Current rapid global temperature rise linked to falling SO$_2$ emissions

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Abstract. It is widely held that global temperature variations on time scales of a decade or less are primarily caused by internal climate variability, with smaller contributions from changes in external climate forcing such as solar irradiance. This paper shows that observed variations in global mean surface temperature, $T_{GS}$, and ocean heat content (OHC) during the last 1–2 decades imply major changes in climate forcing during this period. In a first step, two independent methods are used to evaluate global temperature corrected for ocean–atmosphere heat exchange. El Niño/Southern Oscillation (ENSO) corrected $T_{GS}$ (written as $\bar{T}_{GS}$) is shown to agree closely with a novel temperature metric $\bar{\theta}$ that combines uncorrected $T_{GS}$ with scaled OHC. This agreement rules out a substantial 21st-century contribution to $\bar{T}_{GS}$ from ocean–atmosphere heat exchange. In contrast to $T_{GS}$, the time series $\bar{T}_{GS}(t)$ provides a clear fingerprint of transient global cooling associated with major volcanic eruptions, enabling a more accurate empirical estimate of the climate response of the global mean surface. This allows more accurate estimation of the net climate forcing by stratospheric aerosols and solar irradiance, which is then subtracted from $\bar{T}_{GS}(t)$ to determine the underlying signal of anthropogenic global warming. Key features of this signal are a slowdown from the late 1990s to 2011 – corresponding to the well known climate hiatus – and a subsequent sharp upturn indicating a steep increase in anthropogenic climate forcing. It is argued that the only plausible cause for this increase is a large fractional decrease in tropospheric aerosol cooling. This attribution is supported by satellite-based observations of a >50 % decrease in SO$_2$ emissions from large sources during the last six years. It suggests that current clean-air policies and replacement of coal by natural gas are driving a significant human made climatic event, 2–4 times faster than greenhouse driven warming alone. If confirmed, this implies a considerably shortened timescale to meet the IPCC 1.5°C objective, with major implications for near-term carbon emission policies.

1 Introduction

In the last decade humanity has experienced an apparent increase in the rate of global warming, with accelerating rates of surface warming, ocean warming, mass loss from polar ice-sheets, and sea level rise. There has been much speculation over the relative influences of climate variability and underlying global temperature forcing, the latter arising largely from the effects of greenhouse gases and aerosols, upon this recent acceleration. The question is of great importance, as an attribution to temperature forcing would predict a continuation of the faster warming trend well into the next decade.
This paper uses a comparison between two largely independent measures of global temperature, one potentially dependent on non-ENSO climate variability, the other independent of all internal climate variability, to show that the primary cause of the recent faster warming rate is a sharp increase in global temperature forcing during the last five to six years. The uptick is too abrupt to be explained by changes in any of the warming greenhouse gases (GHGs), as their atmospheric lifetimes are too long. It is however uniquely consistent with a major, rapid reduction in cooling by the short lived sulfur aerosols that form as a result of anthropogenic \( \text{SO}_2 \) emissions. These aerosols form atmospheric haze and influence cloud formation in ways that have historically reflected away a small, but significant, part of Earth’s incoming solar radiation, offsetting about 0.5\( ^\circ \text{C} \) of potential global warming (Hansen 2017). Compellingly then, it turns out that \( \text{SO}_2 \) is one of the few atmospheric pollutants whose emissions have fallen sharply in recent years.

In Section 2 the temperature metrics of interest for this work are presented and discussed. Based on these results, Section 3 evaluates the warming contributions from solar intensity variations and stratospheric aerosols injected by volcanic eruptions, in order to determine more accurately the larger warming contribution from anthropogenic sources. Section 4 discusses the relationship between the recent warming acceleration and falling anthropogenic \( \text{SO}_2 \) emissions measured by the satellite borne Ozone Monitoring Instrument over the last decade. The paper concludes with a brief discussion of projected faster warming and alternative policy approaches to mitigating it.

In summary, during the last 5–6 years global temperature has been increasing 2–4 times faster than the historical warming rate which arose primarily from greenhouse gas emissions. The effect is an unintended consequence of the recent rapid reduction in \( \text{SO}_2 \) emissions driven by clean air initiatives, particularly the replacement of unmitigated coal fired power plants with clean coal and gas fired plants. Owing to the slow response tail of the climate system and likely continued reductions in \( \text{SO}_2 \), further warming is in the pipeline and could potentially bring forward the date when warming reaches 1.5\( ^\circ \text{C} \) to the late 2020s, sooner than estimated by the IPCC special report on 1.5\( ^\circ \text{C} \) global warming (IPCC, 2018). This result underscores the extreme urgency with which humanity must cut emissions of short-lived greenhouse gases such as methane and ozone-generating hydrocarbons, and pursue a fast transition to a zero carbon economy.

2 Global temperature evolution, climate variability and climate forcing

2.1 ENSO corrected global mean surface temperature

Global mean surface temperature, \( T_{\text{GS}} \), is a global measure reconstructed from measurements that sample air temperature just above the land surface and water temperature just below the ocean surface (Hansen et al., 2017). It is the most widely used global temperature metric, well attuned to the human experience of climate and its intrinsic variability driven by processes such as ENSO. However, for the same reason uncorrected \( T_{\text{GS}} \) is a poor measure of the underlying warming produced by climate forcing agents such as greenhouse gases and aerosols. A temperature signal that reduces intrinsic variability can be obtained by explicitly removing the ENSO signal from the \( T_{\text{GS}} \) time series. Owing to the response time of the global atmosphere
to changes in sea surface temperature in the El Niño affected Pacific, the ENSO component of $T_{GS}$ is delayed by about six months with respect to the Ocean Niño Index, $T_{ONI}$ (NOAA, 2018). Here I apply the simplest available method to account for this delay, a corrected temperature

$$
\bar{T}_{GS}(t) = T_{GS}(t) - \varepsilon T_{ONI}(t - t_r).
$$

Using the values $t_r = 0.5$ y and $\varepsilon = 0.1$, correlations between the $\bar{T}_{GS}$ and ENSO signals are reduced to an insignificant level and the magnitude of intrinsic variability in $\bar{T}_{GS}$ is also significantly reduced, as shown in Fig. 1. The magnitudes of the peak cooling responses to sulfur aerosols injected into the stratosphere by major volcanic eruptions in 1963, 1982 and 1991 (Textor et al., 2003) are in the region of 0.2 – 0.3°C, the decrease of 0.3°C for Mt Pinatubo being at least a factor 2 weaker than the previously reported 0.7°C peak response of ENSO-corrected lower troposphere temperature, $\bar{T}_{LT}$ (Soden et al., 2002). The $\bar{T}_{GS}$ time series also provides insight into more recent temperature changes, in particular, a slowdown in warming during the first decade of this century, both in the uncorrected and ENSO-corrected temperature records, and a more recent steep rise in temperature most clearly evident in the corrected record.

### 2.2 Earth system temperature metric

Up to now the most widely accepted explanation for the variations discussed has been intrinsic climate variability associated with heat transfers between the ocean and atmosphere, while decadal variations caused by changes in climate forcing have been thought to be small (Trenberth, 2015). Since the advent of accurate ocean temperature measurements by the Argo sensor network this viewpoint can be tested rigorously against experiment. Here I propose an ‘Earth-system’ temperature metric, $\theta$, consisting of a weighted sum of $T_{GS}$ and the upper-ocean heat content anomaly $H_{100}$, scaled to equivalent surface temperature. The weighting is chosen to cancel opposing variations in $T_{GS}$ and scaled $H_{100}$ caused by heat exchange between the bulk ocean and the global surface, the thickness of upper ocean included in the metric being chosen here to be 700 m, sufficient to capture variability driven by fluctuations in ocean heat transport on decadal timescales and below (detailed analysis in Supplementary Information). The symbols in Fig. 1(b) show the result. Values are given for the period since 2002, based on analysis of accurate ocean temperature measurements available since 2005 (Ishii and Kimoto, 2009), (JMA, 2018), (Cheng et al., 2017) and on the model-assisted analysis approach of Ishii and Kimoto (2009) applied to data of the Japan Meteorological Agency (2018) for the three previous years when available ocean data were sparser. Using the $\theta$ metric, the strong peak in $T_{GS}$ associated with the very large El Nino event in 2016 is removed. Moreover, in principle $\theta$ removes all ocean-atmosphere heat-exchange fluctuations, including any arising from the quasi-biennial oscillation (QBO) and the Pacific Decadal Oscillation (PDO) (see Supplementary Information).
Fig. 1 (b) shows that the trend in $\bar{T}_{GS}$ during this period is consistent with the trend in $\theta$, even though the $\theta$-weighting takes an $\approx 80\%$ contribution from scaled $H_{10}$ and only a $\approx 20\%$ contribution from $T_{GS}$ (Supplementary Information). The only substantial difference between the curves is short-term variability associated with the QBO, which shows up as fluctuations in $\bar{T}_{GS}$ but not in $\theta$. A subtler difference arises because $\theta$ is dominated by the thermal response of the upper ocean, leading to a heavier-tailed climate response and a smoother slope change than that of $\bar{T}_{GS}$, which rises steeply after 2011.

Figure 1: (a) Monthly global mean surface temperature anomaly (black curve) and $1/10 \times$ Ocean Nino Index delayed by 6 mo (blue curve), presented as 12-mo running means. The four ‘very strong’ El Niño events and six ‘strong’ La Niña events during this period (NOAA 2018a) are shaded in orange and blue, respectively, to illustrate the close correlation between the two time-series. (b) ENSO-corrected global mean surface temperature, showing strongly reduced fluctuations and the global cooling signatures of three major explosive volcanic eruptions, which are only weakly identifiable in the unprocessed GST signal. Symbols represent the effective temperature anomaly $\theta$ of the combined global mean surface and 0–750 m upper ocean, which in principle eliminates the perturbing effects of all ocean-atmosphere heat exchange processes, although at the cost of a more damped climate response (see text).
However, the slope of the $\theta$ time series still nearly doubles between the periods 2005-2012 and 2012-2017. These results provide no support for a significant contribution to $\bar{T}_{GS}$ from ocean-atmosphere heat exchange linked to non-ENSO climate variability, despite a transition in 2013 from a negative to a positive phase of the PDO (Trenberth, 2015). In contrast, they strongly suggest that the recent change in global warming rate is a response of the global ocean-atmosphere system to a change in climate forcing. This conclusion is consistent with previous analysis by Cheng et al. (2015) showing that climatic fluctuations in the heat content of the upper ocean averaged over the 0–750 m depth range have been primarily associated with changes in the relative frequency of El Niño and La Niña events, which are already accounted for in Fig. 1(b).

Figure 2: (a) Climate forcing by volcanic aerosols and solar irradiance variations between 1960 and 2000 (dashed curve) and the resulting temperature evolution of the lower troposphere (solid black curve) obtained by convoluting the forcing data with the lower troposphere response function described in the text. Symbols represent satellite measurement data. (b) Global mean surface temperature evolution obtained by the same method (solid black curve) using the updated global surface response function described in the text. The dashed curve in (b) is the tropospheric response and symbols denote the time series calculated from the annual forcings and global surface response function used by Hansen et al. (2017). The gold line represents temperature anomaly data from Fig. 1(b) after subtracting a linear background representing the rising temperature trend from anthropogenic emissions. (c) Historical evolution of the ENSO-corrected global mean surface temperature anomaly (dashed line), the temperature response to volcano and solar irradiance variations (gold solid line), and the global mean surface temperature signal after removal of the volcano and solar contributions (black solid line). The red curve shows the corresponding result after suppression of quasi-biennial oscillations using a 26-month running mean. The recent increase in slope indicates a steep rise in anthropogenic global temperature forcing, confirming the results in Fig. 1.
3 Volcanic eruptions, climate response, and the anthropogenic contribution to global warming

The shape of the volcano dips in Fig. 1(b) suggests that their influence on temperature change in this century is small and that the slowdown and recent rapid rise in global temperature are likely of anthropogenic origin. However, current understanding of the short-term response of global mean surface temperature to a forcing impulse $\delta(t)$ is limited, with commonly used models typically overestimating the magnitude of the volcano dips. In order to correct this, I have revisited the previous work of Hansen et al. (2005, 2011, 2017) in order to estimate semi-empirical climate pulse-response functions, $P_{LT}$ and $P_{GS}$, for the lower troposphere and global mean surface, respectively (details in Supplementary Information). Fig. 2 shows results for the temperature responses $T(t) = \lambda \int F_e(t - t')P(t')dt$, where $F_e$ is the net forcing in W cm$^{-2}$ and $\lambda$ is the equilibrium fast climate response. Here I use $\lambda = 0.75 ^\circ C / W m^{-2}$, a mid-range choice supported by evidence from Ref. 13 and this work (see Supplementary Information). Owing to the influence of the ocean, which generally acts as a heat sink (Hansen 2017), $P_{GS}$ has a significantly attenuated short-term and slightly enhanced long-term response, as shown in Fig. 2 (b).

Using this updated $P_{GS}$ the contribution of volcanic and solar irradiance variations, given by the solid black curve in Fig. 2(b), can be subtracted more accurately from the long-term ENSO-corrected time series in Fig. 1, in order to estimate the evolution of global mean surface temperature arising from anthropogenic climate forcing. Fig. 2 (c) shows the resulting time series. On short time scales the series contains QBO fluctuations (Zhi-Xiu, 2013), which are not removed by the ENSO correction, but these can largely be filtered out using a 26-month moving average (thick red curve). It is clear from Fig. 2(c) that the correction for volcano and solar forcing from 2000–2017 has been small, in the range 0$^\circ$C to $-0.05^\circ$C, with a time variation that tends to slightly flatten the underlying warming up to 2012 and marginally reduce the rate of recent temperature rise.

The recent acceleration in global temperature rise is of great interest and concern. Fig. 3 shows detail of the results from Fig. 1(b) for the period 1995–2017.5, including the evolution of ENSO-corrected temperature, $\bar{T}_{GS}$, and of $\theta$ based on two independent analyses of ocean heat content data (JMA, 2018), (Cheng et al., 2017), (Cheng, 2018) during the ARGO period. Also shown are the uncorrected $T_{GS}$ and scaled upper-ocean heat content curves.

The magnitude of the increase in $T_{GS}$ during the 2016 El Nino event, shown by the difference between the red dashed and black solid curves, is consistent (see Supplementary Information) with the quantity of heat transferred from ocean to atmosphere, shown by the difference between the blue dashed and black solid curves. All of the curves exhibit a long-term rising slope, whereas a decadal shift to a warmer atmosphere and cooler ocean would bend the ocean curve downwards. The average slope of the $\theta$ time series increases by a factor of two between the periods 2005-2012 and 2012-2017, and that of $\bar{T}_{GS}$ increases from nearly flat during the decade from 2002-2012 to an average slope of 0.4 – 0.5$^\circ$C/decade in the period from 2012 to mid-2017. It is inescapable, then, that the recent acceleration of global temperature is the response of the Earth system to a decadal increase in climate forcing.

Only one influence can have produced this sharp increase in climate forcing. Changes in all of the major greenhouse gases (CO$_2$, CH$_4$, N$_2$O and CFCs) are ruled out because they or their reaction products have long or intermediate atmospheric lifetimes and are thus slowly varying atmospheric constituents. Black carbon emissions (Wang, 2014) and tropospheric ozone
concentrations (Helmig et al., 2016) may have risen as a result of increased diesel use and rising emissions of non-methane hydrocarbons from the oil and gas industry, respectively, but not sufficiently to cause a drastic increase in forcing. The sole plausible candidate is SO$_2$, which forms short-lived climate-cooling aerosols (McNeill, 2007) that have historically been a powerful counterweight to greenhouse warming (Hansen et al., 2005).

### 4 An unintended consequence: recent faster warming driven by governmental anti-pollution measures

In the last decade, efforts to reduce pollution from coal-fired power plants and other sources, together with a global trend towards replacement of coal by natural gas, have led to a strong decrease in SO$_2$ emissions. In the geographical area of China, until recently the world’s largest emitter of SO$_2$, emissions from large sources measured by the Ozone Monitoring Instrument
(OMI) on EOS Aura fell by approximately 80% over the four years from 2012–2016 (Li et al., 2017), with comparable reductions in emissions from smaller sources likely as a result of domestic pollution-control measures. Moreover, global SO$_2$ emissions from (coal) power plants, currently the dominant flux of SO$_2$ to the atmosphere, fell by about 40% from 2007–2014 (Fioletov et al., 2017). The large fall in OMI-measured SO$_2$ emissions in China is especially significant because deep circulation in that region can loft aerosols to the tropopause (Neely et al., 2014), (Lau et al., 2018) and lower stratosphere (Bourassa et al., 2012), where their negative climate forcing effect may be an order of magnitude stronger than in the lower troposphere. It is therefore also plausible that the strong rise in SO$_2$ emissions in East Asia in the first decade of this century contributed to the climate hiatus during that decade. Because the sulfur aerosols formed from SO$_2$ have a short atmospheric lifetime (< 2 y), the very large decrease in emissions since 2011 will inevitably have fed through aerosol forcing.

![Figure 4: Global mean surface temperature corrected for ENSO, volcano and solar irradiance contributions (light green curve) together with an illustrative fit that ignores biennial fluctuations (dark green solid curve). The black dashed curve represents the net climate forcing by anthropogenic greenhouse gases and tropospheric aerosols which is needed to generate the dark green temperature curve. The near-term projection to 2022 is based on extrapolation of the current forcing trend (see text). Blue and orange shading correspond to periods of rising and falling global SO2 emissions, respectively, based on inventory estimates from 1950–2005 (Smith, 2011), (Klimont, 2013) and satellite observations from 2005 onwards (Fioletov et al., 2016), (Li et al., 2017).](image)

Fig. 4 illustrates the magnitude of changes in forcing required to account for the observed evolution of $\bar{T}_{GS}$. Two plateau regions in the periods 1960–1975 and 2000–2011 coincide with phases of rapid growth in SO$_2$ emissions which effectively stall the rising forcing caused by greenhouse gases. The subsequent rises correspond to periods of falling SO$_2$ emissions, which
reinforce the greenhouse warming trend. The first plateau corresponds to a 15–20 y period when global SO$_2$ emissions rose by ~2× to a record 130 Mt y$^{-1}$ in 1975 (Smith et al., 2011), which likely enhanced the negative aerosol contribution to climate forcing by nearly −0.5 W m$^{-2}$, while the second corresponds to a period of rapid emissions growth in China (Klimont, 2013). The recent rise, which is several times steeper than the greenhouse forcing trend, corresponds to a rate of decrease in negative aerosol forcing of ~16% y$^{-1}$, consistent with recent SO$_2$ emissions reductions from large sources (Fioletov, 2016), (Li et al., 2017). The extrapolation to 2022 illustrates the potential for further significant near-term warming, if the recent fall in aerosol forcing and steady rise in greenhouse gas emissions are projected at the same proportional rate as in the last five years. This further rise may become less steep if emissions elsewhere, for example, from unmitigated coal-fired power plants in India (Li et al., 2017), rise in the near future prior to transition from coal to low-carbon energy.

Negative aerosol forcing in recent history has offset about 40% of net climate forcing (Hansen et al., 2017) with about 0.5°C of additional warming to be expected if this contribution is removed. Consequently, it is no surprise that a factor > 2 decrease in SO$_2$ emissions should have such a powerful warming effect. This is the payoff from Hansen’s ‘Faustian bargain’ which has been extensively discussed (Hansen and Lacis, 1990) but has until recently been viewed as a long-term issue (Hansen, 2017), although this year subtle hints of potentially imminent changes have emerged from processes such as Arctic sea ice decline (Mueller, 2018). In reality, that future has already arrived and is driving a significant global climatic event.

5 Conclusions

El Nino corrected global mean surface temperature data suggest that, since 2011, global warming has accelerated to 2–4 times the long-term warming rate. An Earth system temperature metric comprised of upper-ocean and uncorrected global mean surface temperature data confirms an acceleration in warming since 2011, indicating that the rise is not a result of variability in ocean–atmosphere heat exchange but is likely caused by a steep increase in external climate forcing. This implies a large change in a major short-lived climate forcing agent, almost certainly tropospheric aerosols. This conclusion is consistent with satellite-based observations of a major decrease in global SO$_2$ emissions from large anthropogenic sources, particularly coal-fired power plants.

There are two potential routes to controlling further rapid temperature rise while health-harming SO$_2$ pollution continues to be phased out. They are not mutually exclusive, indeed an effective mitigation response with the least possible adverse impacts likely requires both. In the first route, the historical cooling effect of polluting tropospheric aerosols, most of which reside in the planetary boundary layer (PBL) for a relatively short time before precipitating out, is approximately replicated by injecting a smaller quantity of SO$_2$ into the stable troposphere (above the PBL). This geoengineering approach has been criticised for the potential climate shifts it may cause (Trisos et al., 2018). However, humanity has already been engaged for many decades in major inadvertent geoengineering through its increasing injection of cooling aerosols into the lower troposphere. The approach may not be excessively costly if flue stacks are used which exceed the local PBL height or are located in regions of strong vertical circulation.
The second route involves steep reductions in short-lived and intermediate greenhouse gases, which could partly offset the loss of aerosol cooling. By far the most important of these is methane, with a further contribution from ozone (Hansen et al., 2017). This presents a huge challenge to current energy and food production systems, as the mole fractions of atmospheric methane and tropospheric ozone are currently on the rise as a result of increasing emissions from oil and natural gas systems (Helmig, 2016), (Worden, 2017), with an additional contribution to rising methane from biogenic processes (Worden, 2017). A rapid reversal of this trend, together with the potential involvement of SO2-based geoengineering and intensified adaptation efforts, will be critical for global stability in the next 1–2 decades while the world tackles the still larger problem of CO2 emissions.

Appendices

Appendix 1: Time-series data and forcings

All time-series data used in the analysis for the paper are monthly values, unless otherwise stated. Global mean stratospheric optical depths used to infer direct radiative forcing by stratospheric aerosols are from NASA (2018) with the exception of values after 2007, where the GISS values are adjusted upwards in response to the recent GloSSAC aerosol analysis (Thomason et al., 2018). Solar direct radiative forcing is obtained by linear interpolation between the annual solar forcing estimates of Sato (see Supplementary Material), which agree closely with monthly estimates of direct radiative forcing based on the NOAA Solar Irradiance Climate Data Record (NOAA, 2018a). Effective radiative forcing, both by aerosols and solar irradiance variations, is calculated as 0.55 × direct radiative forcing, based on climate simulations and satellite measurements of direct short wave and secondary long wave forcing following the Mt. Pinatubo eruption (Hansen, 2005). Based on the extracted effective forcing per unit optical depth \( \tau \), 21 W m\(^{-2}\)/\( \tau \) (see Supplementary Information), the forcing correction for volcanoes prior to the 1850 – 2017 period modelled by Hansen et al. (2017) is scaled from the value used therein to 0.27 W m\(^{-2}\). ENSO-corrected lower troposphere temperature data are taken from Soden et al. (2010). Global mean surface temperature values are taken from the 12-month running mean NASA GISTEMP dataset maintained at Columbia University (2018). Ocean Niño index (ONI) monthly values used to correct the GISTEMP data for ENSO variations in equation (1) of the paper are from NOAA (2018). For consistency with the GISTEMP data, the ONI monthly time series is transformed here to a 12-month running mean. In order to maintain consistency between model curves and measurement data, time series for global temperature forcing are used without smoothing when compared to tropospheric temperature data and smoothed using a 12-month running mean when compared to the smoothed global surface temperature data.

Appendix 2: Climate response functions

Response functions for lower troposphere temperature, \( P_{LT} \), and global mean surface temperature, \( P_{GS} \), are constructed based on the ‘intermediate climate response’ function of Hansen et al. (Hansen 2007). Both functions are digitised as monthly values and convoluted with effective global temperature forcing, \( F_e \), to generate the resultant temperature evolution:
\[ T(t) = \lambda \sum P(t') F_e (t - t') \Delta t' \]

where the sum runs over monthly time points (thus \( \Delta t = \frac{1}{12} \text{ y} \)) from January 1850 to the present. The formulation here is pulse response, formally equivalent to the Greens function approach (Eq. (1) used by Hansen et al. (2017) but arguably more transparent in the context of transient volcano forcing because the pulse response shape mirrors the curve of cooling and temperature recovery after a volcanic eruption. In this formulation the intermediate climate response function used by Hansen et al. (2017) becomes

\[
P_H(t) = \begin{cases} 
  a_0 & (0 < t \leq t_1) \\
  a_n/t & (t_n < t < t_{n+1})
\end{cases}
\]

where \( t_1 = 1 \text{ y}, t_2 = 10 \text{ y}, t_3 = 100 \text{ y}, t_4 = 2000 \text{ y}, \) and \( a_0 = 0.15, a_1 = 0.1737, a_2 = 0.08685, \) and \( a_3 = 0.08345. \)

In the above monthly digitized representation, the first year’s response has been distributed evenly throughout that year, giving a slightly different early response from that of Hansen et al. (2017). The two responses converge rapidly within a few years, but the distinction is significant during the peak portion of the volcano response: if parameters are correct the present approach is more accurate. In all other respects, the treatments are identical.

The response function using the parameters from Hansen (2017) leads to a transient temperature evolution after volcanic eruptions which is intermediate between the observed lower troposphere response (Fig. 2(a) of the paper) and the global mean surface response ((Fig. 2(b) of the paper). In order to fit more accurately the lower troposphere and global surface responses to the temperature observations the function is empirically modified by varying the time \( t_1 \), which controls the short-time behaviour of the response, while keeping the curve continuous at time \( t_1 \) by adjusting the value of \( a_0 \). The values of \( a_2 \) and \( a_3 \) are then slightly adjusted, by a common factor \( \sim 1 \), to preserve the normalisation \( \sum P(t) \Delta t = 1 \). The revised values are reported in the Supplementary Material.

**Competing interests**

The author declares no competing interests.
Acknowledgement

I thank Lijing Cheng for providing recent data and analysis updates on ocean heat content.

References


Columbia GISTEMP analysis. URL: http://www.columbia.edu/~mhs119/Temperature/, last access: June 2018.


Li, C. et al.: India is overtaking China as the world’s largest emitter of anthropogenic sulfur dioxide. Scientific Reports 7:14304, doi:10.1038/s41598-017-14639-8, 2017.


National Oceanographic and Atmospheric Administration (NOAA), Oceanic Niño Index (ONI), URL: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, last access: June 2018.

National Oceanographic and Atmospheric Administration (NOAA), solar irradiance Climate Data Record, URL: https://www.ncdc.noaa.gov/ cdr/atmospheric/total-solar-irradiance, last access: June 2018.


Supplementary Information

Climate response function for global mean surface temperature, $P_{GS}$

Outline discussion of modeling procedure

In previous work, top of the atmosphere measurements of global temperature forcing following the Mt Pinatubo eruption in 1991, together with climate model simulations, have suggested (Hansen 2005) that effective global temperature forcing by stratospheric aerosols, $F_e$, and stratospheric optical depth, $\tau$, are related by $F_e (W m^{-2}) \sim -23 \tau$. It has also been shown that the large reduction in $F_e$ following the Mt Pinatubo eruption led to a 0.7°C peak decrease in ENSO-corrected $T_{LT}$ (Soden 2002). However, as Fig. S1(b) shows, the corresponding peak decrease in ENSO-corrected $T_{GS}$ was about a factor 2 smaller, in contrast to climate model simulations. In the following paragraphs I will compare the post-eruption evolution of $\bar{T}_{LT}$ and $\bar{T}_{GS}$, where the bars denote ENSO-corrected quantities, in order to estimate and compare the transient climate response functions $P_{LT}(t)$ and $P_{GS}(t)$ for these two interrelated parts of the global climate system.

Modelled changes in radiative forcing by volcanic aerosols and solar irradiance during the period 1960–2000, together with ENSO-corrected satellite measurements of lower troposphere temperature during the Mt Pinatubo event (Soden 2002), are shown in Fig. S1(a). The symbols represent temperature measurements and the dashed line shows the time-dependent forcing estimated from stratospheric optical depth (NASA 2018) and solar irradiance data (NOAA 2018). In order to fit the temperature data, the forcing data are convoluted with a trial climate pulse-response function for the lower troposphere, $P_{LT}(t)$, based on the intermediate climate model response of Hansen et al. (2017), defined during years 1–10 as $P_{LT} = 0.1737/t$. To adequately fit the climate response at times $< 1$ y this curve is extended back to $t = 0$, with a cut-off $P_{LT} = 0.6$ y$^{-1}$ at $t < 0.25$ y to match the observed temperature drop at the peak of cooling after the Mt. Pinatubo eruption. The equilibrium climate response of 0.75°C/W cm$^{-2}$ used by Hansen et al. (2017) is preserved by downscaling $P_{LT}(t)$ at times after the initial cut-off by a factor $\sim 1$. The model uses a forcing of $F_e (W m^{-2}) = 21 \tau$ to fit the observed magnitude of the temperature response. The resulting temperature evolution, obtained by convoluting $F_e$ with $P_{LT}$ (details in the Supplementary Information) is given by the solid curve in Fig. S1(a).

Fig. S1(b) shows the corresponding response of $\bar{T}_{GS}$ to the same forcing evolution. For clarity the plot has been background-subtracted to offset the average growth in global temperature during this period, which is largely of anthropogenic origin. It is clear that the surface temperature response is strongly damped in comparison to the troposphere response (dashed curve in Fig. S1(b)). This is perhaps not surprising as global mean surface temperature is known to be damped by the buffering influence of the ocean (Hansen 2017). However, the early transient response (during the first 2–3 y after eruption) is also significantly weaker than predicted by climate models, e.g. Hansen et al. (2017) (symbols).

The damping introduced by the ocean cannot be treated as a straightforward smoothing of temperature response. In the initial 1–2 years after the Mt Pinatubo eruption there is a prompt response with a steep drop in $\bar{T}_{GS}$, but the magnitude of this decrease is smaller than that in $\bar{T}_{LT}$. On the other hand, the tail of the temperature response appears to be stronger than that of $\bar{T}_{LT}$, consistent with the thermodynamic requirement that the cumulative troposphere and global surface responses converge as the atmosphere-ocean system relaxes towards equilibrium. This suggests that
the climate response function for the global mean surface may differ significantly from that used in existing climate models. The challenge here is to be able to model both the troposphere and global surface temperature responses satisfactorily, using a single common volcano forcing time series, consistent with thermodynamics.

In principle, a straightforward method of extracting an observationally-based global mean surface temperature response function would be to invert the temperature time-series data using the volcano forcing (stratospheric optical depth) time series as input. However, this approach has practical difficulties as the long-term temperature background generated by other forcings (greenhouse gases, aerosols, etc) is not exactly known, and any systematic variations may misdirect a statistically-based inversion.

Fig. S1: (a) Climate forcing by volcanic aerosols and solar irradiance variations between 1960 and 2000 (dashed curve) and the resulting temperature evolution of the lower troposphere (solid black curve) obtained by convoluting the forcing data with \( P_{LT} \). Symbols represent satellite measurement data. (b) Global mean surface temperature evolution obtained by the same method (solid black curve) using the updated response function \( P_{GS} \). The dashed curve in (b) is the tropospheric response and symbols denote the time series calculated from the annual forcings and global surface response function used by Hansen et al. (2017). The gold line represents \( T_{GS} \) after subtracting a linear background representing the rising temperature trend from anthropogenic emissions. (c) Historical evolution of \( T_{GS} \) (dashed line), the temperature response to volcano and solar irradiance variations (gold solid line), and \( T_{GS} \) after removal of the volcano and solar contributions (black solid line). The red curve shows the corresponding result after suppression of quasi-biennial oscillations using a 26-month running mean. The recent increase in slope indicates a steep rise in anthropogenic global temperature forcing, confirming the trend seen in Fig. 1 of the paper.

Here a physically motivated approach is used to construct the trial climate response function, \( P_{GS} \), which is then optimized. At short times \( P_{GS} \) is assumed to be a function of the troposphere response,
\( P_{LT} \), partially modified by thermal interaction with the ocean, and at sufficiently long times the function is based on that of Hansen et al. (2017), expressed here in the pulse-response form \( P_{GS} = a_n/t \) where \( a_n \) is a constant with values for \( n = 1 – 3 \) specified in the ranges \( t < 10 \) y, \( 10 \) y \( \leq t < 100 \) y, \( 100 \) y \( \leq t < 2000 \) y, respectively. The \( a_n \) values are scaled by a factor \( \sim 1 \) to compensate for the modification to the response function at short times, so that, as with the troposphere, the equilibrium climate response remains equal to 0.75°C/W m\(^{-2}\) (see detailed discussion in the subsection below).

Two distinct subsets of the global surface have radically different thermal properties. In the first, primarily land and sea-ice areas, the heat flux through the surface is much weaker than that into the open ocean, as thermal diffusion below the surface is slow. As a result, the surface in these areas acts similarly to a Neumann boundary. In contrast, the ice-free global ocean is a powerful source/sink of heat with a mixed boundary condition for tropospheric heat and can thus maintain a significantly different surface temperature anomaly from that of the troposphere. The result is a land surface temperature anomaly that is roughly similar to that of the lower troposphere and a sea-surface temperature anomaly \( T_{SS} \) that is somewhat smaller – intermediate between the land and ocean anomalies. Thus \( T_{GS} \approx \alpha T_{LT} + (1 – \alpha)T_{SS} \), where \( \alpha = 0.31 \) is the fraction of Earth’s surface occupied by land and sea ice.

It is therefore appropriate to model \( P_{GS} \) in terms of two components: \( P_{GS} = \alpha' P_{LT} + (1 – \alpha')P_{SS} \). In the first component, \( P_{LT} \) is the lower troposphere response and \( \alpha' \) is a free parameter which should be similar to \( \alpha \). In the second component, \( P_{SS} \) is a modification of \( P_H \) in Ref. 7 obtained by truncating \( P_H \) to a maximum value of 0.038 y\(^{-1}\), creating a plateau response at times shorter than 2.5 y. This strongly reduces the magnitude of the initial global surface response while the term \( \alpha' P_{LT} \) maintains its initial sharp response, as shown in Fig. 2(b).

With this approach the post-eruption evolution of \( T_{LT} \) (Fig. 2a) and \( T_{GS} \) (Fig. 2b) can be consistently modeled using the same global temperature forcing time series. The fitted value of \( \alpha' \), which is constrained by the relative contributions to \( T_{GS} \) of the initial sharp volcano response and the longer response tail, lies in the range 0.35–0.45, slightly larger than \( \alpha \). This modest discrepancy may arise from transient sea-surface warming prior to mixing of the added heat into the epipelagic zone. Still, it is clear that the sea surface response in the second term of \( P_{GS} \) varies more slowly than the trend in \( P_H \) after an initial forcing pulse. This slower response may, for example, reflect faster epipelagic mixing than is assumed in most climate models. The key point for this work is that \( P_{GS} \) gives a satisfactory fit to the volcano dips shown in Fig. 2(b) and thus an improved semi-empirical estimate of global mean surface temperature response which can be applied to volcano and solar irradiance forcings (and in principle to other forcings as well).

Model analysis

Climate response functions for different components of the climate system differ according to their thermal mass and strength of coupling with other components. In this work the responses of the lower troposphere and global mean surface to volcano and solar forcing on time scales \( \sim 1–20 \) y have been fitted to the time series \( T_{LT} \) reported by Soden et al. (2002) and \( T_{GS} \) reported in this work, respectively. For this purpose, the multi-decadal time series \( T_{GS} \) is fitted after background subtraction to remove the slowly-varying, approximately linear, contribution from anthropogenic temperature rise.
The fitting function, representing the response of global mean surface temperature to volcano and solar forcings, is of the form

$$T(t) = \lambda \sum P_{GS}(t') F_e (t - t') \Delta t'$$

where the sum runs over monthly time points (thus $\Delta t = \frac{1}{12}$ y) from January 1850 to the present and a mid-range climate sensitivity $\lambda = 0.75$°C/W m$^2$ is used. Here

$$P_{GS} = \alpha' P_{LT} + (1 - \alpha') P_{SS}$$

where $\alpha'$ is an adjustable parameter that approximately represents the fraction of Earth’s surface occupied by land and sea ice, and $P_{LT}$ and $P_{SS}$ are given by

$$P_{LT}(t) = a_n^{LT} \frac{t}{t_n^{LT}} \quad (0 < t \leq t_n^{LT})$$
$$P_{LT}(t) = a_n^{LT} \frac{t}{t_n^{LT}} \quad (t_n^{LT} < t < t_{n+1}^{LT})$$

$$P_{SS}(t) = a_n^{SS} \frac{t}{t_n^{SS}} \quad (0 < t \leq t_n^{SS})$$
$$P_{SS}(t) = a_n^{SS} \frac{t}{t_n^{SS}} \quad (t_n^{SS} < t < t_{n+1}^{SS})$$

and the values of $a_n^{LT}$ and $a_n^{SS}$ are derived from prior values used by Hansen et al. (2017), modified as described below. The times $t_n$ ($n < 0$) for both lower troposphere and global surface temperature are kept at the values used in Ref. (Hansen 2017). The complete set of adjusted values of $a_n$ and $t_n$ is given in Table S1.

The forcing $F_e = F_e^{volcano} + F_e^{solar}$ represents the sum of volcano and solar forcings, where the volcano contribution is derived from global time series data for stratospheric optical thickness, $\tau$, (NASA 2012) using a forcing efficiency $\eta$ such that $F_e^{volcano} = \eta \tau$, and the forcing $F_e^{solar}$ is derived from solar irradiance data, applying a geometrical correction of 0.25 and an albedo correction of 0.7 (Lean 2001). Estimates based on the monthly solar irradiance data held by NOAA (2018) agree closely with the annualized solar forcing estimates used by Hansen et al. (2017), suggesting that the latter also represent direct radiative forcing. However, as they were used by Hansen et al. (2017) as effective forcing values it appears that the effect of secondary infrared radiative forcing on the solar forcing contribution may have been neglected. Here it is assumed that secondary radiative forcing is a fraction $-0.45$ of direct radiative forcing, consistent with the ratio of secondary to direct stratospheric aerosol forcing reported by Hansen et al. (2005). Thus, the estimate of effective solar forcing used in this work is 0.55 × that used by Hansen et al. (2017). This correction has only a small impact on the results: for example, had it not been included, the black solid curve in Fig. (c) would have shifted downward by $\leq 0.03$°C. The impact on decadal changes this century is $\sim 0.01$°C. The correction likewise only has a minor impact on the results in Hansen’s 2017 paper.

The fit to $T_{LT}$ in Fig. 2(a) of the paper, reproduced here as Fig. S1(a), is obtained by adjusting $\eta$ in the expression for $F_e$ and $t_1^{LT}$ in the expression for $P_{LT}$ with a corresponding adjustment to $a_1^{LT}$ to maintain continuity at time $t' = t_1^{LT}$. The remaining $a_n^{LT}$ are adjusted by a common factor to preserve the normalisation $\sum P_{LT} = 1$. The extracted values are $\eta = (21 \pm 2)$°C $\tau^{-1}$/W m$^2$ and $t_1^{LT} = (0.25 \pm 0.05)$y. Uncertainty in $\eta$ is associated with the area of the temperature dip in Fig.
S1(a) and originates mainly from potential systematic climatic variations in the lower troposphere temperature background during and after the Mt Pinatubo eruption, which although corrected for ENSO (Soden 2002) may also be influenced by QBO. Similar considerations may apply to previous analysis (Hansen 2005) based on measurements of primary and secondary radiative forcings, as the latter is also influenced by global temperature.

Within the uncertainties the present result agrees with the estimate of \( \eta \approx 23^\circ C \, \tau^{-1/2} \, W \, m^2 \) from Hansen et al. (2005). This is interesting, as what is really determined here is the product \( \eta \lambda \) which relates stratospheric optical depth, \( \tau \), to temperature response, \( T(t) \), whereas Hansen’s 2005 paper determined \( \eta \). This is significant support for the mid-range climate sensitivity \( \lambda \approx 0.75^\circ C / W \, m^2 \), assuming that the long-term response tail is adequately described by Hansen’s response function.

The uncertainty in \( t_1^{LT} \) is associated with the depth of the dip in Fig. 1(a) which is also mainly affected by unknown variability in the background troposphere temperature, in this case during the time interval around the minimum in stratospheric optical depth following the eruption. The estimated uncertainty in \( t_1^{LT} \) corresponds to a \( \sim 10\% \) uncertainty in the depth of the temperature minimum.

Having established an estimate for \( \eta \) based on the lower troposphere data, the resultant volcano forcing is used together with the solar forcing time series discussed above to fit the time evolution \( T(t) \) of background-subtracted global mean surface temperature, in order to extract \( P_{GS}(t) \). Prior values in the equations for the \( P_{SS} \) contribution to \( P_{GS} \) are treated in the same manner as above.

Fitting parameters are the fraction \( \alpha' \) and the time \( t_1^{SS} \) at which the initial plateau response in equation (S4) reverts to the \( 1/t \) trend. The extracted values are \( \alpha' = 0.4 \pm 0.05 \) and \( t_1^{SS} = (2.4 \pm 0.5) \, y \). The uncertainties in the extracted values of \( \alpha' \) and \( t_1^{SS} \) mainly arise from the unknown time evolution of the QBO in the background of the three volcano dips shown in Fig. S1(b) of the paper, thus the extracted optimal values and uncertainties are partly subjective. However, it is clear from Fig. S1(b) that the optimal fit gives substantially improved agreement with the historical time series for background-subtracted \( T_{GS} \). Moreover, subtraction of \( T(t) \) from the \( T_{GS} \) time series in Fig. S1(c) leaves no residual evidence of artefacts such as volcano dips or peaks, suggesting that the function \( T(t) \) accurately represents the effects of volcano and solar variations over the period of interest. For example, subtraction of the largest dip, associated with the 1991 Mt Pinatubo eruption, leaves only small quasi-biennial fluctuations in the remaining temperature evolution (black solid curve) during the period from 1990–1995.

Table 1: Adjusted values of \( a_n \) and \( t_n \) in units of \( y^2 \) and \( y \), respectively, used in the expressions for \( P_{LT} \) and \( P_{GS} \). Uncertainties for the fitted parameter \( t_1 \) are shown in brackets. Values for \( t_2 \)–\( t_4 \) are from Hansen (2017).

<table>
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<th>( a_0 )</th>
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<td>0.13</td>
<td>0.086</td>
<td>0.083</td>
<td>0.25 (0.05)</td>
<td>10</td>
<td>100</td>
<td>2000</td>
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<tr>
<td>( P_{SS} )</td>
<td>0.038</td>
<td>0.16</td>
<td>0.11</td>
<td>0.106</td>
<td>2.4 (0.5)</td>
<td>10</td>
<td>100</td>
<td>2000</td>
</tr>
</tbody>
</table>

Earth system temperature metric, \( \theta \)

Global temperature fluctuations arising from heat exchange between ocean and atmosphere can be eliminated, in the framework of a simple climate model description, by considering an effective temperature metric, \( \theta \), which includes contributions from global mean surface temperature, \( T_{GS} \), and upper ocean heat content, \( H_{UO} \). In order to capture cyclical heat-transfers involved in decadal
processes such as the PDO and shorter-duration cycles such as ENSO and the QBO, it is necessary to choose a sufficiently deep upper-ocean layer that fully contains these processes. Data from the Argo network re-analysed by Cheng et al. (2017) show that ocean depths below 700 m have warmed approximately linearly since the mid-1990s, with no significant fluctuations in the warming rate during this time. Thus, the depth range 0–750 m appears sufficient to capture all significant ocean–atmosphere heat cycling processes at time scales up to 1–2 decades. At the same time, in order to avoid an excessively heavy-tailed climate response for the function \( \theta \), it is desirable to choose an upper ocean layer that is as shallow as possible. The depth range 0–750 m is thus well suited as the upper ocean depth in the formulation of \( \theta \).

The quantities \( T_{GS} \) and \( H_{UO} \) both include a contribution from global temperature forcing and a contribution from heat exchange between the upper ocean and atmosphere. Since heat leaving the ocean goes predominantly to the lower troposphere, one may write

\[
\Delta H = C_A T_{LT}
\]

where \( \Delta H \) is the excess heat that has been transferred from ocean to atmosphere relative to normal globally forced climate response, and \( C_A \) is an effective heat capacity for the atmosphere.

As discussed in the manuscript, \( T_{GS} \approx \alpha T_{LT} + (1 - \alpha) T_{SS} \). Since \( T_{LT} \) is large compared to \( T_{SS} \), the term involving \( T_{SS} \) may conveniently be neglected in the heat transfer term, which itself is small compared to climate forcing. Neglecting radiative losses from the atmosphere in the first instance, this approximation leads to

\[
T_{GS} = \lambda P_{GS} \ast F_e + \frac{\Delta H}{C_A}
\]

\[
T_{UO} = \Lambda P_{UO} \ast F_e - \frac{\Delta H}{C_{UO}}
\]

where \( P \ast F_e \) denotes the convolution \( \int P(t') F_e(t - t') dt' \), \( \lambda \) is the equilibrium climate response for global mean surface temperature, \( \Lambda \) is the equilibrium response for upper-ocean temperature \( T_{UO} = H_{UO}/C_{UO} \), and \( C_{UO} \) is the heat capacity of the upper ocean.

When radiative losses are included, variations in \( T_{LT} \) are significantly reduced. This is accounted for here by applying a scaling factor \( 1 - \gamma \), where \( \gamma \) represents the radiative losses, leading to

\[
T_{GS} = \lambda P_{GS} \ast F_e + (1 - \gamma) \alpha \frac{\Delta H}{C_A}
\]

The equilibrium response \( \Lambda \) in equation (S7) can be formulated in terms of \( \lambda \) by considering the temperature distribution as a function of depth, \( T(z) \). In the simple fast climate model framework, the temperature at the bottom of the ocean is implicitly assumed constant while the equilibrium temperature anomaly at depth \( z \) (and height \( h \) in the atmosphere above) is proportional to the forcing. Consequently

\[
\Lambda = \rho \lambda
\]
where $\rho = (T_{UO}/T_{GS})_{eq}$ is the equilibrium ratio between $T_{UO}$ and $T_{GS}$, determined by the heat transport properties of the ocean-atmosphere system.

The heat exchange terms can be eliminated by adding equations (S6') and (S7):

$$T_{GS} + (1 - \gamma)\alpha\frac{C_{UO}}{C_A}T_{UO} = \lambda \left( P_{GS} + (1 - \gamma)\alpha\rho\frac{C_{UO}}{C_A}P_{UO} \right) * F_e$$

which can be expressed as

$$\theta = \lambda P_{\theta} * F_e$$  \hspace{1cm} (S8)

where

$$\theta = \left( T_{GS} + \frac{(1 - \gamma)\alpha}{\epsilon}T_{UO} \right)/\left( 1 + \frac{(1 - \gamma)\alpha\rho}{\epsilon} \right)$$

$$P_{\theta} = \left( P_{GS} + \frac{(1 - \gamma)\alpha\rho}{\epsilon}P_{UO} \right)/\left( 1 + \frac{(1 - \gamma)\alpha\rho}{\epsilon} \right)$$

with $\epsilon \approx C_A/C_{UO}$, and $T_{UO} = H_{UO}/C_{UO}$. The function $\theta$ is an effective temperature metric representing the evolution of heat in the combined atmosphere-upper ocean system. It is thus in principle directly related to forcing without interference from internal climate variability.

The heat capacities of the atmosphere and the 0–750 m upper ocean are approximately $6.0 \times 10^{21}$ J K$^{-1}$ and $1.1 \times 10^{24}$ J K$^{-1}$, respectively, which implies $\epsilon \sim 0.0055$. The value of $\alpha$ is set to 0.31, the average area of land and sea ice, and $\gamma$ is assumed equal to 0.45. Then,

$$\theta = (T_{GS} + 31 T_{UO})/(1 + 31 \rho)$$

To enable consistency between the $T_{GS}$ and $T_{UO}$ time series, OHC data must be referred to the same baseline period as is used for $T_{GS}$. Since OHC data are not available for the $T_{GS}$ baseline period 1880–1920, the time series data reported by the Japan Meteorological Agency (2018) are offset from their reported 1981–2010 baseline by $-9 \times 10^{22}$ J, thus placing the baseline just below the reported minimum in OHC between 1968 and 1970. This choice appears reasonable as $T_{GS}$ has minima in the 1950s and 1960s which are just above its 1800–1920 baseline.

A value of $\rho = 0.141$ is estimated from

$$\rho = \frac{T_{UO}}{T_{GS}} \approx \frac{\langle T_{UO} \rangle}{\langle T_{GS} \rangle}$$

where the triangular brackets represent mean values for the period 2005–2011. This rough equality may slightly underestimate $\rho$ because the climate response of $T_{UO}$ lags a few years behind that of $T_{GS}$. However, it has the advantage that the curves for $T_{GS}$ and $\theta$ can be conveniently overlaid and compared visually. With these parameters the equation for $\theta$ becomes

$$\theta \approx A T_{GS} + B T_{UO}$$
where $A = 0.195$ and $B = 5.78$. Fig. S2 shows the resultant time series for $\theta$ and the contributing terms in $AT_{GS}$ and $BT_{UO}$, together with the uncorrected $T_{GS}$ curve for comparison.

Owing to the large contribution from the upper ocean, $\theta$ has a heavy-tailed distribution that makes its response to forcing smoother than that of $T_{GS}$. However, fast diffusion within the epipelagic zone, which is typically around 300 m deep – nearly half the depth of the 0–750 m upper-ocean depth considered here – may produce a significant upper ocean temperature response on the timescale of 2-3 years identified in the previous section. This can be expected to generate a gradually steepening slope of the $T_{UO}$ term since 2012, in addition to the sharp increase in slope of the $T_{GS}$ term.

The recent 5-year period has been too short to allow definitive confirmation of an increase in slope of the $T_{UO}$ term, but the combination of analyses by Ishii (2009) used in the Japan Meteorological Agency data (2018) and by Cheng et al. in their 2017 paper is consistent with this hypothesis, with the ocean curve rising noticeably above its initial trend (blue dotted line) after 2012.

Moreover, it is clear that

(a) there has not been the prompt decrease in the slope of $T_{UO}$ which a transition to warmer atmospheric and cooler ocean conditions would require

(b) the combined ocean-atmosphere response represented by $\theta$ is on a steepening curve that reflects an increase in forcing $F_e$. 

Fig. S2: Time series for $T_{GS}$ (gold curve), $\theta$ (black solid curve and symbols) and its components $AT_{GS}$ (red dashed curve) and $BT_{UO}$ (blue dashed curve and symbols), during the Argo period. Symbols are based on data from Ishii et al. (Ishii, JapMet) and the blue and black curves are based on the OHC data of Cheng et al. (Cheng 2017, Cheng 2018) with a baseline offset chosen to match the two datasets during the period since 2005. The dotted line is a straight-line fit to the scaled upper-ocean data ($BT_{UO}$) from 2004–2010, indicating a possible recent increase in the rate of ocean warming.
The above analysis benefits from simplicity but has some potential limitations due to its reliance on a simple fast-climate model. It includes a correction for variations in outgoing infrared radiation caused by atmospheric temperature change, but does not account for forcing variations arising from changing atmospheric water content and other climatic variables that play out in three dimensions within the ocean-atmosphere system, particularly on short time scales. The neglect of an explicit sea-surface temperature contribution to the second term in equation S2’ may also have a noticeable effect on $\theta$. A combination of these issues may account for the slight shift in timing between ocean temperature decrease and global mean surface temperature rise during the two El Niño events visible in Fig. S2, in 2010 and 2015/16, which lead to a small peak (dip) in $\theta$ at the start (end) of each event, especially in the second, larger event. However, such effects are of second order in comparison to the gross heat-exchange effects accounted for by $\theta$. In the period of accurate ocean temperature measurements initiated by the current Argo experiment, the $\theta$-metric may be of value in focusing attention on the whole Earth system as a monitor of decadal forcing changes.

Such a decrease would not be smoothed by climate response inertia because it arises from heat transfer, not forcing (see second term in equation (S7)).

References


NOAA solar irradiance Climate Data Record (2018) URL: https://www.ncdc.noaa.gov/cdr/atmospheric/total-solar-irradiance