

Making sense of the early-2000s warming slowdown

Article

Accepted Version

Fyfe, J. C., Meehl, G. A., England, M. H., Mann, M. E., Santer, B. D., Flato, G. M., Hawkins, E., Gillett, N. P., Xie, S.-P., Kosaka, Y. and Swart, N. C. (2016) Making sense of the early-2000s warming slowdown. *Nature Climate Change*, 6 (3). pp. 224-228. ISSN 1758-678X doi:
<https://doi.org/10.1038/nclimate2938> Available at
<http://centaur.reading.ac.uk/65738/>

It is advisable to refer to the publisher's version if you intend to cite from the work.

To link to this article DOI: <http://dx.doi.org/10.1038/nclimate2938>

Publisher: Nature Publishing Group

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

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

3 John C. Fyfe¹, Gerald A. Meehl², Matthew H. England³, Michael E. Mann⁴,
4 Benjamin D. Santer⁵, Gregory M. Flato¹, Ed Hawkins⁶, Nathan P. Gillett¹,
5 Shang-Ping Xie⁷, Yu Kosaka⁸ & Neil C. Swart¹

6 ¹*Canadian Centre for Climate Modelling and Analysis, Environment and Climate*
7 *Change Canada, University of Victoria, Victoria, British Columbia, V8W 2Y2,*
8 *Canada*

9
10 ²*National Center for Atmospheric Research, Boulder, Colorado 80307, USA*

11 ³*ARC Centre of Excellence for Climate System Science, University of New South*
12 *Wales, New South Wales 2052, Australia*

13 ⁴*Department of Meteorology and Earth and Environmental Systems Institute,*
14 *Pennsylvania State University, University Park, PA, USA*

15 ⁵*Program for Climate Model Diagnosis and Intercomparison (PCMDI), Lawrence*
16 *Livermore National Laboratory, Livermore, California 94550, USA*

17 ⁶*National Centre for Atmospheric Science, Department of Meteorology,*
18 *University of Reading, Reading RG6 6BB, UK*

19 ⁷*Scripps Institution of Oceanography, University of California San Diego, 9500*
20 *Gilman Drive MC 0206, La Jolla, California 92093, USA*

21 ⁸*Research Center for Advanced Science and Technology, University of Tokyo,*
22 *4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan*

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)¹ – 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 warming². 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 datasets³⁻⁵, 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 rate⁶. 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 length¹⁰. 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)¹. 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 Century⁶.
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 slowdown¹¹⁻¹⁴ (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^{15,16}. 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 Indian¹⁷ and Atlantic Oceans¹⁸. 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 trends⁴, and of the role of decadal
102 changes in volcanic forcing in partially offsetting human-caused warming¹⁹.
103 Research has also identified a systematic mismatch during the slowdown
104 between observed volcanic forcing and that used in climate models¹⁹.

105 It has been suggested²⁰ 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^{21,22} 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 uncertainties²¹, they
110 corroborate the slowdown of GMST increase²³ 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 hiatus¹³.

129 Research motivated by the warming slowdown has also led to a fuller
130 understanding of ocean heat uptake^{17,24} 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)²⁵, 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”²⁶ 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 thought²⁷, 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 phase¹³.

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”⁴ or “claims of a hiatus in global warming lack
170 sound scientific basis”⁹. 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 forcing¹, 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 observations⁴ 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 ΔF , the
191 estimate of anthropogenic radiative forcing²⁸. 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 ΔT
213 and ΔF , 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 conclusion²⁹.

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^{11-13,15,16,24} and observationally based studies^{14,18} 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 record⁴
237 is of high scientific value. Investigations have also identified non-climatic artifacts
238 in tropospheric temperatures inferred from radiosondes³⁰ and satellites³¹, 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 variability¹¹⁻¹⁸, volcanic^{19,23} and solar
244 activity, and decadal changes in anthropogenic aerosol forcing³². 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 Century³³, 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^{34,35}.

252 In summary, climate models did not (on average) reproduce the observed
253 temperature trend over the early 21st Century⁶, 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 considered²³.

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 years³⁶.

274 References

- 275 1. Flato, *et al.* Evaluation of Climate Models. In: Climate Change 2013: The
276 Physical Science Basis. Contribution of Working Group I to the Fifth
277 Assessment Report of the Intergovernmental Panel on Climate Change
278 [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
279 Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press,
280 Cambridge, United Kingdom and New York, NY, USA.
- 281 2. Trenberth, K. E. Has there been a hiatus? *Science* **349**, 691-692 (2015).
- 282 3. Morice, C. P., Kennedy, J. J., Rayner, N.A. & Jones, P. D. Quantifying
283 uncertainties in global and regional temperature change using an ensemble
284 of observational estimates: The HadCRUT4 dataset. *J. Geophys. Res.* **117**,
285 (2012).
- 286 4. Karl, T. R., *et al.*, Possible artifacts of data biases in the recent global surface
287 warming hiatus. *Science* (2015).
- 288 5. Hansen, J., Ruedy, R., Sato, M. & Lo, K. Global surface temperature change.
289 *Rev. Geophysics* **48** (2010).
- 290 6. Fyfe, J. C., Gillett, N. P. & Zwiers, F. W. Overestimated global warming over
291 the past 20 years. *Nature Clim. Change* **3**, 767–769 (2013).
- 292 7. Easterling, D. R. & Wehner, M. F. Is the climate warming or cooling?
293 *Geophys. Res. Lett.* **36** (2009).
- 294 8. Lewandowsky, S., Risbey, J.S., & Oreskes, N. On the definition and
295 identifiability of the alleged “hiatus” in global warming. *Scientific Reports*,
296 (2015).

- 297 9. Rajaratnam, B., Romano, J., Tsiang, M & Diffenbaugh, N. S. Debunking the
298 climate hiatus. *Climatic Change* **133**, 129-140 (2015).
- 299 10. Santer, B. D. *et al.* Separating signal and noise in atmospheric temperature
300 changes: The importance of timescale. *J. Geophys. Res.* **116** (2011).
- 301 11. Meehl, G. A., *et al.* Externally forced and internally generated decadal
302 climate variability associated with the Interdecadal Pacific Oscillation, *J.*
303 *Climate* **26**, 7298-7301 (2013).
- 304 12. Kosaka, Y. & Xie, S.-P. Recent global-warming hiatus tied to equatorial
305 Pacific surface cooling. *Nature* **501**, 403-407 (2013).
- 306 13. England, M. H., *et al.* Slowdown of surface greenhouse warming due to
307 recent Pacific trade wind acceleration. *Nature Clim. Change* **4**, 222–227
308 (2014).
- 309 14. Steinman, B. A., Mann, M. E. & Miller, S. K. Atlantic and Pacific multidecadal
310 oscillations and Northern Hemisphere temperatures. *Science* **347**, 988-991
311 (2015).
- 312 15. Risbey, J., Lewandowsky, S., Langlais, C., Monselesan, D., O’Kane, T. &
313 Oreskes, N. Well-estimated global surface warming in climate projections
314 selected for ENSO phase. *Nature Clim. Change* **4**, 838-840 (2014).
- 315 16. Meehl, G.A., Teng, H. & Arblaster, J. M. Climate model simulations of the
316 observed early-2000s hiatus of global warming. *Nature Clim. Change* **4**
317 (2014).
- 318 17. Nieves, V., Willis, J. K. & Patzert, W. C. Recent hiatus caused by decadal
319 shift in Indo-Pacific heating. *Science* **349**, 532-535 (2015).
- 320 18. Dai, A., Fyfe, J. C., Xie, S.-P. & Dai, X. Decadal modulation of global surface
321 temperature by internal climate variability. *Nature Clim. Change* **5**, 555-559
322 (2015).
- 323 19. Solomon, S., Daniel, J. S., Neely III, R. R., Vernier, J.-P., Dutton, E. G. &
324 Thomason, L. W. The persistently variable “background” stratospheric
325 aerosol layer and global climate change. *Science* **333**, 866-870 (2011).
- 326 20. Cowtan, K. & Way, R. G. Coverage bias in the HadCRUT4 temperature
327 series and its impact on recent temperature trends. *Quart. J. of the Royal*
328 *Met. Soc.* **140**, 1935-1944 (2014).
- 329 21. Mears, C., Wentz, F. J., Thorne, P. & Bernie, D. Assessing uncertainty in
330 estimates of atmospheric temperature changes from MSU and AMSU using
331 a Monte-Carlo technique. *J. Geophys. Res.* **116**, D08112 (2011).
- 332 22. Christy, J. R., Norris, W. B., Spencer, R. W. & Hnilo, J. J. Tropospheric
333 temperature change since 1979 from tropical radiosonde and satellite
334 measurements. *J. Geophys. Res.* **112**, D06102 (2007).
- 335 23. Santer, B. D., *et al.* Volcanic contribution to decadal changes in tropospheric
336 temperature. *Nat. Geosci.* **7**, 185-189 (2014).
- 337 24. Meehl, G. A., *et al.* Model-based evidence of deep ocean heat uptake during
338 surface temperature hiatus periods. *Nature Clim. Change* **1**, 360-364 (2011).
- 339 25. Domingues, C. M., *et al.* Improved estimates of upper-ocean warming and
340 multi-decadal sea-level rise. *Nature* **453**, 1090-1093 (2008).

- 341 26. Lewandowsky, S., Risbey, J. & Oreskes, N. The “pause” in global warming:
342 Turning a routine fluctuation into a problem for science. *Bull. Amer. Meteor.*
343 *Soc.*, *in press*.
- 344 27. Marotzke, J. & Forster, P. M. Forcing, feedback and internal variability in
345 global temperature trends. *Nature* **517**, 565–570 (2015).
- 346 28. Meinshausen, M., *et al.* The RCP greenhouse gas concentrations and their
347 extensions from 1765 to 2300. *Climatic Change* **109**, 213–241 (2011).
- 348 29. Huber, M. & Knutti, R. Natural variability, radiative forcing and climate
349 response in the recent hiatus reconciled. *Nature Geoscience* **7**, 651–656
350 (2014).
- 351 30. Sherwood, S. C. & Nishant, N. Atmospheric changes through 2012 as
352 shown by iteratively homogenized radiosonde temperature and wind data
353 (IUKv2). *Environ. Res. Lett.* **10** (2015).
- 354 31. Po-Chedley, S., Thorsen, T. J. & Fu., Q. Removing diurnal cycle
355 contamination in satellite-derived tropospheric temperatures: Understanding
356 tropical tropospheric trend discrepancies. *J. Climate* **28**, 2274–2290 (2015).
- 357 32. Schmidt, G. A., Shindell, D. T. & Tsigaridis, K. Reconciling warming trends.
358 *Nature Geoscience* **7**, 158–160 (2014).
- 359 33. Hawkins, E., Edwards, T. & McNeill, D. Pause for thought. *Nature Clim.*
360 *Change* **4**, 154–156 (2014).
- 361 34. Thoma, M., Greatbatch, R. J., Kadow, C. & Gerdes, R. Decadal hindcasts
362 initialized using observed surface wind stress: Evaluation and prediction out
363 to 2024. *Geophys. Res. Lett.* **42**, 6454–6461 (2015).
- 364 35. Meehl, G.A., Hu, A., & Teng, H. Initialized decadal prediction for transition to
365 positive phase of the Interdecadal Pacific Oscillation and resumption of larger
366 rates of global warming. *Nature Comms.*, submitted.
- 367 36. Meehl, G.A., *et al.* Decadal climate prediction: An update from the trenches.
368 *Bull. Amer. Meteorol. Soc.* **95**, 243–267 (2014).

369 **Acknowledgements**

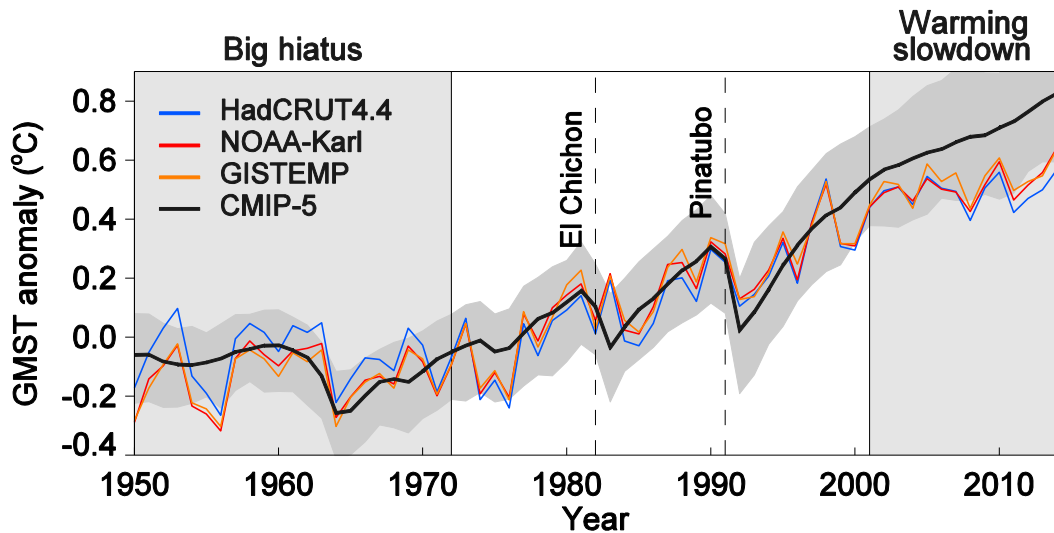
370 We thank Thomas Karl, Susan Solomon, Jochem Marotzke, Stefan Rahmstorf,
371 Steve Lewandowsky, James Risbey and Naomi Oeskes for their comments on
372 earlier drafts. We acknowledge the Program for Climate Model Diagnosis and
373 Intercomparison and the World Climate Research Programme’s Working Group
374 on Coupled Modelling for their roles in making the WCRP CMIP multi-model
375 datasets available. Portions of this study were supported by the Regional and
376 Global Climate Modeling Program (RGCM) of the U.S. Department of Energy’s
377 Office of Biological & Environmental Research (BER) Cooperative Agreement #
378 DE-FC02-97ER62402, and the National Science Foundation.

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**

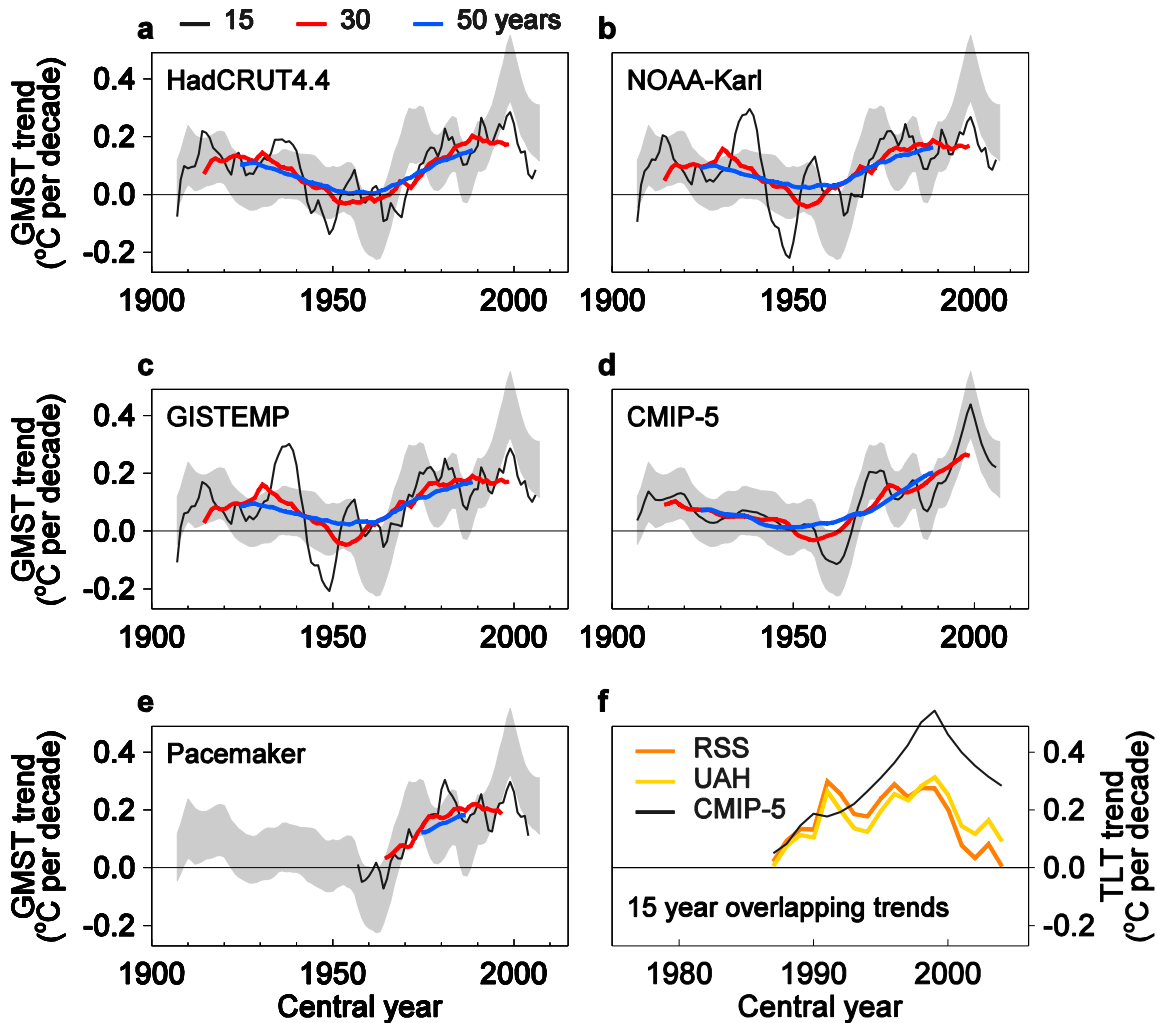
384 None.



385
386

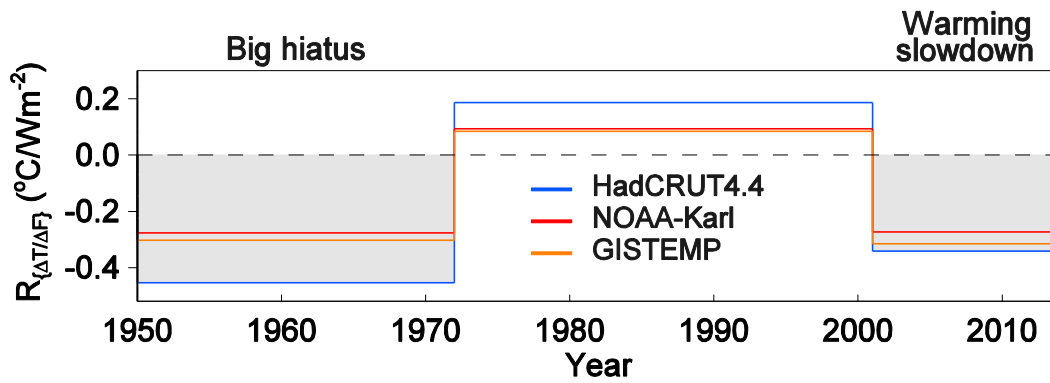
387 **Figure 1 | Annual-mean and global-mean surface temperature anomaly.**

388 Anomalies are from three updated observational datasets³⁻⁵ 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 2005²⁸.
 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).



401
 402
 403
 404
 405
 406
 407
 408
 409
 410
 411
 412
 413
 414
 415
 416

Figure 2 | Overlapping trend in annual mean temperature. a-d, Overlapping trend in global mean surface temperature (GMST) in three updated observational datasets³⁻⁵ and ensemble mean GMST from 124 simulations from 41 CMIP-5 models using rcp4.5 extensions from 2005²⁸. The shading is plus to minus one standard deviation of the 15-year overlapping trends from the CMIP-5 simulations. e, Overlapping trend in so-called “pacemaker”¹² experiments where a CMIP-5 climate model was forced with observed eastern tropical Pacific sea surface temperature variability and rcp4.5 extensions from 2005²⁸. f, Overlapping trend in the temperature of the lower troposphere (TLT), spatially averaged over the near-global (82.5°N-70°S) coverage of two satellite-based datasets^{21,22}; model results are from 41 simulations of historical climate change performed with 28 CMIP-5 models, with rcp8.5 extensions from 2005²⁸. 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.



417

418

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
 422 2001-2014) 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).