

Climate model simulations of the observed early-2000s hiatus of global warming

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The slowdown in the rate of global warming in the early 2000s is not evident in the multi-model ensemble average of traditional climate change projection simulations¹. However, a number of individual ensemble members from that set of models successfully simulate the early-2000s hiatus when naturally-occurring climate variability involving the Interdecadal Pacific Oscillation (IPO) coincided, by chance, with the observed negative phase of the IPO that contributed to the early-2000s hiatus. If the recent methodology of initialized decadal climate prediction could have been applied in the mid-1990s using the Coupled Model Intercomparison Project Phase 5 multi-models, both the negative phase of the IPO in the early 2000s as well as the hiatus could have been simulated, with the multi-model average performing better than most of the individual models. The loss of predictive skill for six initial years before the mid-1990s points to the need for consistent hindcast skill to establish reliability of an operational decadal climate prediction system.

Traditional free-running climate simulations that start in the mid-nineteenth century and proceed through the twentieth century with observed human-produced forcings, such as increasing greenhouse gases (GHGs), aerosols and ozone, along with natural forcings, such as aerosols from volcanic eruptions and solar variability, are designed to simulate the response of the climate system to those changes in external forcings. To do this, multiple realizations or ensemble members are run with each model. These are then averaged together to remove the effects of naturally occurring interannual and decadal timescale variability, leaving only the response to the external forcings. If the early-2000s hiatus is mostly a result of internally generated climate variability^{2–5}, the average of all those simulations for the early 21st century would, and indeed does, lie above the actual plateau of warming that occurred in the observations^{1,6}. Furthermore, the models could be overly sensitive to increasing GHGs (ref. 7), and there could have been contributions from a collection of moderate volcanic eruptions or other forcings^{8–10}, suggesting that the forcings specified in the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments may not have been adequate to simulate all aspects of the early-2000s hiatus. But the fact that all model simulations, when averaged together, do not simulate the hiatus has been touted as a failure of any model to simulate what actually occurred in the early-2000s^{11,12}.

However, inspection of the individual ensemble members from these same model simulations reveals that ten members actually produced the observed warming trend (defined as a trend less than 0.04 °C per decade as observed) during the period of the hiatus 2000–2013 (Fig. 1a and refs 4,13). A composite of those ten ensemble members out of 262 possible CMIP5 realizations (Methods) shows a negative phase of the IPO, characterized by cooler-than-normal average surface temperatures over the tropical Pacific, with opposite sign anomalies in the northwest and southwest Pacific, lasting 14

years (Fig. 1b and Supplementary Fig. 1). There are 21 ensemble members that simulate a hiatus from 2000 to 2012—nine continue through 2000–2014, six from 2000 to 2015, and six from 2000 to 2016, one of which from 2000 to 2017 continues to 2018 (a hiatus of 19 years). Average hiatus composites have a negative IPO phase, as opposed to the overall average of a larger set of ensemble members showing mostly warming in the tropical Pacific¹⁴. Thus, although not specifically designed to do so, in some of the uninitialized simulations the internally generated variability associated with the IPO happens to synchronize with the phase of naturally occurring variability in the observations purely by chance. The pattern correlation of the observed IPO (Supplementary Fig. 1b) with the surface temperature trends from 2000 to 2013 in all ensemble members shows a roughly Gaussian distribution around zero pattern correlation as the internally generated variability is more or less random (Fig. 1c). The same quantity from the hiatus ensemble members shows a shift of the distribution towards statistically significant positive values greater than +0.4 (Methods), indicating that internally generated variability with a negative IPO is tending, on average, to sync up with what happened in the observations in those members (Supplementary Fig. 1a and Fig. 1b,c). This is a compelling application of the result derived from other analyses, in that tropical Pacific surface temperatures in the negative phase of the naturally-occurring IPO can temporarily counteract the warming from increasing GHGs to produce a hiatus of warming in globally averaged surface air temperatures that can last for a decade or more^{2–5}, even as the climate system is still trapping excess heat of about 0.5–1.0 W m⁻² (refs 15,16).

These results by themselves do not provide predictive information. What would have been required to predict the hiatus in advance is the application of recently developed decadal climate prediction methodology^{17,18} to capture the time evolution of the interplay between externally forced response and internally generated climate variability. There are indications that the observed vertical global heat content distribution in the ocean for the hiatus¹⁹ can be simulated in a single model²⁰, as well as a negative IPO surface temperature pattern in the Pacific after the late 1990s IPO transition^{21–25}. But could a multi-model ensemble initialized from the 1990s have predicted the transition to the negative phase of the IPO and the hiatus at the right time, involving the processes thought to produce the hiatus?

Here we show hypothetical decadal climate predictions that could have been made in the 1990s to simulate the climate of the early 2000s, not to advocate for an operational decadal climate prediction system, but to address the issues involved with such a system, including that of false-alarm forecasts that would affect the reliability of an operational decadal climate prediction system.

So if we could be transported back to the 1990s with this new decadal climate prediction capability, a set of the current CMIP5 (ref. 26) global coupled climate models, and a current

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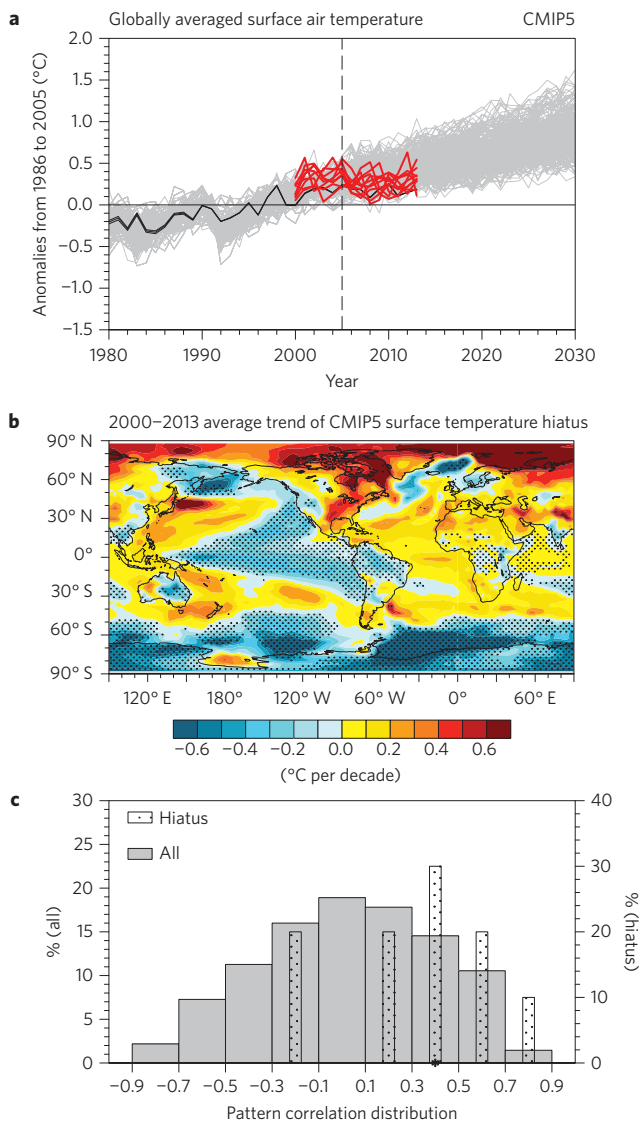


Figure 1 | Climate model simulations of the early-2000s hiatus. **a**, Time series of globally averaged surface air temperature anomalies (°C) in relation to the 1986–2005 time period for the observations (black lines with 5%, median and 95% values from HadCRUT4), and individual ensemble members from the 262 uninitialized CMIP5 simulations (light grey); red lines are individual ensemble members that simulate the early-2000s hiatus as observed (linear trend less than 0.04 °C per decade) for the period 2000–2013; the dashed line indicates the transition year (2005) between the CMIP5 historical and scenario experiments. **b**, Average sea surface temperature trends (°C per decade) from ten uninitialized ensemble members that simulate the hiatus (their individual time series in red in **a**). Stippling indicates the 5% significance level from a two-sided t-test. **c**, Histogram of pattern correlations of the IPO from observations (Supplementary Information) and the 2000–2013 CMIP5 model trends (grey bars), and similarly for the ensemble members with a hiatus from 2000–2013 (stippled). The observed value of 0.4 is indicated by the star on the x axis. Units are the percentage of the total number of members in each distribution. Note y axis scales are different for the all-members and hiatus-members cases.

supercomputer to run them on, could we have simulated the early-2000s hiatus?

To test whether this would have been possible, the first thing to do in the 1990s would have been to run a set of retrospective predictions (also called hindcasts) using only observed data up to

1993 (post-Mt. Pinatubo eruption) for model verification and for computing bias adjustments^{25,27}; Supplementary Information. For operational decadal climate predictions in the 1990s, the question would have been: How different will the climate averaged 3–7 years in the future be from the climate just experienced (the previous 15 years; 3–7 year predictions are a compromise between the interests of climate prediction on decadal time scales and the extent of initial-value predictability residing in the ocean initial conditions) compared to a persistence prediction (defined as years 3–7 in the future having the same climate anomalies as the previous 5 years)?

We first take a set of hindcasts with the 16 available CMIP5 models (Supplementary Table 1) using observed data up to the early 1990s, with initial years starting in 1960 until 1987 (since the year 3–7 prediction for the latter would be centred on 1991 for the prediction period 1989–1993). As compared to previous studies that use the entire period 1960 to present, bias adjustments are calculated using observations only from 1960 to 1990. Greenhouse gas and aerosol concentrations would have been required for predictions in the 1990s and are taken as observed for this exercise. Those quantities could have been credibly projected from previous trends, as such short-term forcing information depends little on choice of scenario¹, although the estimates available in the 1990s would not have been as good as those at present used in climate change experiments.

For hindcasts of five-year average predictions for years 3–7, by the early 1990s the initialized simulations beat persistence (defined as the initialized predictions being closer to the observations than the persistence values) in 18 out of 28 prediction periods (64% success rate), often by a large margin (Fig. 2a). Taking with us to the 1990s the knowledge that the largest amplitude internally generated decadal variability occurs in the Pacific and Atlantic oceans^{28–32} and computing anomaly pattern correlations for the hindcasts up to the period 1989–1993 for ocean grid points in the Pacific–Atlantic area (40° S–70° N, 100° E–360°), 25 out of 28 prediction periods have statistically significant skill (Fig. 2b, values above the dashed line, Methods).

To give an idea of the actual predicted surface temperature patterns involved with the results in Fig. 2b, an example of the skilful simulation across the transition from the negative phase of the IPO before roughly 1977 to the positive phase after 1977 is for the initial year 1974 and the 3–7 year prediction for 1976–1980 (Supplementary Fig. 2b). Recall that only hindcast information from before the early 1990s is used going back to initial years starting in 1960. In the early 1990s, all these data would have been available to check the hindcast skill of any time period before the mid-1990s, such as the mid-1970s shift. Previous analyses of hindcasts have shown surface temperature patterns only after the transition occurred^{21,24,25}. The prediction of the transition to the positive phase of the IPO with positive surface temperatures over the tropical Pacific in observations (Supplementary Fig. 2a) is represented by a significant anomaly pattern correlation with the initialized prediction of +0.60 in Fig. 2b. This is more skilful than persistence, which still shows the negative phase of the IPO (Supplementary Fig. 2c) or the uninitialized simulations with nearly uniform warming (Supplementary Fig. 2d), both having insignificant anomaly pattern correlation values. To check that the skilful hindcast is made for the right reasons in terms of processes, we compute two indices that are indicative of how heat is distributed vertically in the ocean (Methods). The Pacific trade wind index difference (for the area 10° S–5° N, 160° E–150° W, where the models project most strongly onto the IPO, for the multi-model mean and \pm one standard deviation; 14 models in Supplementary Table 1) is $+0.28 \pm 0.16 \times 10^{-2} \text{ N m}^{-2}$ (compared to the observed value of $+0.53 \times 10^{-2} \text{ N m}^{-2}$). The net surface heat flux anomaly averaged over the global oceans (eight models in Supplementary Table 1) is $-0.11 \pm 0.12 \text{ W m}^{-2}$. These indicate the positive phase of the IPO characterized by weaker trade winds (positive trade wind index) and more heat remaining in the

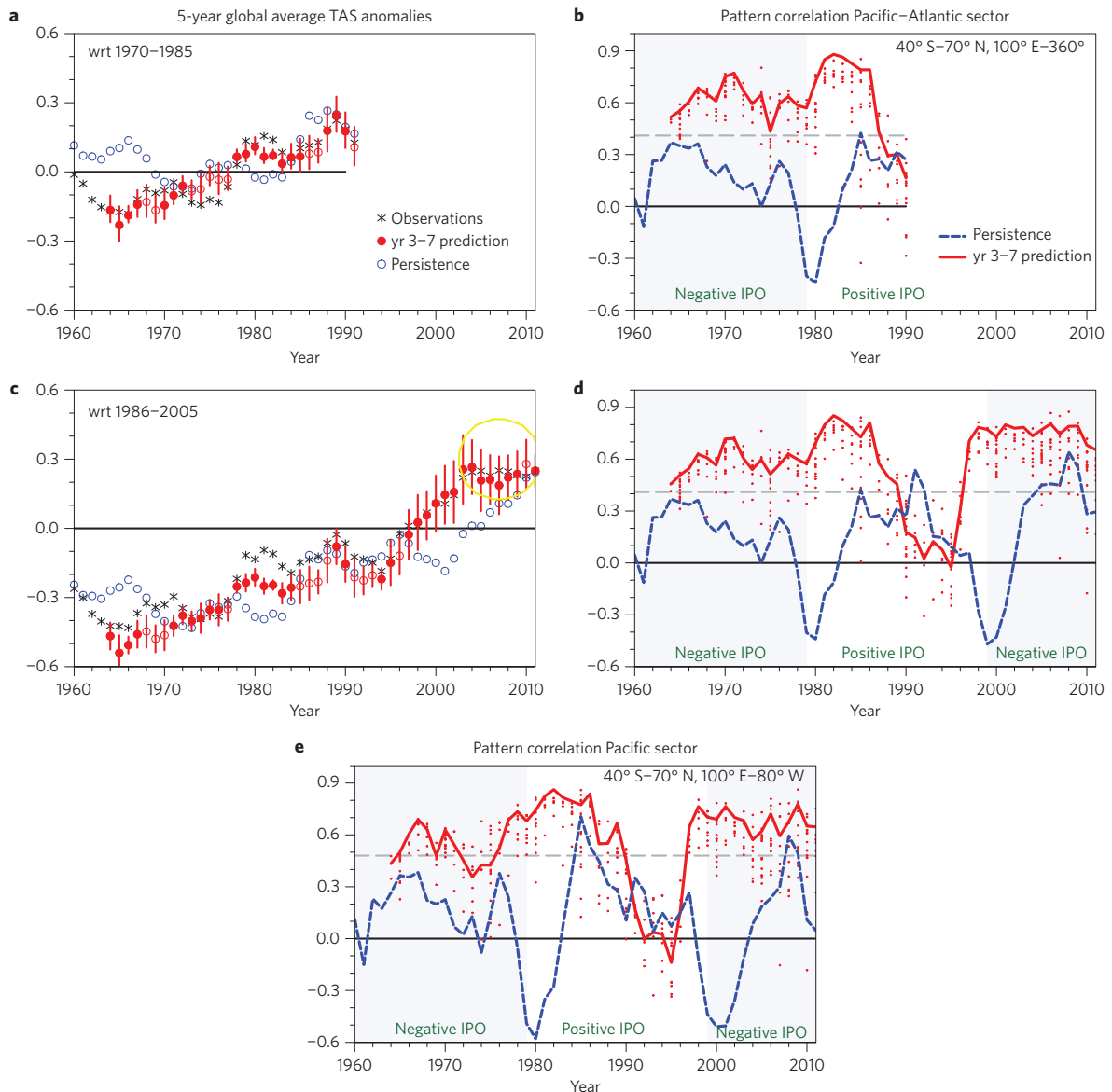


Figure 2 | Hindcasts of surface temperature. **a**, Time series of globally averaged surface air temperature anomalies ($^{\circ}\text{C}$, TAS, initialized hindcasts), averaged for years 3–7 using observations for years 1960 to 1991 (the corresponding prediction periods are 1962–1966 to 1989–1993) with respect to 1970–1985 climatology; x axis indicates the central year of the hindcast; red circles with red whiskers indicate \pm one standard deviation of the model hindcasts; stars indicate observations, blue circles are persistence hindcasts; filled red circles indicate hindcasts that beat persistence). **b**, Anomaly pattern correlations for surface temperature hindcasts for the Pacific–Atlantic Ocean region (40°S – 70°N , 100°E – 360°), ocean points only, observed data only from 1960 to 1990 (red line is the multi-model average, red dots are single model results, blue dashed line is persistence prediction, grey dashed line indicates 95% significance). **c**, Same as **a** except using observed data from 1960 through 2011, yellow circle highlights the hiatus. **d**, Same as **b** except using observed data available from 1960 through 2011. **e**, Same as **d** except for just the Pacific (40°S – 70°N , 100°E – 80°W).

surface layer—this heat is not being mixed into the subsurface (negative heat flux anomaly), therefore contributing to an acceleration of globally averaged surface warming^{3,24,25}.

So to return to our prediction exercise in the 1990s, to illustrate the surface temperature pattern that would have been simulated for the transition to the negative phase of the IPO, we show an example for a prediction from the initial year 1996 for the 3–7 year average for years 1998–2002. Previous analyses of hindcasts showed geographical surface temperature patterns after the IPO transition occurred^{21–25}, or analysed only globally averaged quantities across the transition^{20,22}. Here the transition of the surface temperature pattern to the negative phase of the IPO is simulated with cooler than normal temperatures in the tropical Pacific (Fig. 3b), with a significant anomaly pattern correlation with observations of $+0.75$

(Fig. 2d). This is better than persistence or uninitialized (Fig. 3c,d). The mixing of heat into the subsurface during the negative phase of the IPO is indicated by a positive value of net surface heat flux anomaly of $+0.51 \pm 0.10 \text{ W m}^{-2}$. A part of this mixing is being driven by stronger winds, with a negative Pacific trade wind index difference of $-0.51 \pm 0.20 \times 10^{-2} \text{ N m}^{-2}$ (the observed value is $-0.68 \times 10^{-2} \text{ N m}^{-2}$). Also successfully simulated is the warming of the North Atlantic in the late 1990s (Fig. 3b), which has previously been documented as a skilful feature of decadal hindcasts for this time period^{29,30}. Now to return to present day, Fig. 2c,d shows the full verification data for the post-1990s era using all observed data from 1960 to 2011 to compute the bias adjustments and verification metrics. The multi-model average outperforms most of the individual model hindcasts, consistent with multi-model metrics

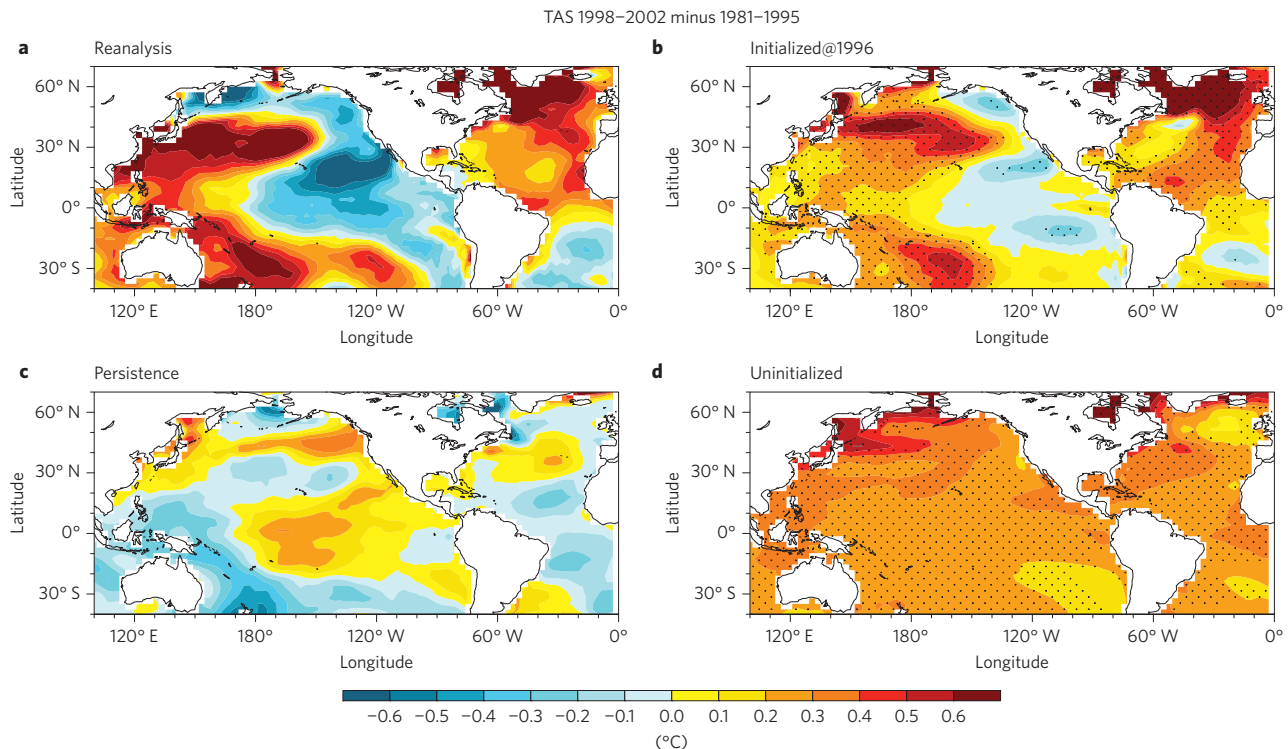


Figure 3 | Surface air temperature patterns for prediction of the IPO transition in the late 1990s. a, Observed surface temperature anomalies (TAS) for 1998–2002 minus 1981–1995. **b**, 3–7 year average prediction initialized in 1996 for years 1998–2002 minus the observed reference period 1981–1995. **c**, Persistence prediction for years 1998–2002. **d**, Uninitialized prediction for years 1998–2002 minus the models' reference period 1981–1995. Stippling in **b,d** indicates the 10% significance level from a two-sided *t* test.

in other contexts³², and there is no obvious relationship between model spread (individual red dots in Fig. 2d) and skill (greater forecast skill is defined as higher anomaly pattern correlation values). The slowing of global warming in the early 2000s is seen in the predictions made in the second half of the 1990s (Fig. 2c), as well as statistically significant pattern correlations for the negative phase of the IPO through the initiation of the hiatus in the late 1990s (Fig. 2d). The IPO region in the Pacific basin shows a similar result (Fig. 2e). However, the drop of predictive skill for the six initial years 1986–1991 (verifying for prediction periods 1988–1992 through 1993–1997) indicates a conditional predictive skill that would have been difficult to anticipate in advance. A similar loss of skill for those same years is also seen in the Atlantic (Supplementary Fig. 3), although the overall skill levels in the Atlantic are higher than in the Pacific^{33,34} (for example, 20 hindcast periods have anomaly pattern correlation values above +0.8 for the Atlantic in Supplementary Fig. 3, whereas there are only 5 in the Pacific in Fig. 2e). Examples of this can be seen by eye in Fig. 3 and Supplementary Fig. 2, where the simulated surface temperature anomaly patterns in the Atlantic basin have a greater similarity to the observations than in the Pacific basin. The loss of IPO skill for those initial years results in a more neutral IPO state in the Pacific for those hindcasts, and consequent globally averaged surface air temperature values less than observed (Fig. 2c).

It is also possible that using the previous 15 years as a climatology to compute predicted temperature anomalies could introduce artificial skill. However, using the entire hindcast period (1960–2010) as a climatology produces a similar result for the late-1990s IPO transition (Supplementary Fig. 4), although this procedure introduces an externally forced trend from increasing greenhouse gases that resembles the IPO pattern. Using yet another metric, the anomaly pattern correlations between the model hindcasts for decadal temperature trends in the Pacific with the observed IPO

pattern (Supplementary Fig. 1b), also shows skill in simulating the late-1990s transition (Supplementary Fig. 5). It has been noted that IPO transitions often occur in conjunction with ENSO interannual variations. This is an intriguing research question that is currently under investigation, and thus beyond the scope of this paper.

The lack of skill for the six initial years 1986–1991, out of the 46 possible initial years in the hindcast period, probably contributes to the lower overall skill for some areas of the Pacific region for the entire hindcast period from 1960 to 2005 for grid-point time series correlations^{1,33,34}. Reasons for this drop in skill for those initial years are at present under investigation. One possibility is that those initial years contain prediction information that includes the Mt. Pinatubo eruption in 1991. Although it is thought that large volcanic eruptions could provide externally forced skill in hindcasts¹, these results suggest that processes associated with that large eruption could either have been not well-simulated in the initialized hindcasts, or the forcing data used by the models could have had problems.

Methods

Uninitialized model simulations. All available uninitialized CMIP5 climate model simulations²⁶ are analysed, with all possible ensemble members for all four RCP scenarios. This amounts to 262 possible realizations from 45 models, with up to 10 ensemble members for the period 2000–2020. These model simulations all start from some pre-industrial state in the nineteenth century, and use observations for natural (volcanoes and solar) and anthropogenic (GHGs, ozone, aerosols, land use) forcings through 2005—with the four RCP scenario forcings after 2005. For the early 2000s, there is little difference among the RCP scenarios for this short-term time frame¹, so all are used.

Initialized model simulations. All available initialized CMIP5 climate model simulations²⁶ are analysed from the 16 models that ran the decadal hindcasts and predictions. Some models used initial years for hindcasts every year, starting with 1960–2011, and some used initial years every five years from 1960 to 2011, with various ensemble sizes for each model and each initial year (Supplementary Table 1). Results are shown for each initial year, with different

numbers of models and ensemble members depending on the initial year. All available ensemble members for each model are averaged together to produce one value for each model for each available initial year. The multi-model averages for hindcasts for adjacent initial years are qualitatively similar, indicating that a multi-model average for a given initial year is comparable across all years.

For the initialized model simulations, we focus on five-year averaged annual mean values during years 3–7 of the hindcasts. The prediction is compared with persistence corresponding to five-year annual means before the initialization time.

For evaluation of the predictions of surface air temperature we employ two metrics including: global average surface temperature, and pattern correlation over the Pacific–Atlantic sector (ocean area over 40° S–70° N, 100° E–360°) and the Pacific and Atlantic sectors separately. To test whether the pattern correlation coefficient between the prediction and observations is distinguishable from chance associations in the large-scale pattern, a Monte Carlo test is performed that consists of 10,000 randomly constructed patterns based on detrended twentieth-century simulations from the same group of models. The 95th percentile of the pattern correlation coefficient of the random pattern is 0.41, with a value of 0.47 for the Pacific-only region in Fig. 2e.

Indices. To determine whether the physical processes in initialized ensemble members that produce the hiatus are correct, we use two indices that have been shown to represent the vertical distribution of heat in the ocean crucial to producing hiatus decades. An index of Pacific trade winds near the dateline and equator, where the IPO exhibits maximum regression onto Pacific Ocean winds, is an indicator of heat mixed into the subsurface by the Pacific Ocean subtropical cells during hiatus decades⁵. Net surface heat flux averaged over the global oceans is an index of the vertical heat content distribution in the ocean, with positive (downward) net surface heat flux indicating more heat going into the subsurface ocean³⁵.

To quantify the credibility of these indices, a composite of model-produced hiatus decades with negative IPO and roughly 10–20% greater rates of ocean heat content increase in layers below 300 m (refs 3,7) shows net surface heat flux values over the ocean of +0.48 W m⁻² per decade and a Pacific trade wind index of $-0.14 \times 10^{-1} \text{ N m}^{-2}$ per decade (positive net surface heat flux indicates more heat is going into the deeper ocean; a negative trade wind index indicates stronger Pacific trade winds mixing more heat into the subsurface); recent observed values of the trade wind index are roughly $-0.2 \times 10^{-1} \text{ N m}^{-2}$ per decade, producing an estimated net wind-driven heat gain below 125 m of $+5.0 \times 10^{22} \text{ J}$ (ref. 5). Opposite sign values of -0.57 W m^{-2} per decade and $+0.12 \times 10^{-1} \text{ N m}^{-2}$ per decade (less heat going into the deeper ocean, and weaker Pacific trade winds mixing less heat into the subsurface) characterize the accelerated warming decades⁵.

Received 17 April 2014; accepted 25 July 2014;
published online 7 September 2014

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Acknowledgements

Portions of this study were supported by the Regional and Global Climate Modeling Program (RGCMP) of the US Department of Energy's Office of Biological & Environmental Research (BER) Cooperative Agreement # DE-FC02-97ER62402, and the National Science Foundation. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Table 1 of the Supplementary Information) for producing and making available their model output. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Author contributions

G.A.M. conceived the study and wrote the initial draft of the paper. H.T. conducted and analysed the CMIP5 hindcasts. J.M.A. analysed the model and observational data. All authors contributed to interpreting the results, discussion of the associated dynamics and refinement of the paper.

Additional information

Supplementary information is available in the [online version of the paper](#). Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.A.M.

Competing financial interests

The authors declare no competing financial interests.