

# *Making sense of the early-2000s warming slowdown*

Article

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1 **Making sense of the early-2000s global warming**  
2 **slowdown**

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

27 A large body of scientific evidence – amassed before and since the Fifth  
28 Assessment Report of the Intergovernmental Panel on Climate Change (IPCC  
29 AR5)<sup>1</sup> – indicates that the so-called surface warming “slowdown”, also  
30 sometimes referred to in the literature as the “hiatus”, was due to the combined  
31 effects of internal decadal variability and natural forcing (volcanic and solar)

32 superimposed on human-caused warming<sup>2</sup>. Given the intense political and public  
33 scrutiny that global climate change now receives, it has been imperative for  
34 scientists to provide a timely explanation of the warming slowdown, and to place  
35 it in the context of ongoing anthropogenic warming. Despite recently voiced  
36 concerns we believe this has largely been accomplished.

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

46 Serious scientific interest in the slowdown began around 2009 (e.g., Ref. 7)  
47 when decadal GMST variability was found to be a relatively common feature in  
48 20th Century observations and climate model simulations. Initial attention was  
49 focused on the role of internal variability; this work built on an extensive body of  
50 research into the nature and causes of internal decadal climate variability –  
51 research that had been actively pursued since the 1990s. Subsequent slowdown  
52 studies examined contributions from external forcing and observational  
53 uncertainty, as we discuss below. This important historical perspective is missing  
54 in recent critiques of research into the slowdown (e.g., Refs 4, 8 and 9).

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

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

#### 74 **Scientific advances**

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

88 A different perspective on the role of internal variability is obtained through the  
89 analysis of the individual models and realizations comprising the MME. In ten out

90 of 262 ensemble members, the simulations and observations had the same  
91 negative phase of the IPO during the slowdown period – i.e., there was a  
92 fortuitous “lining up” of internal decadal variability in the observed climate system  
93 and the ten simulations<sup>15,16</sup>. These ten ensemble members captured the muted  
94 early 21st century warming, thus illustrating the role of internal variability in the  
95 slowdown.

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

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

112 These examples have built upon earlier advances in our scientific  
113 understanding of the causes of fluctuations in GMST. For example, the cooling  
114 after the Pinatubo eruption in 1991 was predicted before it could be observed.  
115 The ability of climate models to simulate this cooling signal was reported in  
116 published papers and IPCC assessments. Previous work noted the importance of  
117 the “spring-back” from Pinatubo, which contributed to relatively rapid rates of

118 global warming over the decade of the 1990s (e.g., Ref. 23); a similar “spring-  
119 back” occurred in the 1980s after El Chichón.

120 Understanding of the recent slowdown also built upon prior research into the  
121 causes of the so-called “big hiatus” from the 1950s to the 1970s. During this  
122 period, increased cooling from anthropogenic sulphate aerosols roughly offset  
123 the warming from increasing GHGs (which were markedly lower than today). This  
124 offsetting contributed to approximately constant GMST. Ice core sulphate data  
125 from Greenland support this interpretation of GMST behaviour in the 1950s to  
126 1970s, and provide compelling evidence of large temporal increases in  
127 atmospheric loadings of anthropogenic sulphate aerosols. The IPO was another  
128 contributory factor to the big hiatus<sup>13</sup>.

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

### 139 **Claims and counterclaims**

140 Recent claims that scientists “turned a routine fluctuation into a problem for  
141 science” and that “there is no evidence that identifies the recent period as unique  
142 or particularly unusual”<sup>26</sup> were made in the context of an examination of whether  
143 warming has ceased, stopped, or paused. We do not believe that warming has  
144 ceased, but we consider the slowdown to be a recent and visible example of a  
145 basic science question that has been studied for at least twenty years: what are  
146 the signatures of (and the interactions between) internal decadal variability and

147 the responses to external forcings, such as increasing GHGs or aerosols from  
148 volcanic eruptions?

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

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

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

176 **Baseline periods**

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

190 Our exploration of an alternative baseline period is motivated by  $\Delta F$ , the  
191 estimate of anthropogenic radiative forcing<sup>28</sup>. This represents the perturbation to  
192 the radiative budget of the planet from the combined effects of human-caused  
193 increases in GHGs and aerosols. Since the Industrial Revolution, human  
194 activities have caused net positive forcing of the climate system, leading to  
195 overall warming of the surface. Superimposed on this forced anthropogenic  
196 response are internal variability, cooling and recovery from volcanic eruptions,  
197 and small signals of solar irradiance changes.

198 The role of these factors is illustrated in Fig. 3, which shows  $R_{\{\Delta T/\Delta F\}}$ , the  
199 anomalies in the ratio of trends in GMST and global-mean anthropogenic  
200 radiative forcing. Results are calculated over the big hiatus and warming  
201 slowdown periods, as well as over the intervening period.  $R_{\{\Delta T/\Delta F\}}$  provides  
202 information on the change in GMST per unit change in anthropogenic forcing. A  
203 simple interpretation is that variations in  $R_{\{\Delta T/\Delta F\}}$  reflect influences other than  
204 anthropogenic forcing, such as external forcing from volcanic eruptions and/or

205 internal variability. Changes in the sign of  $R_{\{\Delta T/\Delta F\}}$  indicate periods over which  
206 non-anthropogenic influences add to or subtract from the anthropogenically-  
207 forced warming response.

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

219 The big hiatus and warming slowdown periods correspond to times during  
220 which the dominant mode of decadal variability in the Pacific – the IPO – was in  
221 its negative phase. In the intervening period the IPO was in its positive phase.  
222 Recent modelling<sup>11-13,15,16,24</sup> and observationally based studies<sup>14,18</sup> indicate an  
223 important role for Pacific decadal variability in modulating temporal changes in  
224 GMST. Based on both of these factors – the relatively steady increase in net  
225 anthropogenic forcing over 1972 to 2001, and the consistent sign of the IPO  
226 during this period – we argue that as a baseline for evaluating whether the  
227 surface warming rate is unchanged in the early 21st Century, 1972 to 2001 is a  
228 preferable choice to 1950 to 1999. Using this more physically interpretable 1972-  
229 2001 baseline, we find that the surface warming from 2001-2014 is significantly  
230 smaller than the baseline warming rate.

231

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

232 **Concluding remarks**

233 Our results support previous findings of a reduced rate of surface warming **since**  
234 **the beginning of the 21st Century** – a period in which anthropogenic forcing ~~has~~  
235 ~~been~~ increasing at a relatively constant rate. Recent research that has identified  
236 and corrected errors and inhomogeneities in the surface air temperature record<sup>4</sup>  
237 is of high scientific value. Investigations have also identified non-climatic artifacts  
238 in tropospheric temperatures inferred from radiosondes<sup>30</sup> and satellites<sup>31</sup>, and  
239 important errors in ocean heat uptake estimates (Ref. 25 and references  
240 contained therein). Newly-identified observational errors do not, however,  
241 negate the existence of a real reduction in the surface warming rate in the early  
242 21st Century relative to the 1970s-1990s. This reduction arises through the  
243 combined effects of internal decadal variability<sup>11-18</sup>, volcanic<sup>19,23</sup> and solar  
244 activity, and decadal changes in anthropogenic aerosol forcing<sup>32</sup>. The warming  
245 slowdown has motivated substantial research into decadal climate variability and  
246 uncertainties in key external forcings. As a result, the scientific community is now  
247 better able to explain temperature variations such as those experienced during  
248 the early 21st Century<sup>33</sup>, and perhaps even to make skillful predictions of such  
249 fluctuations in the future. For example, climate model predictions initialized with  
250 recent observations indicate a transition to a positive phase of the IPO with  
251 increased rates of global surface temperature warming<sup>34,35</sup>.

252 In summary, climate models did not (on average) reproduce the observed  
253 temperature trend over the early 21st Century<sup>6</sup>, in spite of the continued increase  
254 in anthropogenic forcing. This mismatch focused attention on a compelling  
255 science problem – a problem deserving of scientific scrutiny. Based on our  
256 analysis, which relies on physical understanding of the key processes and  
257 forcings involved, we find that the rate of warming over the early 21st Century is  
258 slower than that of the previous few decades. This slowdown is evident in time  
259 series of GMST and in the global mean temperature of the lower troposphere.  
260 The magnitude and statistical significance of observed trends (and the magnitude

261 and significance of their differences relative to model expectations) depends on  
262 the start and end dates of the intervals considered<sup>23</sup>.

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

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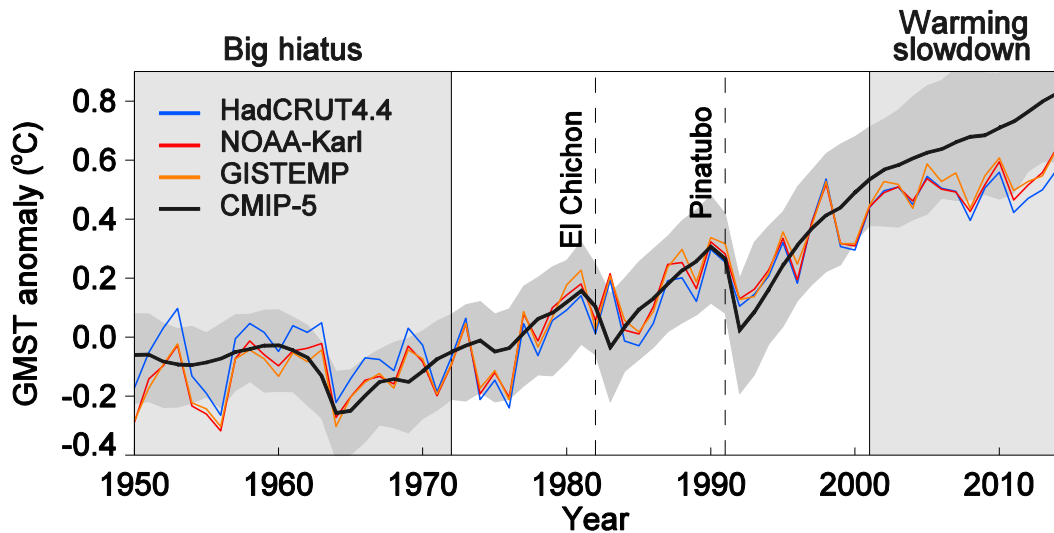
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## 379 **Author Contributions**

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

383 **Additional information**

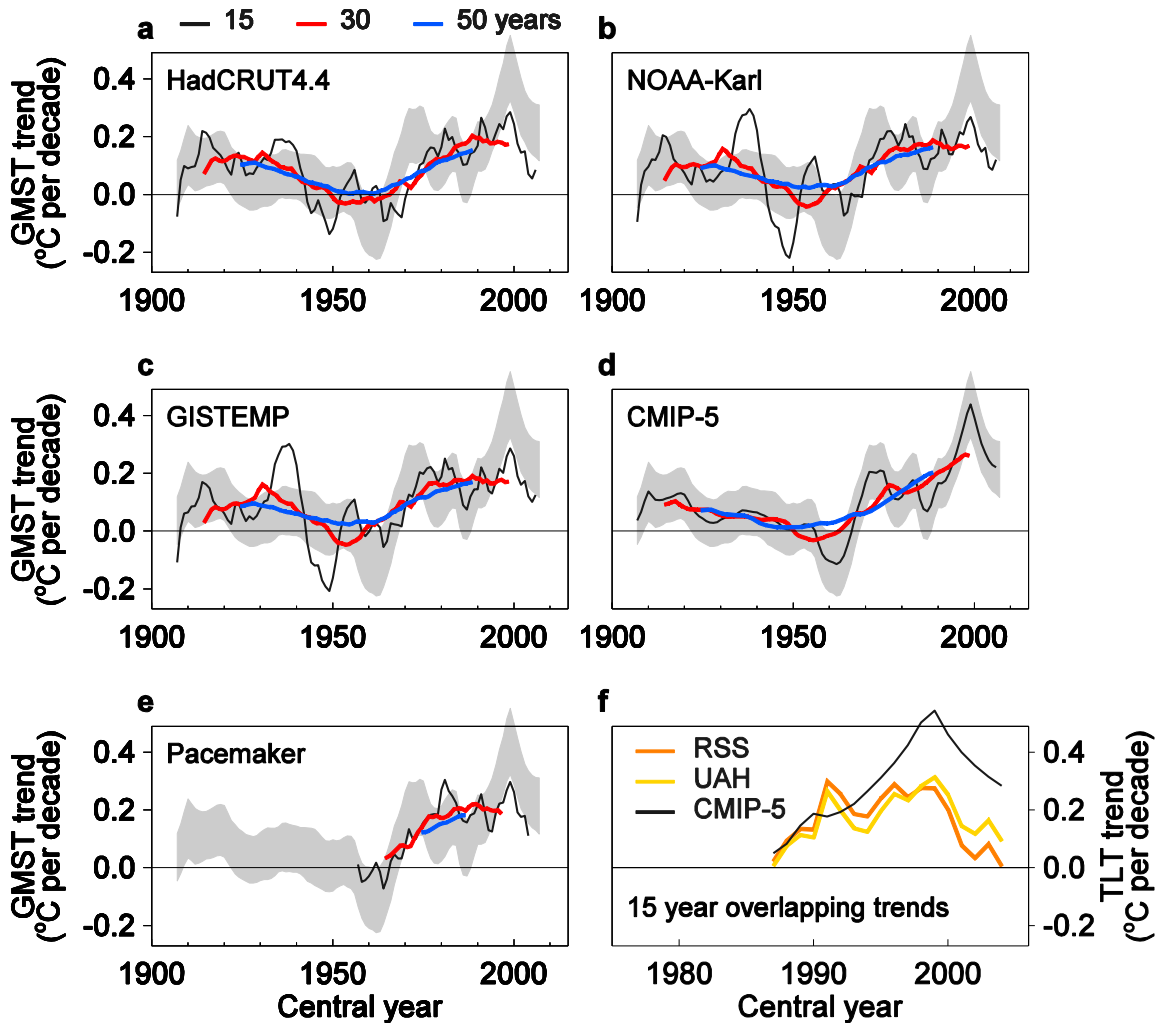
384 None.



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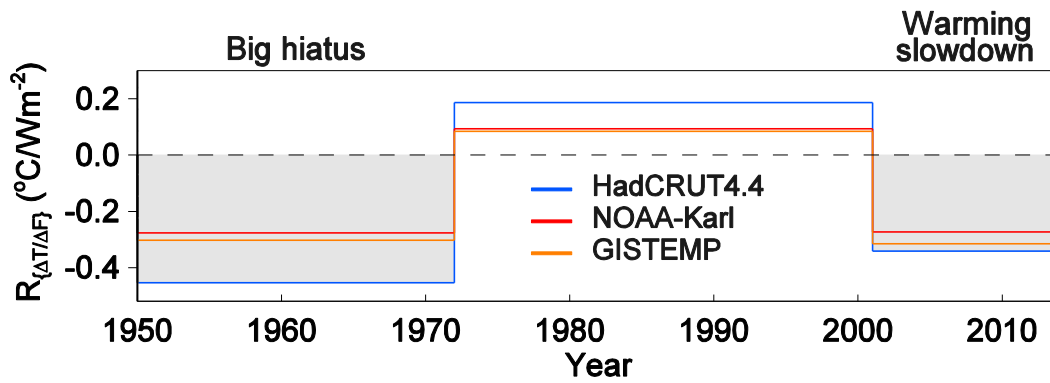
387 **Figure 1 | Annual-mean and global-mean surface temperature anomaly.**

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



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



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419 **Figure 3 | Ratio of trend in annual-mean and global-mean surface**  
 420 **temperature to trend in anthropogenic radiative forcing.** The ratio of trends  
 421 over each period shown in this figure (i.e., 1950-1972, 1972-2001 and 2001-  
 422 2014) is expressed as an anomaly relative to the trend computed over the full  
 423 period from 1950 to 2014. The caption to Fig. 1 explains the rationale for the end  
 424 date and start date for the big hiatus and warming slowdown periods  
 425 (respectively).