Our error estimation indicates that there is a possibility that a few (primarily sixteenth century) years exceeded the 2015 low, but the estimated return interval for the 2015 SWE value — as calculated based on a generalized extreme value (GEV) distribution (Supplementary Information) — is 3,100 years and confirms its exceptional character. GEV-estimated return intervals can have large confidence intervals (Supplementary Fig. 2), but the 2015 SWE value exceeds the 95% confidence interval for a 500-year return period (Supplementary Fig. 3). In comparison, the previous lowest SWE reading (in 1977) exceeds the 95% confidence interval for only a 60-year return period. We also find that the 2015 SWE value is strongly exceptional — exceeding the 95% confidence interval for a 1,000-year return period — at low-elevation Sierra Nevada sites where winter temperature has strong control over SWE[9], but less so at high-elevation sites, where it exceeds the 95% confidence interval for only a 95-year return period (Supplementary Information and Supplementary Fig. 2).

The 2015 record low snowpack coincides with record high California January–March temperatures[10] and highlights the modulating role of temperature extremes in Californian drought severity. Snowpack lows, among other drought metrics, are driven by the co-occurrence of precipitation deficits and high temperature extremes[11], and we find that the exacerbating effect of warm winter temperatures[12] is stronger at low than at high Sierra Nevada elevations. Anthropogenic warming is projected to further increase the probability of severe drought events[13], advance the timing of spring snowmelt and increase rain-to-snow ratios[14]. The ongoing and projected role of temperature in the amount and duration of California's primary natural water storage system thus foreshadows major future impacts on the state's water supplies. ❐

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Additional information

Supplementary information is available in the online version of the paper.

Author contributions

S.B., F.B. and V.T. conceived and designed the study, and wrote the Correspondence with input from E.R.W. and D.W.S. E.R.W. and D.W.S. contributed data and S.B. and F.B. performed the analyses with input from V.T. All authors contributed to the interpretation of the data set and discussion.

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CORRESPONDENCE:

Volcanic effects on climate

To the Editor – Johansson *et al.*[1] use an energy balance model (EBM) and a Bayesian statistical framework to estimate individual components of changes in observed global mean surface temperature (GMST). Here we consider $\Delta T^{\mathrm{Vol}}_{\{t\}}$, the volcanic component of GMST as a function of time *t*. We argue that: (1) the observed radiative forcing caused by the June 1991 Mt Pinatubo eruption, F^{Pn}, is inconsistent with the posterior value of F^{Pn} estimated by Johansson *et al.*, and (2) the true uncertainties in $\Delta T^{\mathrm{Vol}}_{\{t\}}$ are substantially larger than those claimed in their study.

The volcanic forcing dataset used by Johansson *et al.* yields a prior estimate of $F^{\mathrm{Pn}} \approx -2.8$ W m^{-2}. Johansson *et al.* obtain a markedly smaller average posterior estimate ($F^{\mathrm{Pn}} \approx -1$ W m^{-2}). They argue that −1 W m^{-2} is a credible value for the net radiative forcing caused by Pinatubo. This argument is statistical: it is based on the large assumed uncertainties in their prior volcanic forcing, and on consistency of their posterior volcanic forcing with results from similar statistical studies.

We do not need to rely on statistical arguments for information regarding the size of F^{Pn}. Direct measurements of Pinatubo's impact on long- and short-wave radiation fluxes at the top of the atmosphere are within the range −2.5 to −4 W m^{-2} (refs 2,3). Indirect observational estimates of F^{Pn} vary from approximately −3 to −5 W m^{-2}, consistent with direct observations[4]. The posterior estimate of F^{Pn} obtained by Johansson *et al.* is therefore a factor of 2.5 to 5 times smaller than direct and indirect observational estimates.

This unrealistically small posterior value of F^{Pn} helps to explain why Johansson *et al.* (and studies that have used similar statistical approaches) obtain a relatively small maximum cooling after Pinatubo ($\Delta T^{\mathrm{Pn}} = -0.2$ °C). Other work[5–8] has reported substantially larger Pinatubo cooling signals ($\Delta T^{\mathrm{Pn}} \approx -0.3$ to -0.4 °C). We question how Johansson *et al.* could have obtained credible estimates of ΔT^{Pn} with estimates of F^{Pn} that lie well outside the range of available observations.

One possible explanation for the small F^{Pn} and ΔT^{Pn} values inferred by Johansson *et al.* involves the maximum cooling caused by the 1883 Krakatoa eruption (ΔT^{Kr}). Krakatoa has a large signature (−3.3 W m^{-2}) in the prior volcanic forcing used by Johansson *et al.*

In response to this prior forcing, the EBM of Johansson *et al.* must simulate a large negative value of ΔT^{Kr}. In contrast, observations show only weak cooling after Krakatoa, probably due to sparse coverage of tropical GMST data in the 1880s. This mismatch in simulated and observed ΔT^{Kr} values may provide part of the reason for the downward scaling of the prior volcanic forcing. Because the scaling coefficient on the forcing is being estimated over the period 1880 to 2011, all temperature responses to major eruptions are downscaled — not just the Krakatoa GMST response.

A second issue relates to collinearity between the individual temperature components — volcanic, solar, El Niño Southern Oscillation (ENSO) and anthropogenic — used in the regression with observational GMST and ocean heat content (OHC) data. Collinearity between ENSO and volcanic forcing is relatively weak over the full 1880 to 2011 analysis period. In the 1980s and 1990s, however, El Niño events masked some of the cooling caused by El Chichón and Pinatubo[5,6,8]. This hampers reliable estimation of the true cooling signals caused by these eruptions — which may in turn impact scaling of the prior volcanic forcing.

Johansson *et al.* estimate equilibrium climate sensitivity (ECS) from long-term trends in GMST and OHC, and infer a "most likely" ECS value of ~2.5 °C. Empirical ECS estimates have also been obtained from a variety of other sources, such as the maximum cooling after large volcanic eruptions[6]. In simulations performed with an EBM similar to that of Johansson *et al.*, a ΔT^{Pn} value of -0.2 °C implies an ECS < 1 °C (ref. 6). Johansson *et al.* argue that the ECS inferred from their ΔT^{Pn} value is consistent with their trend-based ECS estimate — but this apparent agreement only occurs because of their unrealistically low posterior value of F^{Pn}.

Finally, Johansson *et al.* report small error bars on estimated trends in $\Delta T_{\{t\}}^{\mathrm{Vol}}$ over the recent 'warming hiatus' (see results for 'Volcanic aerosols' in their Table 1). These error bars do not accurately reflect known shortcomings and uncertainties in volcanic forcing[9,10]. The forcing data used by Johansson *et al.* omit a significant component of volcanic aerosol from the lowermost stratosphere. Inclusion of this component would enhance the surface cooling caused by post-2000 eruptions[9,10]. Short-term trends in $\Delta T_{\{t\}}^{\mathrm{Vol}}$ over the hiatus are also influenced by GMST recovery from Pinatubo (and from the prior cooling caused by the eruptions of Agung and El Chichón). Thus the hiatus period trends in $\Delta T_{\{t\}}^{\mathrm{Vol}}$ are not only sensitive to treatment of post-2000 volcanic effects, but also to volcanic forcing and EBM response uncertainties in the second half of the twentieth century. The true uncertainties in the volcanic component of GMST changes (and in trend-based estimates of ECS) are likely to be larger than those reported by Johansson *et al.*

In summary, it is concerning that Johansson *et al.* infer a posterior average estimate of F^{Pn} that is substantially smaller than that obteined from observations. We believe Johansson *et al.* underestimated the posterior values of both F^{Pn} and (in consequence) ΔT^{Pn}. Future Bayesian inference studies should incorporate physically based constraints on the estimated posterior forcings and temperature responses. ❐

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Reply to 'Volcanic effects on climate'

Johansson *et al.* reply – Our Letter[1] aimed to estimate how probability density functions of the equilibrium climate sensitivity (ECS) change as observations accumulate. To elucidate the causes of these changes we decomposed the observed global mean surface temperature (GMST) variability over the instrumental period into four contributing factors: anthropogenic, solar and volcanic forcing, and the El Niño Southern Oscillation (ENSO). Santer *et al.*[2] argue that we underestimate volcanic forcing in response to the Pinatubo eruption (in absolute terms), and its contribution to temperature variability. While our estimate of Pinatubo forcing is weaker than the observational estimates they cite, we believe that it is justifiable and not crucial for our conclusions regarding the estimate of ECS and how it has been affected by the hiatus period.

Santer *et al.* assert that our estimate of Pinatubo forcing is based on statistical arguments alone. However, our analysis combines empirical estimates, knowledge of physical processes, and statistical methods. The empirical estimates of Pinatubo forcing they refer to fall within the range of our prior distribution for the uncertainty in volcanic forcing, which has a 95% interval of -5.2 to -1.1 W m^{-2}. Observations of many other quantities (such as GMST[3], ocean heat content[4] and atmospheric concentrations) inform additional prior distributions. Knowledge of ECS and physical processes such as ocean heat uptake and ENSO variability, as represented in a simple climate model with prior uncertainty distributions for its parameters, is also incorporated. The Bayesian statistical method used formally combines observations and knowledge of physical processes to produce revised estimates of uncertainty (posterior distributions).

The statistical component of the analysis is critical because it allows each posterior distribution to be based on a wider range of information than its corresponding prior. In the case of volcanic forcing, the posterior is based not only on observations of volcanic forcing, but also on their consistency with observations of other quantities and with process knowledge. Considering all of these factors combined, our analysis suggests volcanic forcing (including Pinatubo) is more likely to be towards the weaker end of the prior range. This result is consistent with other studies[5–7] and produces a temperature response to Pinatubo that is in line with detection and attribution studies assessed in IPCC AR5[8]. Santer *et al.* argue that the value is more likely to be towards the stronger end, based only on observations