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Response to Comment on "No consistent ENSO response to volcanic forcing over the last millennium"

Sylvia G. Dee[1]*, Kim M. Cobb[2], Julien Emile-Geay[3], Toby R. Ault[4], R. Lawrence Edwards[5], Hai Cheng[5,6], Christopher D. Charles[7]

[1]Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX, USA. [2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA. [3]Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089, USA. [4]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA. [5]Minnesota Isotope Laboratory, Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55455, USA. [6]Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an 710054, China. [7]Scripps Institution of Oceanography, San Diego, CA, USA.

*Corresponding author. Email: sylvia.dee@rice.edu

Robock claims that our analysis fails to acknowledge that pan-tropical surface cooling caused by large volcanic eruptions may mask El Niño warming at our central Pacific site, potentially obscuring a volcano–El Niño connection suggested in previous studies. Although observational support for a dynamical response linking volcanic cooling to El Niño remains ambiguous, Robock raises some important questions about our study that we address here.

Modeling studies suggest that the El Niño–Southern Oscillation (ENSO) is sensitive to sulfate aerosol forcing associated with explosive volcanism, yet observational support for a dynamical chain of events linking large volcanic cooling to El Niño occurrences remains inconclusive. In Dee *et al.* (*1*), we used absolutely dated fossil corals from the central tropical Pacific to test ENSO's response to large volcanic eruptions. Superposed epoch analysis reveals a weak tendency for an El Niño–like response in the year after an eruption, but this response is not statistically significant, nor does it appear after the outsized 1257 Samalas eruption. Dee *et al.* suggested that models showing a strong ENSO response to volcanic forcing may overestimate the size of the forced response relative to natural ENSO variability. In a recent comment (*2*), Robock raises relevant questions about the conclusions of Dee *et al.*, addressed below.

First, Robock advocates the use of relative sea surface temperature (RSST) to separate the ENSO signal from tropics-wide volcanic cooling. RSST focuses on spatial gradients and/or anomalies with respect to a large-scale (i.e., global or basin-scale) average, facilitating isolation of dynamical responses in the midst of tropics-wide warming or cooling. Although we agree that RSST is a powerful diagnostic tool for the study of volcano-ENSO dynamics, individual paleoclimate records such as those presented in our study reflect local changes in absolute SST. Our constraints come from monthly-resolved coral $\delta^{18}O$ anomalies at a single site (Palmyra atoll, northern Line Islands), which offer the advantage of a consistent interpretation with well-characterized uncertainties, but, absent other monthly-resolved constraints on tropical Pacific SST during this time, preclude the computation of RSST. That said, we undertook an investigation of RSST in climate model output, as we show in figure S8 of (*1*). Yet another approach would use paleoclimate data assimilation products [e.g., (*3*)] spanning the last millennium. The latter dataset represents a more integrated approach, yet suffers from additional uncertainties with respect to the calculation of RSST (e.g., uneven proxy coverage, imperfect climate model "priors"). As such, even though our reliance on a single well-dated, well-characterized paleoclimate reconstruction is far from ideal, our study does add a new physically based constraint to ongoing research on this key question.

The second part of Robock's argument concerns the lack of apparent cooling in the Palmyra coral $\delta^{18}O$, given "the expected large cooling" that follows sufficiently large volcanic eruptions. This expectation is based on decades of studies on instrumental climate data and models [see (*1*, *4*–*11*)] but is not quantitatively supported by observations. Indeed, the lack of evidence for large cooling after the eruption of the Samalas complex in 1257 CE (*4*), the strongest eruption of the last millennium, has long puzzled researchers (*5*). As Robock points out, the radiative scaling to aerosol loading is sublinear, so one would expect a response that is somewhat less than twice as large. Recently, Guillet *et al.* (*6*) used both tree-ring mixed latewood density data (a sensitive proxy for summer surface air temperature) and highly calibrated documentary data to constrain this response, finding a relatively weak local temperature response in comparison to the inferred Samalas forcing. Although PMIP3 model simulations do simulate a large cooling in response to Samalas, recent studies suggest that the relatively simplistic representation of stratospheric aerosols in these models leads to exaggerated radiative forcing (*7*, *8*), particularly for Samalas (*9*). The inferred amplitude of the forcing used to drive climate models is derived from ice-core sulfate time series, yet the application of this forcing in models yields a large spread in simulated post-eruption climatic responses for CMIP5 experiments (*10*). As we point out in the text, the variable responses could be a result of uncertain forcing and/or structural uncertainties in model physics. Indeed, several volcanic forcing intermodel comparison projects are ongoing to identify the source of this spread [e.g., (*10*, *11*)]. Potentially important details include the eruption month [often unknown, yet critical for ENSO modulation (*12*)], the stratospheric injection height, and the relative forcing by extratropical (versus tropical) eruptions (*13*). None of these details were resolved in the volcanic forcing applied to PMIP3- and CMIP5-era model experiments, casting doubt on the expectations derived from them.

Third, Robock, citing (*6*), argues "that 1258 and 1259 experienced some of the coldest Northern Hemisphere summers of the past millennium." Recent reconstructions [see (*3*) and (*14*), figure S2b] support the notion that these were indeed cold years, but not exceptionally so in the context of the past millennium. Some compensation may occur, but the fact that Palmyra $\delta^{18}O$ anomalies in that year are neutral suggests that if there was an El Niño, it compensated for a minor global cooling, which does not advocate for a strong volcanic effect on ENSO. Guillet *et al.* (*6*)'s suggestion of a possible El Niño phase in 1259 is actually based on work by one of the authors (*15*), and its conclusions stem from a small number of proxy records located far from the core ENSO region. Our new record from the heart of the ENSO region (*1*) provides a more direct constraint on the tropical Pacific's response to this eruption.

Finally, Robock questions the arbitrariness of the 95% confidence level in ruling out a "significant" influence of volcanic forcing on ENSO. Although the choice of a 5% test level (false positive rate) is indeed arbitrary, it follows best statistical practice because it was chosen before the calculation was made, and we applied it consistently throughout the analysis. Adjusting this threshold a posteriori to support a particular hypothesis would constitute a form of confirmation bias.

In summary, as the text makes clear, our study does not rule out a possible volcanic influence on ENSO state; rather, it asserts that the currently available data do not uniformly support such an effect. Absence of evidence is not evidence of absence, and the effect expected by Robock may be revealed at some point in more comprehensive SST reconstructions based on more abundant monthly-resolved coral observations spanning the global tropics. Until then, the lack of evidence for such a response in our analysis is consistent with the null hypothesis—that the internal variability in ENSO is as large as, if not larger than, any volcanically forced signal in ENSO characteristics.

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