CORRESPONDENCE:

Multi-century evaluation of Sierra Nevada snowpack

To the Editor — California is currently experiencing a record-setting drought that started in 2012 and recently culminated in the first ever mandatory state-wide water restriction[1]. The snowpack conditions in the Sierra Nevada mountains present an ominous sign of the severity of this drought: the 1 April 2015 snow water equivalent (SWE) was at only 5% of its historical average[2]. In the Mediterranean climate of California, with 80% of the precipitation occurring during winter months, Sierra Nevada snowpack plays a critical role in replenishing the state's water reservoirs and provides 30% of its water supply[3]. As a result, a multi-year and severe snowpack decline can acutely impact human and natural systems, including urban and agricultural water supplies, hydroelectric power[4] and wildfire risk[5].

The exceptional character of the 2012–2015 drought has been revealed in millennium-length palaeoclimate records[6], but no long-term historical context is available for the recent snowpack decline. Here, we present an annually resolved reconstruction of 1 April SWE conditions over the whole Sierra Nevada range for the past 500 years (Fig. 1). We combined an extensive compilation of blue oak tree-ring series that reflects large-scale California winter precipitation anomalies[7] (Supplementary Information and Supplementary Fig. 1) with a tree-ring-based California February–March temperature record[8] in a reconstruction that explains 63% of the Sierra Nevada SWE variance over the instrumental period (Supplementary Table 1). Our reconstruction shows strong statistical skill (Supplementary Table 2), but underestimates anomalously high SWE values over the instrumental period (for example, in 1952 and 1969). However, SWE lows (for example, in 1934 and 1977) are reliably captured and our reconstruction reveals that the 2015 low is unprecedented in the context of the past 500 years (Fig. 1).

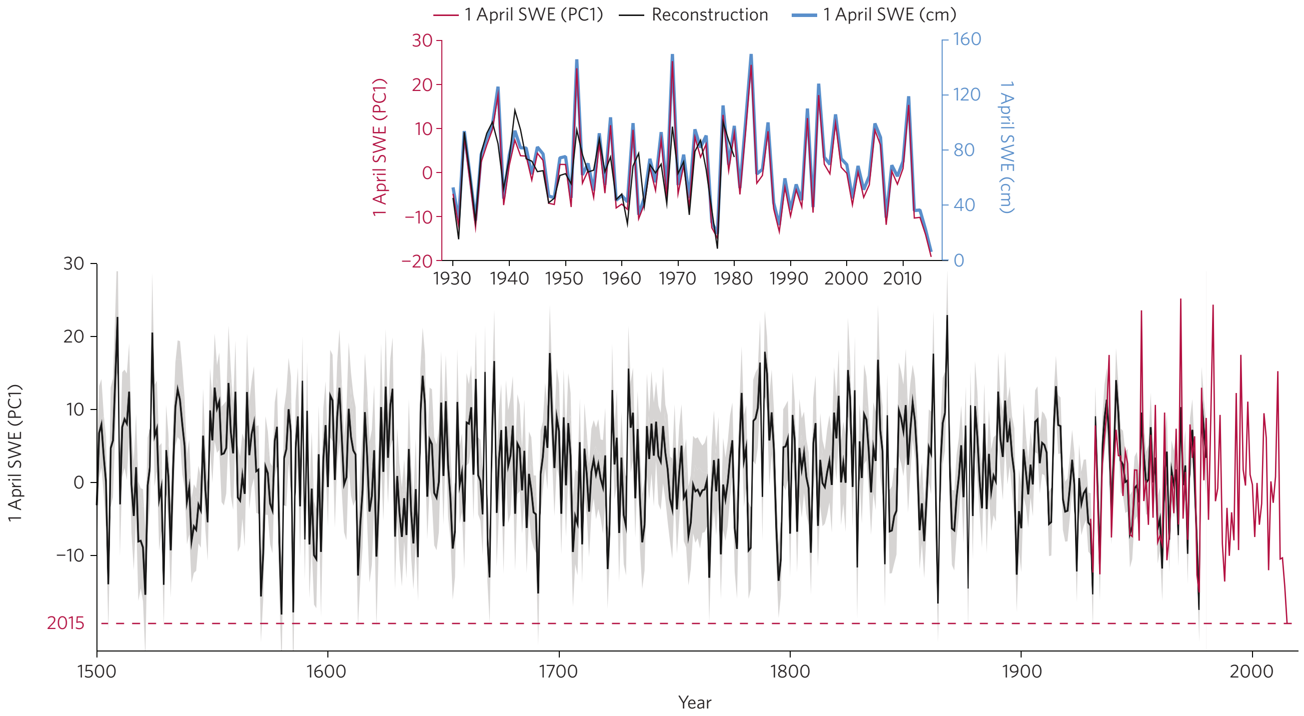

Figure 1 | Sierra Nevada 1 April snow water equivalent reconstruction (1500–1980). Bottom: instrumental (1930–2015; red curve) and reconstructed (1500–1980; black curve) first Principal Component (PC1) of Sierra Nevada 1 April snow water equivalent (SWE) values. The SWE reconstruction was calibrated against the PC1 of 1 April SWE measurements from 108 Sierra Nevada stations and explains 63% of its variance over the period of overlap (1930–1980; top). The 108-station average SWE value (in cm; 1930–2015) is plotted for comparison (blue curve; top). The grey shading around the reconstruction (bottom) indicates the combined error estimation (Supplementary Information). The 2015 SWE value is indicated by the red dashed line.

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.*