

What Caused the Global Surface Warming Hiatus of 1998–2013?

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Abstract Research into the mechanisms for the global warming slowdown or “hiatus” of 1998–2013 is reviewed here. Observational and modeling studies identify tropical Pacific sea surface temperature variability as a major pacemaker of global mean surface temperature (GMST) change, as corroborated by the GMST increase following a major El Niño event. Specifically, the decadal cooling of the tropical Pacific contributes to the recent global warming hiatus. This tropical Pacific pacemaker effect appears larger for decadal than interannual variability, but the decadal effect remains to be quantified from observations. Our critical review of the literature reveals that the internal and radiatively forced GMST changes are distinct in pattern, energetics, mechanism, and predictability. In contrast to greenhouse gas-induced warming that is spatially uniform in sign and driven by energy perturbations, internal variability in GMST is an order of magnitude smaller than spatial variations, for which ocean-atmosphere interaction is of first-order importance while planetary energetics is not. In fact, decadal variability in GMST is poorly correlated with net radiation at the top of the atmosphere, highlighting the need to distinguish internal and forced GMST change in planetary energy budget. While the

planetary energy budget can now be closed observationally over multi-decadal periods, the recent hiatus highlights the need and challenges to measure and quantify decadal changes in both global ocean heat uptake (e.g., for the effect of radiative forcing on the hiatus) and heat redistribution in the ocean. Hiatus research has led to a wide recognition of the importance of internal variability for GMST trends over a decade and longer. The strengthened connection between the climate variability and change communities is an important legacy of hiatus research.

Keywords Global warming slowdown · Hiatus · Anthropogenic warming · Tropical Pacific variability · Energy theory · Ocean heat uptake

Introduction

Anthropogenic global warming gained wide acceptance following the publication of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and the Nobel Peace Prize to IPCC in 2007. Atmospheric concentration of carbon dioxide rose by 30 ppm from 1998 to 2013 and broke the 400 ppm mark in 2013 for the first time since *Homo sapiens* walked the Earth. In comparison, global mean surface temperature (GMST) increased very slowly at 0.027 to 0.086 °C/decade from 1998 to 2013. This is much smaller than the rate of increase simulated by the multi-model ensemble mean or observed during earlier periods from the 1970s to 1990s, both at about 0.2 °C/decade (Fig. 1). This slowdown in the warming rate over the extended period came as a surprise to those who expected a continual, if not intensified, global warming. This “unexpected” global warming slowdown received wide attention, raising important questions such as the following: what caused it? Is it consistent with IPCC’s conclusion that increased greenhouse gas concentrations (GHGs) in the atmosphere cause the Earth to

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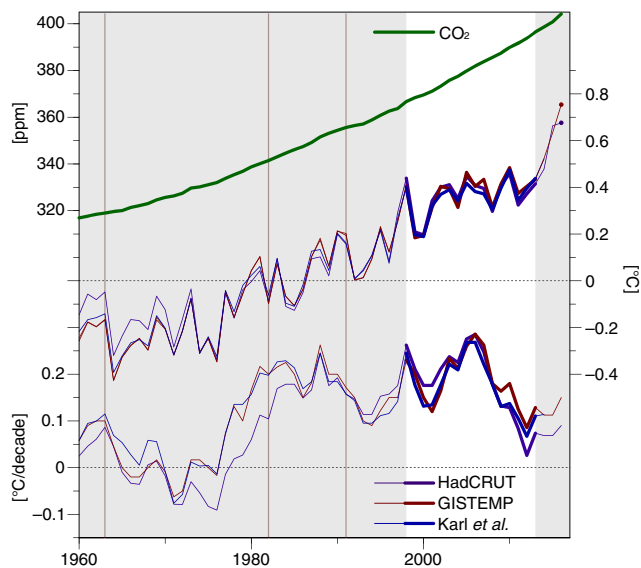


Fig. 1 Observed annual-mean CO₂ concentration at Mauna Loa (*green curve with the top left axis*), GMST anomalies relative to 1970–1999 average (*middle with the right axis*) and trend over the preceding 15 years (*bottom with bottom left axis*). Trend is evaluated as Sen's slope. GMST is based on Hadley Centre Climate Research Unit Temperature (HadCRUT) version 4.5.0.0 [74], Goddard Institute for Space Studies Temperature (GISTEMP; [29]) and Karl *et al.* [39]. *Brown vertical bars* indicate major volcanic eruptions in the tropics. The hiatus period is highlighted with the *white background and thick GMST curves*

warm? Can climate models simulate it? When will this hiatus end? This review adopts the term of hiatus to refer to the temporary slowdown in global surface warming.

Internal variations of the climate system can cause GMST to increase and decrease, independent of the anthropogenic warming. This is obvious in the ups and downs from one year to another in the GMST record, caused by El Niño/Southern Oscillation (ENSO), but an extended hiatus over 15 years is rare, especially in the face of the rapidly increasing radiative forcing. The last time when the rate of 15-year GMST change was that low was during the so-called big hiatus period from the 1940s to 1970s, a time when the rate of change in anthropogenic radiative forcing was much lower. GMST set a record in 2015 and then again in 2016 following the El Niño of 2015–2016. With the El Niño-induced warming dissipated, GMST of December 2016–February 2017 remains the second highest in record. It thus appears that the hiatus ended in 2013. Over short intervals of a decade or two, the magnitude of GMST trends varies somewhat depending on the datasets used and ending points (e.g., GMST is anomalously high in 1998 following a major El Niño) (Karl *et al.* [39]; [30]), but there is a broad consensus that decadal trends in GMST slowed temporarily in the early 2000s compared to those in the 1980s and early 1990s [102]. We focus here on the physical mechanism for the hiatus while referring the issues of data quality and communications to discussions elsewhere ([25, 51, 102, 76]).

Intensive research ensued as the hiatus lengthened through 2013 and interest in the phenomenon rose. The IPCC Working Group I decided at the last of the four lead-author meetings in January 2013 to discuss the hiatus in the Fifth Assessment Report (AR5; [22]). This proved wise as the hiatus was the most asked question 8 months later at the press conference marking the release of the AR5 following the IPCC Plenary in Stockholm. Here, we review the progress made in this hot topic that addresses the above questions.

Broadly, two schools of thought have emerged regarding the cause of the recent global warming hiatus. The “SST view: Tropical Pacific Pacemaker” section presents the sea surface temperature (SST) view that internal variability modulates the rate of GMST increase. Specifically, the hiatus occurred as a result of a decadal cooling of the tropical Pacific Ocean that opposed the anthropogenic warming. The “Energy View” section discusses various versions of energy view that relate the hiatus to changes in energy flux at the top of the atmosphere (TOA) or three-dimensional redistribution of heat in the ocean. The SST and energy views are not mutually exclusive, and we will note the connections where appropriate. The “Summary and Discussions” section is a summary and discusses broad implications. An important finding from this review is that GMST, widely used to track anthropogenic effect on global climate, contains a large component of internal variability that is distinct from the forced component in spatial structure, energetics, mechanism, and predictability. A legacy of hiatus research is that it connects big dots in climate science, between internal climate variability and anthropogenic warming, around which large but separate communities have previously developed. The climate variability community speaks the language of coupled ocean-atmosphere feedback and teleconnection that emphasizes spatial patterns, while the global warming community relies on concepts such as radiative forcing and climate feedback that focus on the global mean. The SST and energy views of the hiatus reflect these distinct traditions, but the hiatus puzzle has forced critical examination of these views and challenged us to quantify decadal variations in TOA radiation and ocean heat uptake.

SST View: Tropical Pacific Pacemaker

GMST is expected to vary without changes in radiative forcing. Indeed, early studies considered such internal variability as a plausible cause of the hiatus [20]. It was unclear at the outset, however, whether cold swings of internal variability are large enough to halt GMST flat for as long as 15 years. Statistical analyses of CMIP5 simulations suggest that internal variability explains the difference in 15-year GMST trend between models and observations [61]. More questions followed: Is such internal variability of GMST organized into coherent spatial patterns of prominent climate modes? What drives

these modes of variability, and are they—hence the hiatus—predictable?

Global climate model (GCM) simulations [5, 58, 65, 66, 72] consistently show that unforced decadal variability of GMST is associated with a global pattern of surface temperature that resembles the Pacific Decadal Oscillation (PDO) [6, 103], a mode sometimes also called the Interdecadal Pacific Oscillation (IPO; [32, 83]). Like El Niño, a positive Pacific Decadal Oscillation PDO is associated with the warming of the tropical Pacific and increased GMST. Unlike El Niño, the tropical Pacific warming is much broader in the meridional direction on decadal than interannual timescales [103]. By regressing out the forced change at each grid point using the CMIP5 ensemble mean GMST, Dai et al. [14] performed the empirical orthogonal function (EOF) analysis of “unforced” surface temperature variability (surface air temperature over land and SST over the ocean) for 1920 to 2013. The leading mode is PDO while the fourth mode resembles the Atlantic Multidecadal Oscillation (AMO). The PDO dominates GMST variability, with a significant contribution from the AMO. The second and third modes, while explaining more regional variability than AMO, do not project onto GMST. A reconstruction using the forced change, PDO and AMO modes successfully reproduced observed GMST, including the recent hiatus.

The Pacific SST change during the hiatus indeed shows a PDO-like pattern with negative anomalies over the tropical Pacific (Fig. 2 top left). The La Niña analogue indicates that this decadal cooling of the tropical Pacific would reduce GMST. Statistical methods have been developed to quantify this tropical Pacific effect from observations by regressing GMST against an ENSO index, typically Niño 3.4 SST. The results show an important contribution from the tropical Pacific cooling to the GMST hiatus [23, 40] as well as to previous slowdown decades [69]. A caveat is that the regression approach assumes an equal tropical Pacific effect between interannual ENSO and decadal PDO. The short observational record precludes a stringent test of this assumption, but climate models consistently show a larger tropical Pacific effect on GMST on decadal than interannual timescales (Fig. 3) because of a broader meridional scales of tropical SST anomalies [45, 96]. Thus, the regression based on limited observations that are dominated by interannual ENSO is likely to underestimate the magnitude of the tropical Pacific effect on GMST.

Pacemaker Experiments

Coupled GCMs under increasing greenhouse forcing simulate decadal hiatus events [34, 84], but the timing of these events is not generally synchronized with observations [65, 66]. In the CMIP5 models where the decadal GMST trend matches the observed hiatus for the early twenty-first century, the PDO is in a negative phase. A coupled model initialized with

observations in the mid-1990s is able to simulate the ensuing hiatus and negative PDO phase much as observed [67]. This demonstrates that climate models capture the processes that produce the hiatus. In a pacemaker experiment that forces SSTs over the tropical Pacific to follow the observed evolution [48], Kosaka and Xie [43] showed that the GCM reproduces the recent hiatus. The decadal trend in GMST is substantially reduced compared to the historical simulation without the tropical Pacific SST restoring, and the pacemaker result agrees much better with observations (Fig. 4). The area where SST anomalies are restored represents less than 9% of the Earth surface. The SST restoring reduces the GMST trend, but the GMST response in the pacemaker run is 3–4 times larger than this trivial direct effect [45], indicating the importance of teleconnections. For example, the tropical Pacific cooling causes nearly the entire tropical warming to slow down (compare Fig. 2 middle and bottom rows).

In the equatorial Pacific, the La Niña-like decadal cooling is associated with the intensified easterly trade winds (Fig. 2), suggestive of Bjerknes feedback of ocean-atmosphere interaction much as in ENSO. Because of this feedback, the pace-making effect of the tropical Pacific on the recent hiatus has been demonstrated by prescribing observed wind variations in GCMs [17, 21, 97], instead of restoring SST. Both SST- and wind-forced pacemaker experiments reproduce a significant slowdown of GMST increase over the hiatus period. The SST restoring produces the intensified trade winds [44, 97] and likewise the prescribed trade wind intensification causes the tropical Pacific to cool.

The wind-forcing method ensures a closed global ocean heat budget unlike the SST-restoring method (Douville et al. [19]). The fact that the SST-restoring method reproduces the hiatus despite not conserving heat in the ocean suggests that energy conservation is not a first-order constraint for the phenomenon (“Decreased Radiative Forcing” section). The pacemaker experiments show that teleconnections induced by tropical Pacific SST change are important, e.g., by holding the entire tropics from warming during the hiatus.

Spatio-Seasonal Fingerprints

Discussions of the hiatus in the literature tend to focus on GMST. Much information on the mechanism for GMST variability is lost in global averaging. By unpacking GMST in spatial and seasonal dimensions, we can identify patterns of internal variability that affects GMST. For example, we have already seen that much of the internal variability in GMST is accompanied by large spatial variations (e.g., the PDO pattern), unlike the anthropogenic warming that varies much less in space (Fig. 2).

Patterns of surface temperature change during the hiatus are in much closer agreement with observations in the pacemaker experiment than in the historical run (Fig. 2). The comparison

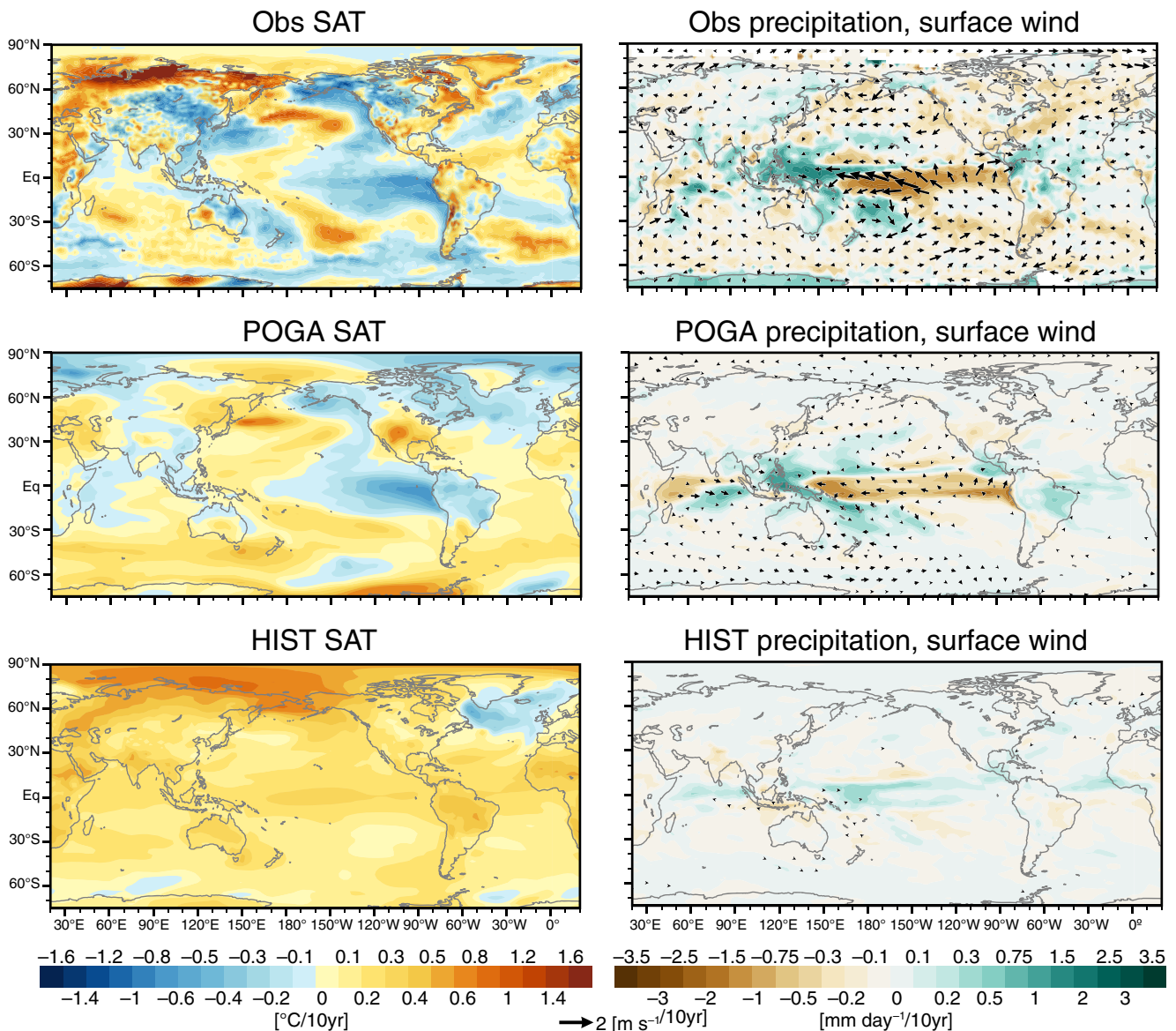


Fig. 2 Trend patterns of surface air temperature (SAT; *left*), precipitation (*right, shading*), and 10 m wind (*right, arrows*) in observations (*top*) and POGA (*middle*) and HIST (*bottom*) ensemble means of Kosaka and Xie [45]. Trends are based on an “ENSO year” (June–May) average for 1997/1998–2012/2013, evaluated with the least squares fit. SAT and

10 m winds of the European Centre for Medium-range Weather Forecast Interim Reanalysis (ERA-Interim; [15]) and Climate Prediction Center Merged Analysis of Precipitation (CMAP; [99]) are used as observations

shows that the tropical Pacific cooling explains many regional changes in observations during the hiatus: cooling in the Northeast and Southeast Pacific, the “V”-shaped warming that extends from the equatorial western Pacific, warm and dry anomalies in the southern and southwest U.S. [17, 43], wetter conditions over the Maritime Continent [63], and the drier central Pacific. These regional anomalies are distinct from radiatively forced response, confirming the spatial fingerprints of the PDO. The warm water piled up in the western Pacific by the intensified trade winds sets a favorable condition for tropical cyclone growth by limiting the cold wake [70]. The anomalously deep thermocline contributed to the growth of the

supertypphoon Haiyan that made landfall on the Philippines in November 2013 [53]. The high sea level further worsened the storm surge.

The GMST change during the recent hiatus displays distinctive seasonal variations. GMST decreased in boreal winter but kept rising in boreal summer [12]. The pacemaker experiment of Kosaka and Xie [43] captures this seasonality (albeit slightly weaker). This seasonality arises from the seasonal variations of the tropical Pacific SST trend [2] and atmospheric eddy heat transport from the tropics to the extratropics. The occurrences of hot extremes over land have continued to increase during the hiatus period [90].

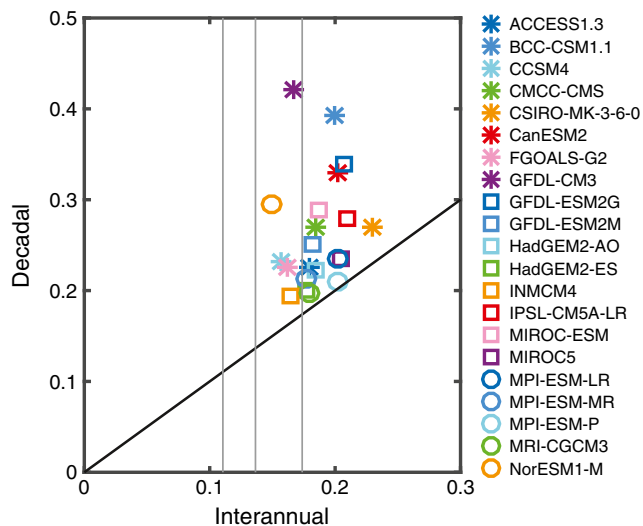


Fig. 3 Comparison of the interannual (*abscissa*) and decadal (*ordinate*) regression coefficients ($^{\circ}\text{C}/^{\circ}\text{C}$) of GMST against the tropical Pacific (15°S – 15°N , 180° – 90°W) SST in 21 CMIP5 pre-industrial control simulations. *Gray vertical lines* represent interannual coefficients from three reanalyses (from the lowest: ERA-Interim, Japanese 55-year reanalysis [42], and National Center for Environmental Predictions/National Center for Atmospheric Research reanalysis [37]). Adopted from Wang et al. [96]

The hiatus is not just a slowdown in GMST increase but is accompanied by rich structures in spatial and seasonal dimensions. Bringing in the spatio-seasonal information strengthens the case of the SST view. The observed patterns broadly match the spatio-seasonal fingerprints of the negative PDO, in surface and tropospheric temperature [38]. The match points to the tropical Pacific as a key pacemaker of GMST change.

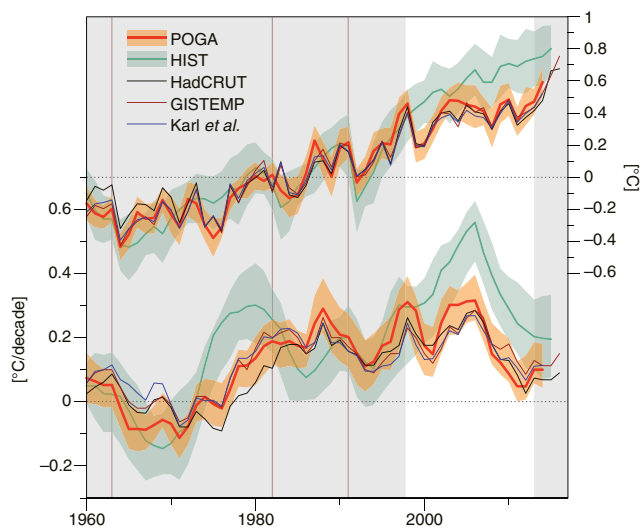


Fig. 4 GMST anomalies (*top with the right axis*) and its trend over the preceding 15 years (*bottom with the left axis*). Based on HadCRUT 4.5.0.0, GISTEMP and Karl et al. [39], and POGA and HIST experiments of Kosaka and Xie [45]. *Green and orange shadings* indicate a unit ensemble standard deviation. Trends are evaluated as Sen's slope. *Brown vertical bars* indicate major volcanic eruptions in the tropics. The hiatus period is highlighted with the *white background*

Origin of Tropical Pacific Cooling

PDO is the decadal component of the leading principal component (PC) of Pacific SST variability (with GMST subtracted at each grid point; [6, 103]). It can also be obtained as the leading EOF of decadal SST variability of the world ocean after the radiatively forced change has been removed [14]. It is an internal mode of the climate system and often emerges as the leading EOF mode of SST in unforced control runs of GCMs (e.g., [32, 64]). Tropical Pacific mean SST tracks this mode well (e.g., [96]). Various mechanisms have been proposed for PDO [78], but a consensus on the dynamical origin has not yet emerged. Subsurface ocean dynamics is of fundamental importance for interannual ENSO, but its role remains to be quantified in PDO. In fact, a motionless ocean mixed layer model coupled with an atmospheric model can generate PDO-like variability with temporal variance and spatial pattern similar to the GCM with a fully dynamical ocean [11, 79, 101].

Interactions among tropical ocean basins appear important for PDO phase transition. For example, the tropical Atlantic warming associated with AMO phase transition might have driven PDO into a negative phase [9, 46, 52, 62] and hence the decadal tropical Pacific cooling from the 1990s, giving rise to the hiatus. The tropical Indian Ocean is an important intermediate in this cross-basin interaction [56, 73]. Indeed, a pan-tropical zonal dipole pattern, with tropical Pacific SST in opposite sign to the rest of the tropics, emerges as the most predictable mode of the tropics at multi-year leads [8]. The cross-basin interaction effect is not deterministic but modulates the phase probability of PDO [9]. The relationship between the PDO and AMO needs further studies. Lag correlations in the Pacific pacemaker experiments of Kosaka and Xie [43] show that the PDO leads the AMO on average by about 3 years [69].

It is interesting to note that the tropical Pacific pacemaking effect is distinct from that by the tropical Atlantic or Indian Ocean. While Pacific variability causes the entire tropics to respond in the same sign, tropical Atlantic or Indian Ocean variability drives the tropical Pacific into an opposite phase to the rest of the tropical oceans [52]. In other words, the warming in part of the tropical oceans does not guarantee an increase in GMST. The tropical Pacific is unique in inducing a large response in GMST as illustrated by the recent hiatus.

PDO has completed a full cycle over the past 45 years since 1970, a period during which the rate of change in anthropogenic radiative forcing remains nearly constant. This suggests that the PDO's transition into negative phase that started in the 1990s is probably due to internal processes of the coupled ocean-atmosphere system, instead of being externally forced [35]. While anthropogenic and volcanic aerosols can induce a weak tendency of a La Niña-like tropical Pacific cooling [59, 88, 91, 93, 100], internal variability in models is often much

larger over the equatorial Pacific. Furthermore, a recent study shows that an increase in Asian aerosols fails to induce an intensification of the equatorial trades over the Pacific [47].

Energy View

Energy imbalance at the top of the atmosphere (N , downward positive) can be decomposed to the radiative forcing (F), say due to anthropogenic changes in GHG and/or aerosols, and climate feedback that is often approximated as proportional to GMST change (T)

$$N = F - \lambda T, \quad (1)$$

where λ is the climate feedback parameter. As 93% of this energy imbalance is absorbed by the ocean, the ocean mixed layer (OML) budget is cast as

$$C_m dT / dt \approx F - \lambda T - \varepsilon (T - T_d), \quad (2)$$

where C_m is the heat capacity of OML, and the heat exchange with the deep ocean is parameterized as a Newtonian cooling, and T_d is the deep ocean temperature change [31]. As the OML represents a very small fraction ($\sim 1/40$) of the whole ocean depth, $T_d / T \ll 1$ for slowly varying forcing such as the anthropogenic increase in GHGs. The effective damping time-scale of GMST $\tau_m = C_m / (\lambda + \varepsilon)$ is about a decade [31], an estimate that satellite observations of the response to a major volcanic eruption confirms [87]. For slowly varying radiative forcing, the time derivative term in Eq. (2) is small. The quasi-steady solution $T = F_{2\times\text{CO}_2} / (\lambda + \varepsilon)$ is called the transient climate response while $T = F_{2\times\text{CO}_2} / \lambda$ the equilibrium climate sensitivity (when the deep ocean is fully adjusted to OML temperature), where $F_{2\times\text{CO}_2}$ is the radiative forcing due to a doubling of CO_2 concentration.

Energy theory of Eq. (2) explains the anthropogenic increase in GMST since the industrial revolution, as affirmed by five generations of IPCC reports (“Box” section). Several types of energy view on the recent global warming hiatus exist, variously invoking a decrease in radiative forcing, increased ocean heat uptake, and/or heat redistribution within the ocean. This section reviews these energy views.

Decreased Radiative Forcing

CMIP5 historical simulations use observational estimates of changes in atmospheric composition (GHGs, aerosols, and ozone) and solar irradiance up to December 2005. Models are subject to Representative Concentration Pathways (RCPs) from January 2006. Near-term projections are not very sensitive to RCPs because the forcing scenarios are similar during the first few decades due to the inertia of existing

socio-economic infrastructures. The multi-model mean GMST from the combined historical-RCP runs increases much faster than observations during 1998–2013 (Fig. 4), thus creating the hiatus problem. (The 2006 peak in 15-year trends in the ensemble-mean historical run is due to the sharp GMST decrease following the June 1991 eruption of Mount Pinatubo.) Only less than 4% of CMIP5 runs simulate the hiatus [24, 67] as internal decadal variability in this small subset of models happens to synch up with observations.

Retrospective analyses show deviations in radiative forcing from RCPs: small volcanic eruptions since 2000, an unusual dip in solar irradiance from 2000 to 2009, and uncertainties in aerosol loading and climate effect. The trend in revised radiative forcing for 1998–2012 varies among studies, from -0.3 W m^{-2} [89] to $+0.1 \text{ W m}^{-2}$ [80]. The uncertainty illustrates the challenge in quantifying short-term (decadal) changes in radiative forcing. Using the transient climate response of 2°C (at CO_2 doubling with $F_{2\times\text{CO}_2} = 4 \text{ W m}^{-2}$), the transient response to a -0.3 W m^{-2} correction in radiative forcing is -0.15°C under the quasi-steady assumption. For a radiative forcing correction $\delta F = \alpha t$ with t representing time (say, starting from 2006), the GMST correction at $t = \tau_m$ (\sim a decade) is $\alpha \tau_m / (\lambda + \varepsilon) / e = -0.055^\circ\text{C}$ for $\alpha \tau_m = -0.3 \text{ W m}^{-2}$. This is only 37% of the quasi-steady response because of the finite thermal inertia of OML. This is consistent with Outten et al. [80] that the updated radiative forcing yields negligible difference in GMST trend during the hiatus period, and with Collins et al. [13] that the near-term GMST projections are largely insensitive to RCPs.

Enhanced Ocean Heat Uptake

An often-heard argument is that the ocean takes up extra heat during the hiatus. This statement is apparently based on Eq. (2): as internal variability of GMST is in the cold phase, ocean heat uptake ($F - \lambda T$) is at the peak. Here, we equate net TOA radiation to ocean heat uptake ($dH/dt = N$, where H is the ocean heat content). ENSO is often invoked to support this argument. For interannual variability, the ocean heat uptake is indeed significantly correlated with GMST but the maximum ocean heat uptake delays behind the peak cold phase by 45° (Fig. 5a) [95]. Since the hiatus corresponds to the transition of GMST from the peak to trough, not at the time of La Niña, ocean heat uptake integrated over the interannual hiatus period actually decreases.

GMST and ocean heat uptake are poorly correlated for decadal and longer internal variability (Fig. 5b; [4, 81]). The correlation is marginal even when time lag is allowed. The phase lag of the maximum ocean heat uptake behind the minimum GMST is about 45° , similar to that of ENSO. Thus, the ocean heat uptake actually slows during a decadal hiatus caused by internal variability [101].

Thus, the global-mean net TOA radiation is generally not simply a function of GMST as in Eq. (2). This simple linear relationship was extensively tested and verified for externally forced climate response [28]. For internal variability, global TOA radiation and GMST are not in phase, and the regression coefficient (“internal climate feedback parameter”) varies with timescale, much larger for ENSO than decadal variability. While ENSO is often invoked as an analogue to PDO, they are quite different in energetics perhaps because ocean dynamics is essential for ENSO but seems secondary for PDO [11, 79]. The distinct energetics between forced and internal changes, and between ENSO and PDO is consistent with the notion that climate feedback, chiefly the low-cloud response, is dependent on spatial pattern of SST change [104]; the anthropogenic warming is uniform to first order while both ENSO and PDO feature strong SST variations of opposite signs. To emphasize the distinct energetics, Xie et al. [101] suggest replacing Eq. (1) with

$$N = F - \lambda T_F - \lambda_I T_I, \quad (3)$$

where the subscripts F and I denote forced and internal changes, respectively, and λ_I is complex to account for the phase lag between GMST and net TOA radiation (Fig. 5).

Heat Redistribution in Ocean

At the limit of $r(N_I, T_I) = 0$, the whole column ocean heat content associated with the internal variability does not systematically change during the hiatus

$$dH_I^m + dH_I^d = 0, \quad (4)$$

where the superscripts m and d denote the OML and deep ocean below, respectively. This supports the notion that the

ocean continues to take up anthropogenic heat and cause thermosteric sea level rise during the surface warming hiatus. The heat content change in the deep ocean layer follows

$$dH^d = dH_F^d + dH_I^d = dH_F^d - dH_I^m. \quad (5)$$

As the internal change in OML heat content is negative during the hiatus by definition, the deep ocean heat uptake underneath accelerates compared to the baseline of the forced change (dH_F^d). Thus, extra heat is indeed stored in the subsurface ocean below OML, but this does not necessarily explain why the hiatus occurs because the relationship between the deep ocean heat storage and surface warming hiatus as expressed in Eq. (5) is merely diagnostic, rather than causal one way or another. That is, the net TOA energy imbalance is about the same for hiatus and accelerated warming decades, with a similar amount of heat absorbed over the full depth of the ocean, but internal ocean processes distribute the heat to different layers in different decades [66].

One may argue that the extra heat stored in the subsurface ocean during the hiatus can somehow find its way into the OML at a later time, causing the internal change in GMST to swing towards a positive phase. This is indeed the case for ENSO as depicted by the delayed oscillator and recharge theories (e.g., [77]). Comparison of coupled simulations with a fully dynamical and slab mixed layer ocean models suggests, however, that decadal variability, both in GMST and the tropical Pacific, might be distinct from ENSO in that subsurface ocean dynamics plays a secondary role [11, 72, 101]. Decadal variability in SST is strikingly similar between the dynamical ocean and OML runs, both in spatial structure and temporal variance. This questions the argument that the vertical heat redistribution is essential for decadal hiatus events. The success of tropical Pacific pacemaker experiments, whether done by restoring SST [43] or by imposing wind variability [17, 21,

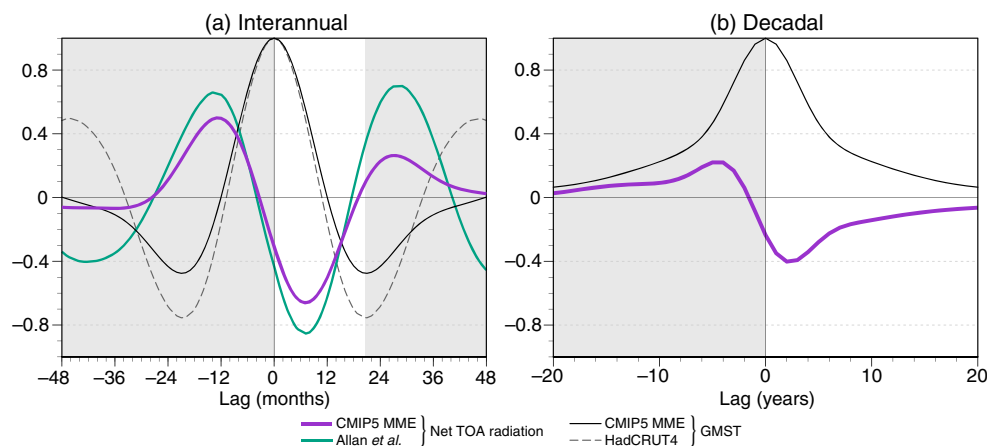


Fig. 5 Lagged correlation of net TOA radiation against GMST in pre-industrial control simulations of 22 CMIP5 models and observations consisting of HadCRUT and net TOA radiation of Allan et al. [1]. In **a**, each monthly time series has been deseasonalized and a 2–10-year band-pass filter has been applied, while in **b**, a 10-year low-pass filter has been

applied to annual time series. In **a**, the observational analysis is performed for January 1985–February 2014 excluding 3 years after the Pinatubo eruption (June 1991–May 1994). The internal cooling period (corresponding to a hiatus when radiatively forced warming is superposed) is highlighted with the *white background*

97], appears to corroborate the notion that the planetary energy balance may not be fundamental for internal variability in GMST and PDO.

Considering that the correlation between full-depth ocean heat uptake and GMST is not zero, we can generalize Eq. (4) as

$$dH_1^m + dH_1^d = dH_1. \quad (6)$$

Internal variability in TOA radiative imbalance ($\sim dH_1$) tends to be in phase with GMST change (Fig. 5). This in-phase co-variability between dH_1^m and dH_1 reduces the internal variance of lower-layer OHC, compared to the limit of adiabatic variability Eq. (4).

The vertical heat redistribution argument has been extended to include horizontal redistribution. The rationale is that to the extent that vertical heat redistribution causes the surface warming hiatus, one can narrow down the mechanisms for the hiatus further by identifying where and how the extra subsurface heat is stored [7, 49, 66]. Like the vertical heat redistribution theory, the horizontal redistribution argument needs dynamical mechanisms by which subsurface heat content anomalies drive SST changes.

The decadal cooling of the tropical Pacific both fits the SST view and meets the vertical heat redistribution requirement for the global surface warming hiatus at the same time. The intensified easterly trades associated with the tropical Pacific surface cooling shoal the thermocline in the east while deepening it in the Indo-western Pacific [49, 54]. This wind-driven thermocline adjustment creates an apparent vertical dipole of heat that helps satisfy Eq. (5).

It is still too early to conclude whether the vertical heat redistribution is merely diagnostic or actually drives and predicts internal variability of GMST. More research is necessary into the processes by which ocean heat content perturbations vary in the vertical and horizontal directions (e.g., [33, 66]) and affect SST.

Summary and Discussions

The recent global surface warming hiatus has spurred wide interest in decadal changes in the climate system. Many studies support the SST view that the tropical Pacific cooling caused the slowdown of GMST increase for 1998–2013 via ocean-atmospheric teleconnections within and out of the tropics. The pacemaker effect of tropical Pacific variability on GMST is corroborated by the analogy of ENSO and by the match of seasonal and spatial fingerprints in observations. Climate models consistently identify the PDO as the mode with a considerable projection onto GMST, but the magnitude of this tropical Pacific effect appears dependent on timescale and models. The GMST regression against tropical Pacific SST is consistently larger for decadal than interannual variability, indicating that statistical methods

based on interannual ENSO underestimate the decadal tropical Pacific effect [96]. Reliable estimates of decadal variance and GMST projection of tropical Pacific SST are necessary.

GMST is a convenient metric to track the progression of anthropogenic climate change. The metric is reliable when trends are calculated over a sufficiently long period of time (say, several decades) to suppress internal variability. The recent hiatus demonstrates that over as long as 15 years, internal variability can be as large as the anthropogenic increase of GMST (~ 0.2 °C/decade) to render this metric ineffective. Extensive studies of the hiatus reaffirm that radiatively forced and internal changes of GMST are distinct in spatial pattern (uniform to first order vs. variations between positive and negative regions), mechanism (driven by TOA energy perturbations vs. positive feedback of coupled ocean-atmosphere interaction), and hence predictability. To the extent that radiative forcing is predictable, the projection of anthropogenic warming for the next decade and two is quite reliable and not sensitive to models and RCPs [13]. The skill in predicting internal variability (tropical Pacific SST and GMST), by contrast, is currently limited to about 1 year [41], although some skill has been suggested in predicting large PDO phase transitions [68, 94]. (Considerable skills exist at shorter leads of a season or two.) Thus, decadal prediction of GMST is limited by the predictability of the internal variability. Deeper understanding of the physical mechanism for PDO (Z. Liu, in this topical section) is necessary to identify and exploit the predictability beyond a year.

Enhanced global observations of the upper 2000 m ocean by Argo floats show robust ocean heat uptake over the past one and half decades [86], a result used to calibrate the global radiative imbalance at TOA from the Clouds and the Earth's Radiant Energy System (CERES) satellite mission [55]. Argo observations in the Southern Ocean prove crucial, which accounts for much of the global heat uptake but was poorly sampled in the pre-Argo era. The recent hiatus highlights the challenges the current observing system faces in testing various energy theories that the “Energy View” section reviews. The hypothesis of reduced radiative forcing during the hiatus is theoretically plausible but remains to be quantified from observations of TOA radiation and ocean heat content change. In fact, decadal variations in ocean heat uptake differ considerably among different Argo datasets and with CERES observations of TOA radiation (Fig. 6). The disagreement among ocean datasets, all based on the same Argo profiles, may indicate the intrinsic challenge of the existing Argo system to sample internal variability in ocean heat content, which features strong three-dimensional structures of opposite signs (Fig. 7). The observing system seems adequate to capture the anthropogenic warming in the ocean, which is horizontally uniform to first order with a simple upward-intensified structure in the vertical. A caveat is that the ocean below 2000 m, beneath sea ice and in marginal seas remains poorly sampled [85].

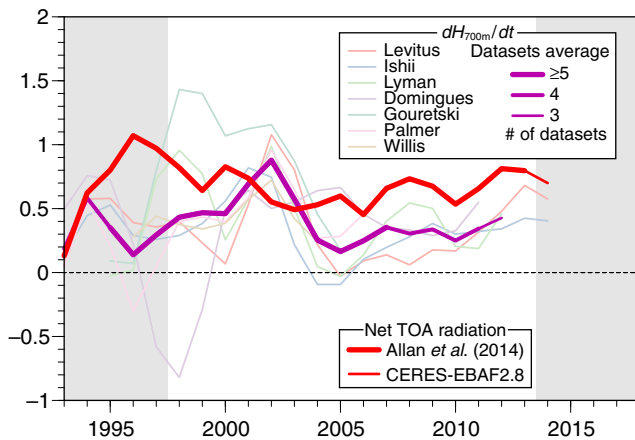


Fig. 6 Observed annual net TOA radiation and top 700 m global ocean heat uptake (dH_{700m}/dt scaled in unit of $W m^{-2}$). Three-year running averaging (centered at each plotted year) has been applied. Net TOA radiation is based on Allan et al. [1] extended with CERES-Energy Balanced and Filled (EBAF) Edition 2.8 [55]. dH_{700m}/dt is evaluated as a centered difference of annual global ocean heat content estimated by Levitus et al. [50], Ishii and Kimoto [36], Lyman and Johnson [57], Domingues et al. [18], Gouretski and Reseghetti [27], Palmer et al. [82] and Willis et al. [98]

Over the instrumental era, global warming took place in two steps, with the first and second warming epochs over the 1910s–1930s and 1970s–1990s. Instead of a two-step rising staircase in observations, the ensemble mean of CMIP5 historical simulations that reflect only external forcing produces piece-wise linear warming, with a change in the linear

rate in the 1960s. An extended Pacific-pacemaker simulation shows that observed tropical Pacific SST variations account for much of the difference of the historical simulation from the observed warming staircase [45]. To the extent this is correct, one can estimate internal variability of GMST from such pacemaker experiments and derive anthropogenic warming by subtracting the model-derived internal variability from observations (Fig. 8). Unlike the conventional model-based method, this new method of deriving forced GMST change is largely free of the uncertainties in radiative forcing and climate sensitivity. The new method yields an anthropogenic warming of $1.2\text{ }^{\circ}C$ from the late nineteenth century, much higher than the visual estimate of $0.9\text{ }^{\circ}C$ from raw data at 2013. The higher estimate from the POGA pacemaker run is now in line with the visual one as GMST has since increased by $0.3\text{--}0.4\text{ }^{\circ}C$, aided in part by the major El Niño event of 2015–2016. The $1.2\text{ }^{\circ}C$ achieved anthropogenic warming heightens the challenges to meet the $1.5\text{ }^{\circ}C$ goal of the Paris Agreement. Further research and the planned multi-model ensemble of the pacemaker experiments in CMIP6 [3] will improve the estimate including the range of inter-model uncertainty.

Hiatus research has led to a wide recognition that internal variability is large enough to cause considerable modulations of global warming rate over a decade and longer. It forged a closer integration of the climate variability and climate change communities, each with different foci and traditions from the other. For example, the planetary energy budget is an important foundation of global warming research. The attempt to

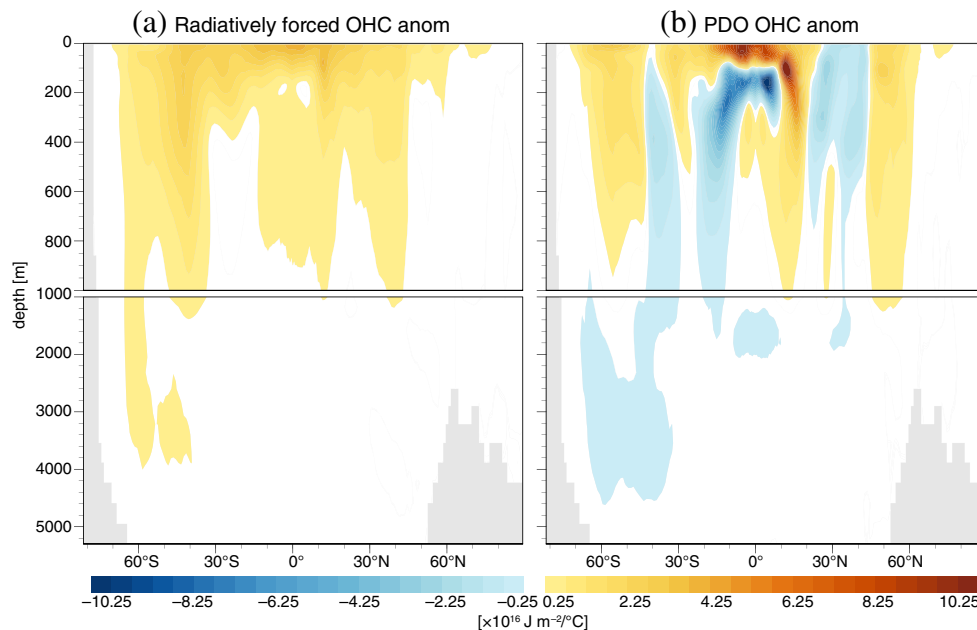


Fig. 7 Zonally accumulated ocean heat content anomalies regressed against **a** GMST and **b** a PDO index defined as the leading PC of 10-year low-pass filtered SST over $[20^{\circ}S\text{--}20^{\circ}N, 160^{\circ}E\text{--}90^{\circ}W]$. Based on ensemble mean of a 10-member historical simulation for 1901–2005 (**a**)

and a 1000-year pre-industrial control experiment (**b**; linearly detrended) with the Geophysical Fluid Dynamics Laboratory Climate Model version 2.1 (CM2.1; [16]). All scaled to $1\text{ }^{\circ}C$ GMST increase

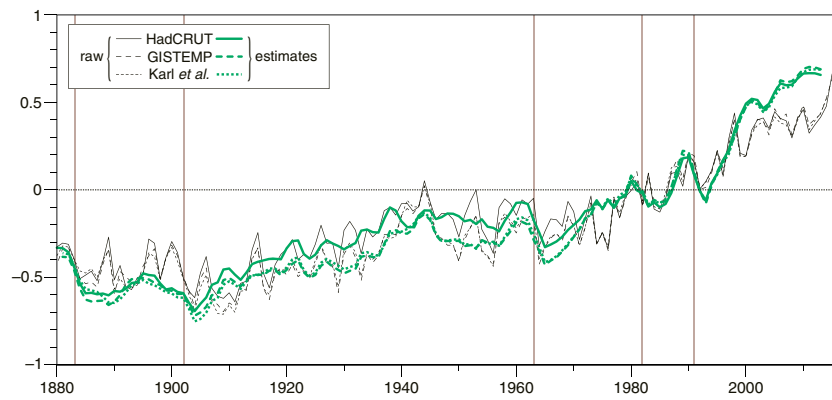


Fig. 8 Radiatively forced GMST anomalies (°C; green curves) estimated as observations minus “the tropical Pacific effect” (POGA minus HIST ensemble mean). Three-year running average is applied to suppress noise. Black curves show raw annual GMST anomalies. The observational

datasets, model experiments, and definition of climatology are the same as in Fig. 4. Brown vertical lines indicate major volcanic eruptions in the tropics

develop an energy view of the hiatus has caused some confusion regarding internal variability, as critically reviewed in the “Energy View” section. The energy view of the hiatus highlighted the need and challenges for accurate measurements and physical interpretation of global ocean heat uptake and the planetary energy budget on the decadal timescale. Hiatus research motivated the climate variability community to look for modes that project on the global mean and develop energy perspectives including how ocean heat content evolves three-dimensionally. The hiatus phenomenon provides a new impetus to understand and predict decadal variability. Likewise, it compels the global warming community to look beyond the global mean and consider spatial patterns. On the regional scale, the superposition of forced warming and a negative PDO explains many observed changes during the hiatus: prolonged droughts in the Southwest US [17], an intensified Walker circulation over the tropical Pacific, weak sea

level change on the west coast of the Americas, and accelerated sea level rise in the tropical western Pacific [71].

Box. Why Cannot the Observed Centennial Warming Be Due to Internal Variability?

The recent hiatus shows that internal variability can cause GMST to increase or decrease over extended periods (“SST view: Tropical Pacific Pacemaker” section). It is indeed hard to reject the above hypothesis based on the GMST record only, but the consideration of the spatial pattern can rule out this possibility. Modes of internal variability in the ocean-atmosphere system feature large spatial variations of SST anomalies with both positive and negative regions (Fig. 2). During El Niño, for example, SST increases in the tropical Pacific but decreases in the midlatitude Pacific in both

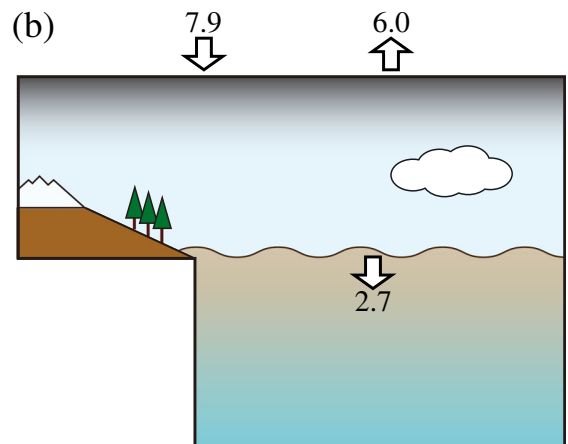
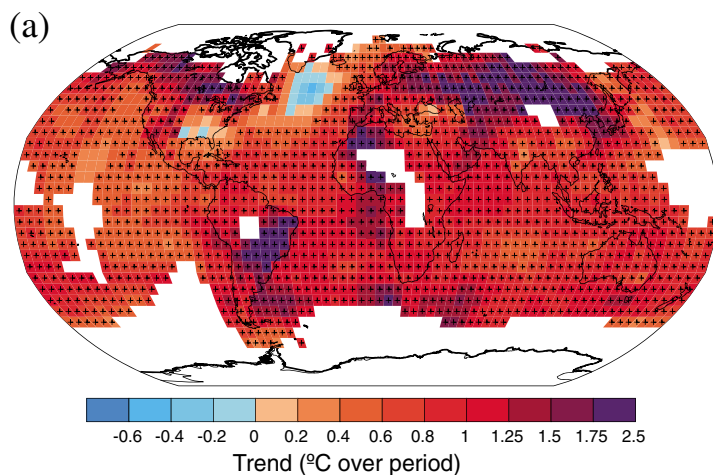


Fig. 9 a Surface temperature trend for 1901–2012. White areas indicate incomplete data. Plus sign indicates 90% statistical confidence of the trend. Adopted from Stocker et al. [92]. **b** A schematic of the Earth’s energy budget. Values are cumulative energy inflow, outflow, and

storage in ocean for 1971–2010 ($\times 10^{23}$ J) based on Box 13.1 of Church et al. [10]. The energy outflow assumes an equilibrium climate sensitivity of 3.0 °C for CO₂ doubling

hemispheres. GMST is the residual of this pattern of SST increase and decrease, one order of magnitude smaller than regional SST anomalies. Surface temperature change during the instrumental era, by contrast, is positive everywhere except over the subpolar North Atlantic (Fig. 9). The spatially “uniform” surface warming, with enhanced magnitude over land and towards the Arctic, is characteristic of climate response to GHG radiative forcing [60].

Global ocean heat content is observed to increase steadily since the 1970s when reliable data are available (Fig. 9). The ocean warming probably started much earlier with the anthropogenic increase of atmospheric GHGs after the industrial revolution [26]. The steady increase in ocean heat content requires a net downward TOA radiative imbalance. As in Eq. (1), one can calculate radiative forcing due to atmospheric composition changes from radiative transfer, while the climate feedback term is indirectly inferred from observed GMST change multiplied by a best estimate of λ . Remarkably, the planetary energy closes within error bars over multi-decadal periods, based on independent observations of subsurface ocean temperature, atmospheric compositions, and surface temperature [75]. The ocean heat uptake is also in quantitative agreement with independent global sea level estimates. The closure of planetary energy and sea level budgets is a major achievement of AR5 [10].

The above discussion does not use climate models and is based solely on observations. One does not have to rely on GCMs to conclude that the observed warming over the past century is due to the anthropogenic emissions of greenhouse gases. The observed warming pattern and energy balance are the compelling support evidence.

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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