of Pinatubo forcing. In addition, each observation they cite is a single best estimate of forcing, and therefore their range only provides an estimate of the mode of the uncertainty distribution, underestimating the full distribution.

We are not convinced by Santer and colleagues' proposed explanations for our weak posterior estimate of volcanic forcing. The estimate is unlikely to be strongly affected by the lack of a strong cooling response in the observations to the 1883 eruption of Krakatoa. The observational errors at the time of this eruption are large[3], and by including this fact in our analysis these observations do not strongly constrain our estimated parameter values. A related study[9] finds that the exclusion of observations before 1900 only has a small impact on the ECS estimate.

In our view, it is too early to draw any conclusions on how the existence of collinearity between volcanic radiative forcing and ENSO affects results. The correlation coefficient between our estimated average GMST signals from volcanoes and from ENSO is only –0.19, suggesting that it is not a critical issue on the timescale of our study. It is unclear how higher correlation over shorter periods could be taken into account without introducing subjective constraints in the statistical model.

In our view, there are two more likely explanations for our results: (1) our estimate should be seen as an estimate of the effective radiative forcing of volcanoes, which is believed to be weaker than the radiative forcing[10,11]; (2) the class of climate model we use is structurally simple. One important simplification is that the ECS is constant. Results based on models with a richer description of the climate system have suggested that the ECS may be state-dependent and increasing over time[12–14]. This state and time dependency of climate sensitivity is likely to have a larger impact on the forcing–temperature relationship over a yearly timescale relevant to volcanoes than over a decadal-to-century timescale. Our estimate of ECS primarily reflects the decadal-to-century timescale response, and therefore may indicate a weaker volcanic forcing than we would find with a more flexible climate system response.

Accounting for this type of structural uncertainty is an important future research direction. Improvements in estimates of uncertainty in observations, including (but not limited to) volcanic forcing would also be important[15]. For these reasons, we do not exclude the possibility that the true uncertainty for ECS is larger than what we presented. As we stated in our Letter, all empirical estimates of ECS should be interpreted with some care. However, we do not see the views of Santer *et al.* as significantly challenging our estimate of ECS. ❐

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CORRESPONDENCE:

Bistability and the future of barrier islands

To the Editor — Writing in *Nature Climate Change*, Dúran Vinent and Moore[1] suggest that barrier islands are intrinsically bistable, existing in one of two equilibrium states, and that the state can be used to predict island response to climate change. Bistability exists when any system can exist in two distinct states of equilibrium[2]. Applied to barrier islands, Dúran Vinent and Moore claim that extrinsic variable changes (that is, reduced sediment supply) alter system parameters (dune-building) and can push entire islands across a threshold from one equilibrium state to an alternate equilibrium state, from high to low, for example. This results in fundamental changes to system properties and affects island resilience. However, barrier islands do not function within a dichotomous framework of bistability where 'low' islands are simply an alternate equilibrium state.

Empirical evidence of bistability at the island level supplied in figure 1 of Dúran Vinent and Moore[1] ignores that many of the Virginia islands exist in both high and low states[3] (Fig. 1). Parramore Island, characterized as a low island[1] displays areas of high elevation near the northern inlet where sediment supply is greater, allowing accumulation and dune-building processes to dominate. Dune ridges >2 m in height exist nearshore, with inland relict dunes >9 m in height and extensive woody cover, including maritime forest. However, some areas of woody cover are now being lost to shoreline retreat[3,4]. Extensive erosion along the transverse shoreline has led to dune scarping, despite high-elevation dunes. Although the presence of high dunes and woody vegetation may slow the overall erosion of the shoreline, external changes in longshore currents and island position are eroding these high-elevation sections of the island.

Hog Island, described as a high island[1], exhibits both high and low elevation

Figure 1 | Images of Hog Island showing that both states exist within a single island. Left: stable high-elevation vegetated dunes backed by extensive woody vegetation on the north end of the island (37° 27′ 43″ N, 75° 39′ 58″ W). Right: large low-elevation overwash fan that bisects the island <3 km away from the location depicted in the left panel (37° 26′ 18″ N, 75° 40′ 09″ W). Images courtesy of S. Brantley.

states[6] (Fig. 1). Until recently, the southern portion of the island was dominated by extensive overwash and was eroding at more than 5 m yr^{-1} (refs 5,6). Despite this low-elevation state, the northern portion of the island was accreting seaward at rates of >5 m yr^{-1} (ref. 5) with woody vegetation expanding into the southern portion of the island[4,7]. Similarly, Smith Island, which was also characterized as a low-elevation island (see figure 1 in ref. 1, ~90 km alongshore distance), has a strong bimodal distribution in elevation and one of the most diverse plant assemblages on the Virginia Barrier Islands due to the evolution of shore-perpendicular dune ridges, island width, human land-use and close proximity to mainland seed sources[8,9]. The southern portion of the island contains primary dune ridges that are 1–2 m in elevation, whereas the elongated northern portion is highly variable and exhibits signs of rollover with exposed peat outcrops in some locations[9]. These examples show that bistability operates at the local level on barrier islands and a single island may consist of a mosaic of alternate states[10]. Therefore, the application of the published models[1] at the island level for coastal management decision-making is not supported by the islands of the Virginia Coast Reserve. However, these models are a valuable contribution to understanding of local-scale processes. ❒

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Reply to 'Bistability and the future of barrier islands'

Durán Vinent and Moore reply — We thank Zinnert *et al.*[1] for the opportunity to elaborate further on the local nature of the bistability (that is, the tendency for islands to exist in alternate states under a given set of conditions) indicated by our numerical results[2]. Because our model assumes uniform alongshore conditions (that is, does not consider alongshore variability) all of our conclusions apply strictly to the local barrier island elevation. In particular, the bistability of local island elevation is supported by the bimodal distribution of dune elevation along the Virginia Barrier Islands (figure 1e,f in ref. 2). Examples shown in figure 1a–d in ref. 2 correspond to sections of the island in a high or low elevation state, where we use the implicit convention of naming an island high (low) if its average elevation is above (below) the crossover elevation defined in figure 1f. Although a detailed analysis of the spatial dynamics is beyond the scope of this work, there are two fundamental spatial scales suggested by our model[2] that are important in determining future barrier island state: the scale of the spatial variation of the vulnerability index (eq. (1) of ref. 2), which is the control parameter that determines whether island elevation is bistable and that quantifies the probability of dune recovery (figures 3e and 4 in ref. 2); and the spatial scale of alongshore variations in extreme water levels that erode dunes and drive a transition from a high to a low state. The stochastic alongshore variation of storm-induced erosion implies that both states can coexist spatially in a bistable system and at different scales, for example, at the scale of individual islands or at the scale of island segments, as observations suggest is the case for the Virginia Barrier Islands. In summary, because alongshore variability in processes and through history may prevent entire islands from existing in the low or high state, our concept of bistability applies most strictly to individual points or local sections of a barrier island. ❒

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