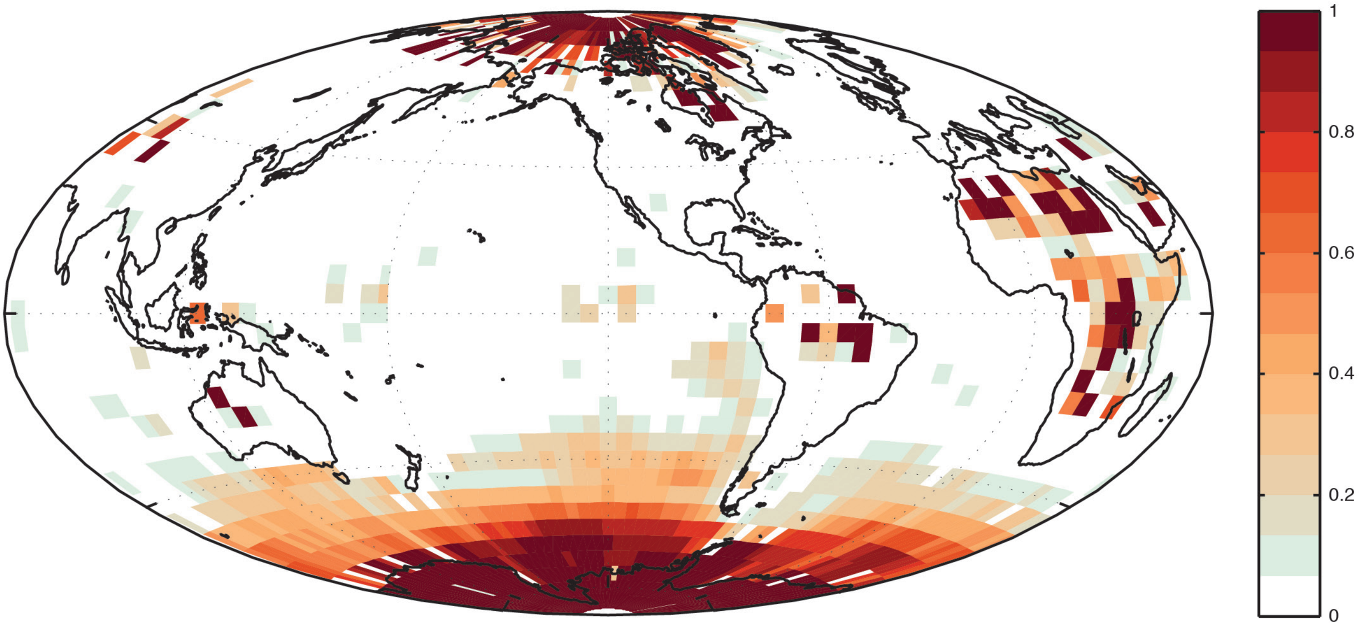
Extended Data Figure 1 | Global-mean temperature trends from observations. a–f, Linear temperature trends for the duration given on the *y* axis calculated from BEST (**a**), GISTEMP (**b**), HadCRUT4 (**c**), NOAA (**d**), Cowtan & Way (**e**) and HadCRUT3 (**f**). The starting year of the trend is indicated on the *x* axis. Dots indicate a trend in the individual datasets that is smaller than the long-term trend for the period 1951–2012.



Extended Data Figure 2 | Global-mean temperature trends. a, **b**, Global surface temperature trends of different durations from 42 CMIP5 models using all years in the piControl simulation (**a**) and of the observations starting in any year after 1880 using 5 observational datasets (**b**). The lines indicate, from bottom to top, the 5th, 25th, 50th, 75th and 95th percentiles. **c**, The 95th percentile of the individual CMIP5 models.



Extended Data Figure 3 | Energy imbalance and ocean heat uptake. **a**, Top of atmosphere (TOA) energy imbalance estimates based on satellite measurements (red shading), observations constrained by climate models (blue) and a sum of energy storage in different components of the climate system (green) for various sub-periods of the hiatus. The values are taken from refs 85, 177, 214 and 233–235. **b**, Ocean heat uptake (OHU) estimates for sub-periods of the hiatus for the depth range 0–700 m (yellow), 0–2,000 m (blue), >4,000 m (grey) and for the full depth range (red). The estimates are taken from refs 27, 47, 53, 85, 92, 209, 213, 214 and 217–221, with updated values from ref. 54. Zero imbalance is shown as the dashed black line. All values are given in W m^{-2} when adjusted for the total surface of Earth.



Extended Data Figure 4 | Fraction of missing data in the HadCRUT4 dataset. The colour scale shows the fraction of months for which there is missing surface temperature data in the HadCRUT4 dataset for the period 1998–2012.