Volcanic and Solar Forcing of the Tropical Pacific over the Past 1000 Years

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ABSTRACT

The response of El Niño to natural radiative forcing changes over the past 1000 yr is investigated based on numerical experiments employing the Zebiak–Cane model of the tropical Pacific coupled ocean–atmosphere system. Previously published empirical results demonstrating a statistically significant tendency toward El Niño conditions in response to past volcanic radiative forcing are reproduced in the model experiments. A combination of responses to past changes in volcanic and solar radiative forcing closely reproduces changes in the mean state and interannual variability in El Niño in past centuries recorded from fossil corals. The dynamics of El Niño thus appear to have played an important role in the response of the global climate to past changes in radiative forcing.

1. Introduction

The El Niño–Southern Oscillation (ENSO) is associated with a quasi-periodic (3–7-yr time scale) warming (El Niño) and cooling (La Niña) of the eastern and central tropical Pacific Ocean surface that influences global-scale climate. Bjerknes (1969) identified the fundamental ocean–atmospheric feedbacks (the "Bjerknes feedbacks") at the core of this instability in the tropical ocean–atmosphere system, and a body of work in past decades has elucidated the factors underlying its natural interannual oscillatory behavior. Only more recently has the role of ENSO in anthropogenic climate change (Meehl and Washington 1996; Trenberth and Hoar 1997; Rajagopalan et al. 1997; Cane et al. 1997; Knutson et al. 1997; Noda et al. 1999; Timmermann et al. 1999; Collins 2000a,b; Boer et al. 2000; Meehl et al. 2000) or longer-term natural climate changes (Clement et al. 2000; Liu et al. 2000) been investigated.

Previous studies employing the simplified Zebiak–Cane (henceforth ZC) model of the tropical Pacific coupled ocean–atmosphere system (Zebiak and Cane 1987) have been used to investigate the potential response of ENSO to anomalous radiative forcing, including that associated with anthropogenic greenhouse gas concentration increases (Clement et al. 1996; Cane et al. 1997). Those studies described an "ocean thermostat" mechanism in which a heating of the tropical Pacific leads to a *cooling* of the eastern part of the basin. This result arises from the different surface temperature responses in the eastern and western Pacific: In the west, where the thermocline is deep, the response to a surface heating is largely thermodynamic and the mixed layer adjusts with an increased temperature. In the east where the thermocline is shallow, cooling by vertical advection offsets the surface heating, producing a smaller temperature response. The increased zonal SST gradient accelerates the trade winds, which leads to further thermocline shoaling and cooling by vertical advection in the east, further accelerating the winds. This "climatological" Bjerknes feedback, akin to that which operates on interannual time scales, leads to a cooling of the eastern equatorial Pacific in response to a heat-

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ing of the basin. Clement et al. (1996) and Cane et al. (1997) referred to this response as "La Niña–like" since there is a cooling in the east, as during a La Niña event, but there is also a warming in the west, which does not generally occur during La Niña. Further, such a response is La Niña–like (and the reverse pattern of response to a *cooling* of the basin is "El Niño–like") in that it resembles the characteristic ENSO pattern, but rather than being associated with a distinct ENSO event, it is associated with a shift in both mean state and variability toward such conditions on a multiyear or even multidecadal time scale. In this paper, we thus use the terminology El Niño–like to mean a warmer eastern equatorial Pacific and increased ENSO variability, and La Niña–like to mean a cooler eastern equatorial Pacific and decreased variability.

The feedbacks governing the above response are often not well represented in coarser-resolution global coupled models (Latif et al. 2001). The response of the zonal gradient in the tropical Pacific of such models to heating of the surface by higher levels of greenhouse gases is quite model dependent (Collins 2000b), possibly because of the behavior of certain feedbacks in the models (e.g., cloud radiative feedbacks) that respond differently in different models and are admittedly absent in the ZC model.

Here we investigate the response of ENSO to estimated changes in *natural* radiative forcing associated with explosive volcanic and solar radiative forcing changes over the past 1000 yr. Several new and distinct insights from the paleoclimate record of the past few centuries guide these investigations: (i) An analysis of reconstructed sea surface temperature (SST) patterns over the past few centuries (Waple et al. 2002) indicates greater warming in the western Pacific warm pool than in the central or eastern tropical Pacific in association with estimated past increases in solar irradiance, reminiscent of a La Niña–like anomaly in response to increased solar irradiance. (ii) An empirical analysis of proxy-based reconstructions over the past three centuries (Adams et al. 2003) finds statistical evidence for a tendency for El Niño conditions during the first few years following explosive tropical volcanic eruptions (with a tendency for a subsequent rebound into La Niña conditions). This evidence seems to substantiate previous claims of a relationship between tropical volcanic eruptions and El Niño events based on the relatively short instrumental record (Handler 1984), though such claims are controversial (e.g., Nicholls 1990; Robock 2000). (iii) Century-scale changes in the state of ENSO appear to have varied oppositely with those in hemispheric or global mean temperature over the past millennium. Cobb et al. (2003) provide evidence (in terms of both mean state and interannual variability) for an El Niño–like state during the otherwise generally cold seventeenth century (e.g., Crowley 2000; Mann et al. 2003) and a La Niña–like state during the otherwise relatively mild twelfth and thirteenth centuries (Crowley 2000; Mann et al. 2003). Hendy et al. (2002) similarly find evidence for a relative absence of cooling in the tropical Pacific during the otherwise cold late sixteenth–nineteenth centuries, while Jones et al. (2001) show evidence for a shift to an El Niño–like mean state during the late seventeenth century/early eighteenth century. Verschuren et al. (2000) provide lake-level evidence in equatorial east Africa (Kenya) for peak wet conditions during the mid-seventeenth to the mid-eighteenth centuries, and dry conditions during the early (eleventh–thirteenth) centuries of the millennium, reminiscent of anomalies typically associated with El Niño and La Niña conditions, respectively. A similar pattern of drought in earlier centuries and wet conditions in later centuries in the desert southwest of North America (Woodhouse and Overpeck 1998; Cook et al. 2004) favors this interpretation as well.

Each of the above observations seems to suggest a relationship that is consistent with the thermostat mechanism of Clement et al. (1996) whereby the temperature of the eastern equatorial Pacific varies negatively with changes in radiative forcing as discussed earlier. In this study, we propose an internally consistent framework—that is, the influence of the "thermostat" mechanism of Clement et al. (1996) active in the ZC model—for explaining each of these observations, employing experiments with a relatively simple model of the coupled tropical Pacific ocean–atmosphere system forced by estimated changes in past natural radiative forcing.

2. Methods

Experiments are performed with the ZC model of the tropical coupled Pacific ocean–atmosphere system (Zebiak and Cane 1987). While global coupled ocean–atmosphere models are capable of simulating ENSO (albeit with some shortcomings; Latif et al. 2001), such models are too computationally expensive to perform many 1000-yr-long integrations. Isolation of the signals of interest in this study requires, as discussed below, ensembles of multiple realizations of millennial forcing scenarios. Moreover, in a global coupled model tropical and extratropical processes and coupling between them must be considered in analyzing the response of the model to a particular forcing scenario. By contrast any response that is observed in our experiments employing the ZC model must, by design, arise from intrinsic tropical Pacific climate mechanisms.

Naturally, there are other potentially important responses associated with cloud radiative feedbacks, or large-scale monsoonal responses, or extratropical feedbacks on the Tropics, that are not included in the ZC model. However, that our model results are in agreement with data, as shown below, suggests that the essence of the response, the dynamical thermostat of Clement et al. (1996), is a potentially important mechanism operating in nature. This mechanism is observed in at least one global coupled ocean–atmosphere model (Otto Bliesner et al. 2003). It is possible that we are getting the right answer for the wrong reason, or an incomplete answer, and that the observed changes are due to processes absent in the ZC model. Similar experiments carried out with global coupled ocean–atmosphere models would provide additional insights to those offered by our analysis.

It should be noted that changes in mean state cannot be separated from changes in interannual variability in these experiments. Intervals of increased variability (increased frequency and amplitude of individual interannual events) are associated with a mean warming of the eastern equatorial Pacific in the ZC model (though not in all coupled models; e.g., Arblaster et al. 2002). This is due to the skewness of the variability about the base (zero anomaly) state in the model, with El Niño events typically characterized by large positive departures and La Niña events somewhat weaker negative departures. As Niño-3 warming associated with an El Niño event is greater than the cooling associated with a La Niña event, increases in the amplitude of interannual variability are associated with a more El Niño–like mean state in the ZC model, while decreases in the amplitude of interannual variability are associated with a more La Niña–like mean state. It should also be noted that the response of ENSO dynamics in the ZC model to radiative forcing is not linear. Clement et al. (1996) show that there is high sensitivity for small forcing, and lower sensitivity for large forcing. The nonlinearity of the response also means that the response to combined (e.g., solar + volcanic) radiative forcing is not simply the sum of the two individual responses.

a. *Model experimental design*

Consistent with the ZC model formulation, the radiative forcing is imposed as an anomalous surface heat flux into the ocean mixed layer. We performed separate experiments employing (a) volcanic only forcing, (b) solar forcing only, and (c) combined (solar + volcanic) natural forcing, over the interval A.D. 1000–1999. To isolate the signal of the model's forced response from the considerable internal variability of the ZC model, we calculate mean responses from an ensemble of realizations of the response of the model to the different 1000-yr forcing scenarios. The initial conditions of each realization differ; each is started using different random conditions from a control simulation with fixed (A.D. 1000–1999 mean) radiative forcing. We employ Crowley's (2000) solar and volcanic radiative forcing estimates over the past 1000 yr, with some minor modifications. Since Crowley (2000) provides radiative forcing estimates representative of the hemispheric mean, we scale the estimates by a factor of 1.57 to yield an estimate of the associated equatorial radiative forcing required by the ZC model. This scaling assumes a cosine latitudinal dependence of top-of-the-atmosphere radiative forcing anomalies associated with uniform changes in solar constant or optical depth. We ignore the slight latitudinal dependence of the forcing within the tropical domain (30°S to 30°N) of the ZC model. For simplicity, all volcanic eruptions are assumed to occur during the January of the eruption year, and responses are examined on a calendar (January–December) annual mean basis. All imposed radiative forcings are assumed uniform within the year, prescribed on an annual basis. Additional experiments demonstrate essentially identical results (i) if the volcanic forcing is instead prescribed on a monthly basis (through fitting of a smooth exponential decay to the annual mean radiative forcing estimates associated with each individual event), (ii) whether eruptions are assumed to occur during the boreal summer or winter, and (iii) whether the mean response is diagnosed based on a traditional calendar (January–December) or boreal-winter-centered (June–May) annual mean basis.

As a diagnostic of the model's ENSO behavior, we evaluate the Niño-3 index of model SST anomalies in the eastern tropical Pacific region closely associated with El Niño and La Niña events (5°S–5°N and 90°–150°W). We adopt the convention that the "year" date is defined by the January of the winter during which an El Niño event occurs.

b. *Radiative forcing estimates*

The hemispheric volcanic radiative forcing of Crowley (2000) is based on contributions from both extratropical and tropical explosive eruptions. However, the relevant eruptions are the ones that can provide a volcanic dust veil over the tropical Pacific domain of interest. The relevant volcanic forcing is thus provided only by eruptions occurring within the tropical band 30°S to 30°N. It should be noted that Adams et al. (2003), for this same reason, considered only tropical eruptions in examining the empirical evidence for the response of ENSO to past volcanic forcing. We thus remove from Crowley's (2000) volcanic radiative forcing series all events that have not been confirmed, based on available historical or geological information (Simkin and Siebert 1994), or bipolar ice core volcanic aerosol deposit evidence (Crowley 2000), as being of tropical origin. The timing of certain eruptions has been shifted by one or two years based on a recent reevaluation of the volcanic forcing chronologies (T. Crowley 2003, personal communication). Solar radiative forcing histories are somewhat uncertain, and a number of different reconstructions of solar irradiance have been produced in recent years (Crowley 2000; Lean et al. 1995, 2002), highlighting the uncertainty that still exists in the history of this forcing. We have used the solar irradiance reconstruction of Crowley (2000) based on a splice of the Lean et al. (1995) estimate with Be^{10} cosmogenic isotope evidence back to A.D. 1000, smoothing the resulting series with a 40-yr low-pass filter to insure homogenous frequency-domain fidelity to the imposed forcing over time. The reconstruction is in the lower range of existing solar irradiance reconstructions, roughly 40% smaller in amplitude than Lean et al. (1995), smaller than several other reconstructions considered by Crowley (2000), and far smaller than the very large solar forcing recently used by Gonzalez-Rouco et al. (2003). However, the amplitude is about twice as large as alternative reconstructions based purely on the amplitude of the 11-yr solar cycle (Lean et al. 2002). We have thus chosen what we consider a "midrange" estimate of this uncertain long-term forcing. Modestly different results would be obtained if other solar forcing histories were used.

We do not consider in this study the potential impact of modern (nineteenth and twentieth century) anthropogenic forcing. While Cane et al. (1997) examined the possible influence of anthropogenic greenhouse gas concentration changes on twentieth-century ENSO trends, the magnitude and spatial pattern of total anthropogenic radiative forcing due to the combined effects of greenhouse gas and aerosol radiative forcing is not yet well constrained (Ramaswamy et al. 2001). Certain impacts, such as production of aerosol from biomass burning in Indonesia, for example, may represent a significant, yet difficult to estimate, radiative forcing over parts of the Indo–Pacific domain (Hauglustaine et al. 1999). Furthermore, the complicating impact of extratropical feedbacks associated with the subduction of extratratropical water masses may be more significant in a nonstationary scenario of steadily increasing forcing, suggesting the greater possibility of potentially offsetting extratropical feedbacks in such a scenario. We defer any discussion of potential anthropogenic impacts to future investigation.

3. Results

In Fig. 1, we show the ensemble-mean Niño-3 response of the model to tropical volcanic and solar radiative forcing over the past 1000 yr. For an ensemble of 100 realizations of the response to the 1000-yr volcanic forcing scenario, an El Niño–like response (and weaker subsequent La Niña–El Niño cycling) is clearly observed in response to each tropical volcanic forcing event. For more modest ensembles (5 and 20 realizations, taken from the first 5 and first 20, respectively, of the 100-realization ensemble), the response to the weaker volcanic forcing events is largely lost in the noise of the ZC model internal variability. However, the response to the greater magnitude eruptions (especially the A.D. 1259 eruption and the eruptions of the early nineteenth century) are evident even in the most modest (five realization) ensemble. In fact, the responses to the largest eruptions are typically evident in individual realizations, consistent with the proposition that the signal should be detectable in the unique realization that the earth's climate has actually experienced over the past 1000 yr.

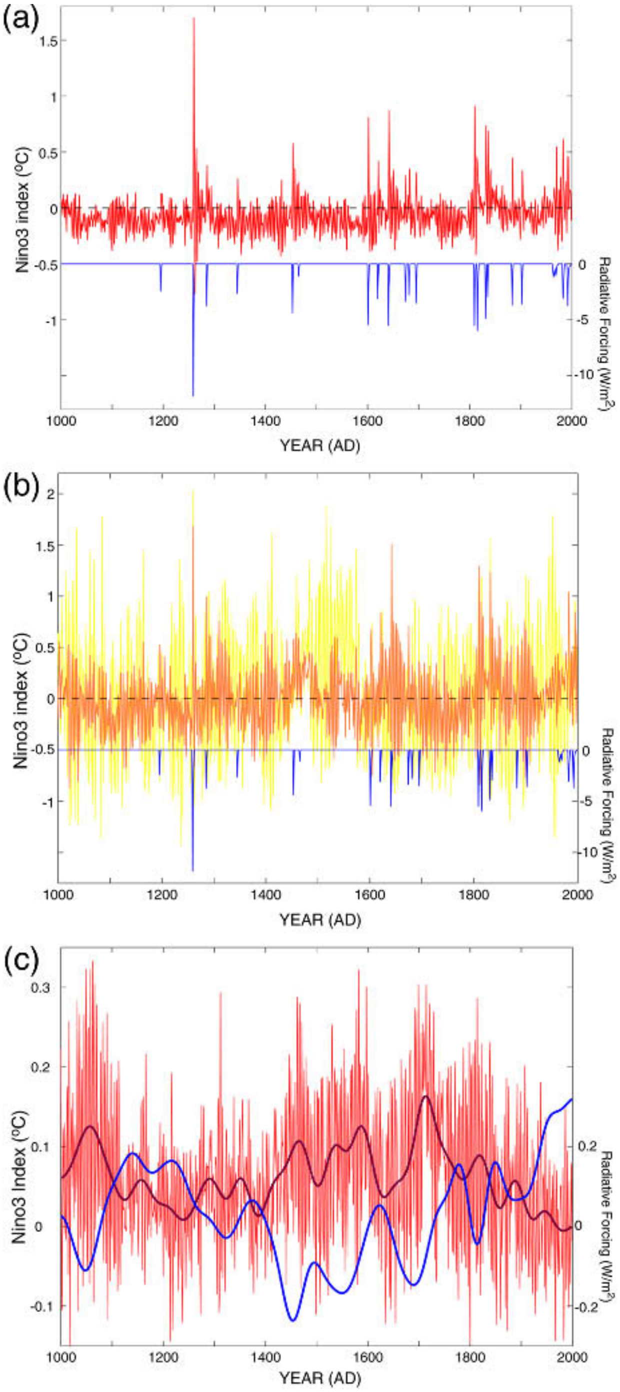

FIG. 1. Ensemble-mean ZC Niño-3 response to natural radiative forcing experiments over the period A.D. 1000–1999. (a) Response to tropical volcanic radiative forcing (red; anomaly in °C relative to A.D. 1000–1999 mean; scale provided on left axis) based on ensemble of 100 realizations. Radiative forcing (blue) is shown in W m^{-2} (scale provided on right axis). (b) Comparison of ensemble-mean responses to volcanic forcing [as in (a)] based on more modest ensembles of 20 (orange) and 5 (yellow) realizations. (c) Response to solar radiative forcing (red; anomaly in °C relative to A.D. 1950–1980 reference period) based on ensemble of 100 realizations. Maroon curve represents 40-yr smoothed response. Solar radiative forcing (blue) shown in W m^{-2} (relative to A.D. 1000–1999 mean).

The ensemble-mean Niño-3 response to volcanic forcing, which consists of individual impulsive forcings, is modest, averaging roughly to a 0.2°C anomaly per -1 W m^{-2} forcing. (It should be noted that the response of the model to radiative forcing is not linear in the radiative forcing; see, e.g., Clement et al. 1996.) Interestingly, while the solar irradiance forcing is roughly an order of magnitude smaller than the volcanic forcing in its peak amplitude, the lower-frequency nature of the associated forcing (which is long compared to the interannual time scales characterizing El Niño events) allows a more equilibrated response to the forcing. On 40-yr and longer time scales, the ensemble-mean Niño-3 and solar forcing time series are strongly negatively correlated ($r = -0.77$, significant at the $p = 0.001$ level taking into account serial correlation) with the response lagging the forcing by 5–20 yr (average of 14 yr), which is likely due to ocean adjustment processes in the model. The typical ensemble-mean Niño-3 response on the centennial time scale is approximately 0.5°C per -1 W m^{-2} (cf. the right and left scales of variation in Fig. 1c). Thus, while solar forcing is considerably weaker in peak amplitude to the volcanic forcing, the lower-frequency nature of the forcing appears to allow a substantially larger relative Niño-3 response.

In Fig. 2, we show the results of a "superposed epoch analysis" (SEA), similar to that used by used by Adams et al. (2003) to identify the Niño-3 response to tropical volcanic radiative forcing based on proxy reconstruction of volcanic forcing and ENSO indices back through the mid-seventeenth century. The SEA approach (see, e.g., Panofsky and Brier 1958; Bradley et al. 1987; Sear et al. 1987; Mass and Portman 1989) composites anomalies by their lead/lag relative to the timing of explosive volcanic eruption events to establish whether or not a statistically significant response to volcanic forcing is evident in a particular set of events. These analyses demonstrate the composite behavior preceding, coinciding with, and following tropical volcanic eruptions. Figure 2a shows the results using moderate eruptions (radiative forcing exceeding -2 W m^{-2}) between A.D. 1649 and 1868, the preinstrumental period considered by Adams et al. (2003) that includes seven eruptions (A.D. 1674, 1681, 1695, 1809, 1815, 1831, 1835). In Fig. 2b we show the results based on the seven largest eruptions (radiative forcing exceeding -4 W m^{-2}) over the full A.D. 1000–1999 period (the eruptions were in A.D. 1259, 1453, 1601, 1641, 1809, 1815, and 1831). We determined (positive and negative) 95% confidence levels for the post-eruption anomalies from the distribution of the pre-eruption composites. For both eruption lists, the results are highly reminiscent of the empirical results of Adams et al. (2003), showing a significant multiyear ENSO response. The response is characterized by a tendency for El Niño conditions to emerge in the year of the eruption, weaken, and exhibit damped subsequent oscillations between La Niña and El Niño conditions in subsequent years. Based on the 100 realizations, the probability of an El Niño event (Niño-3 anomaly $> 1°C$) occurring in the year following a larger eruption (as in Fig. 2b) is 63%; for the eruptions between 1649 and 1868 (Fig. 2a) it is 55%. For comparison, the probability over all years is 33%. The approximate doubling of the probability of a warm event in the year following the eruption is similar to that observed by Adams et al. (2003).

It should be stressed that these results suggest a statistical, rather than deterministic, relationship between volcanic forcing and ENSO-like response. As discussed earlier (e.g., in the context of the discussion of Fig. 1b), in any one single realization of the actual climate, there is a sizable probability that an El Niño event will not occur. Only for the largest amplitude forcing events (e.g., A.D. 1259) is an El Niño–like response expected to be observed in almost any independent realization of the climate based on our experiments. For the relatively modest amplitude volcanic eruptions of the twentieth century (which contrast with numerous larger eruptions in prior centuries), it is difficult to relate the observed actual sequence of El Niño events to explosive volcanism (see Nicholls 1990; Robock 2000; Adams et al. 2003). Indeed, the fact that most El Niño events during the late nineteenth and twentieth century appear predictable more than a year in advance without including the effects of volcanic forcing (Chen et al. 2004) speaks to the likelihood that internal variability, rather than explosive volcanism, dominates the observed recent history of ENSO. The similarity in timing between certain notable recent El Niño events and large tropical forcing events (e.g., the 1982 El Chichón eruption and the 1991 Pinatubo eruption) may in fact be entirely coincidental. Our results, as the empirical results of Adams et al. (2003), suggest, however, that some changes in the statistical attributes of ENSO are in fact likely to be related to changes in explosive volcanic forcing over multidecadal or longer intervals.

In Fig. 3, we show the Niño-3 response (100-realization ensemble mean) for the combined solar + volcanic forcing from A.D. 1000–1999. Peak-to-peak variations on multidecadal and century time scales (Fig. 3b) range from 0.2° to 0.4°C, indicating climatically significant long-term change in ENSO mean state. Also shown is a history of ENSO inferred from oxygen isotopes in fossil corals. The corals, collected at Palmyra in the tropical central Pacific, are from intermittent time periods over the past millennium (see Fig. 3). The corals are interpreted as indicating warm-event (cold event) conditions for negative (positive) isotopic departures, based on extrapolation from recent conditions (Cobb et al. 2003). ENSO-related salinity and temperature influences in the region of Palmyra (which are currently associated with wet and warm conditions during a warm event) have a mutually reinforcing influence on oxygen isotopic fractionation (negative isotopic departures during warm events). An important caveat in this regard is that Palmyra lies at the fringe of the cold-

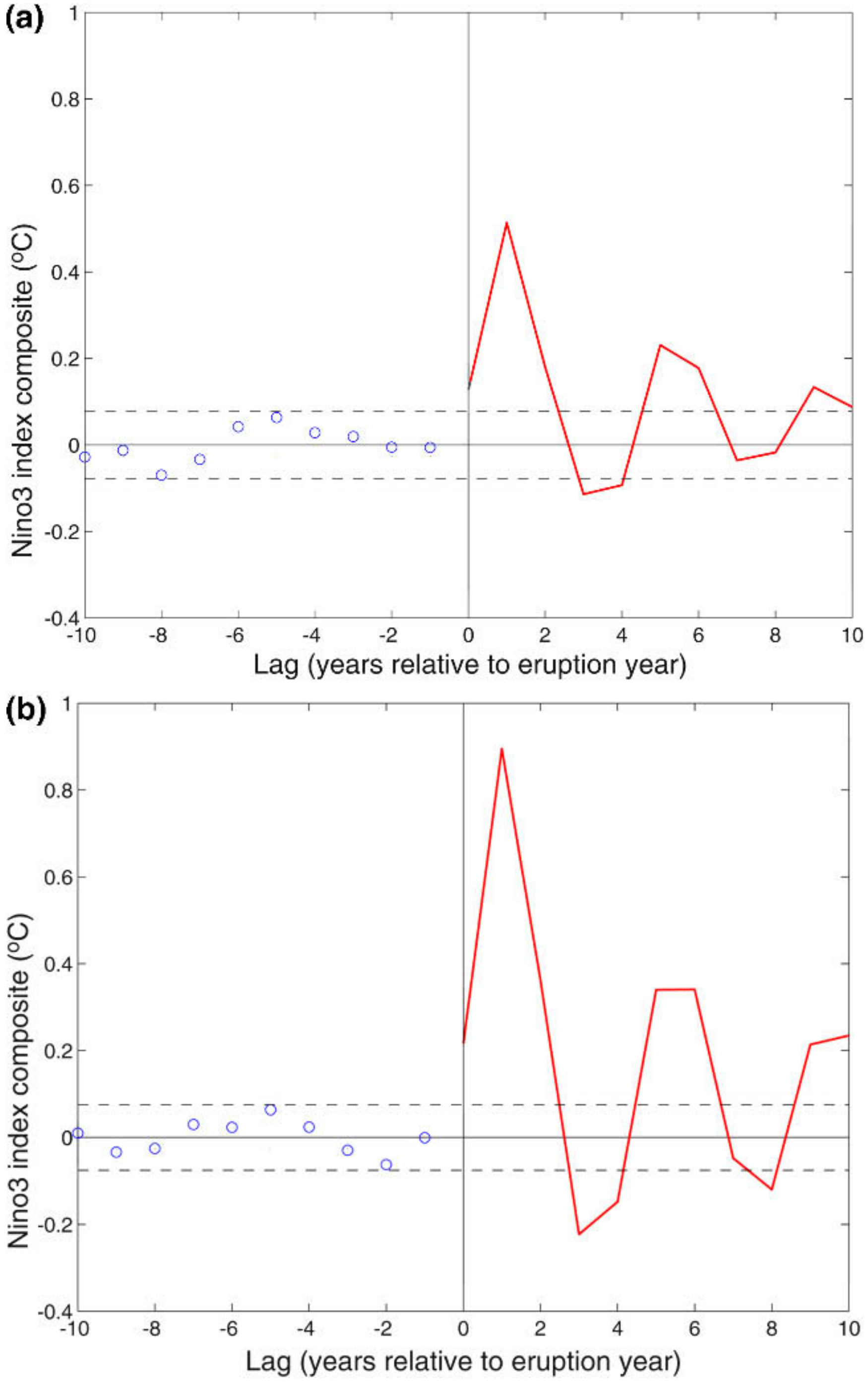

FIG. 2. SEA for volcanic forcing experiments based on composites of (a) the seven volcanic events exceeding -2 W m^{-2} over the A.D. 1649–1868 period and (b) the seven volcanic forcing events exceeding -4 W m^{-2} over the A.D. 1000–1999 period. Anomalies represent departures relative to the pre-eruption mean. Vertical solid lines indicate the timing of occurrence of the eruption, values prior to the eruption are shown as a scatterplot, while post-eruption values are shown as a continuous curve, to emphasize the structure in the post-eruption response. The horizontal dashed lines indicate ± two standard error (approximate 95% confidence) intervals, while horizontal solid line indicates the composite pre-eruption mean. Year "0" defines the year during which the eruption occurs. Unlike Adams et al. (2003) we have not normalized event magnitudes prior to compositing.

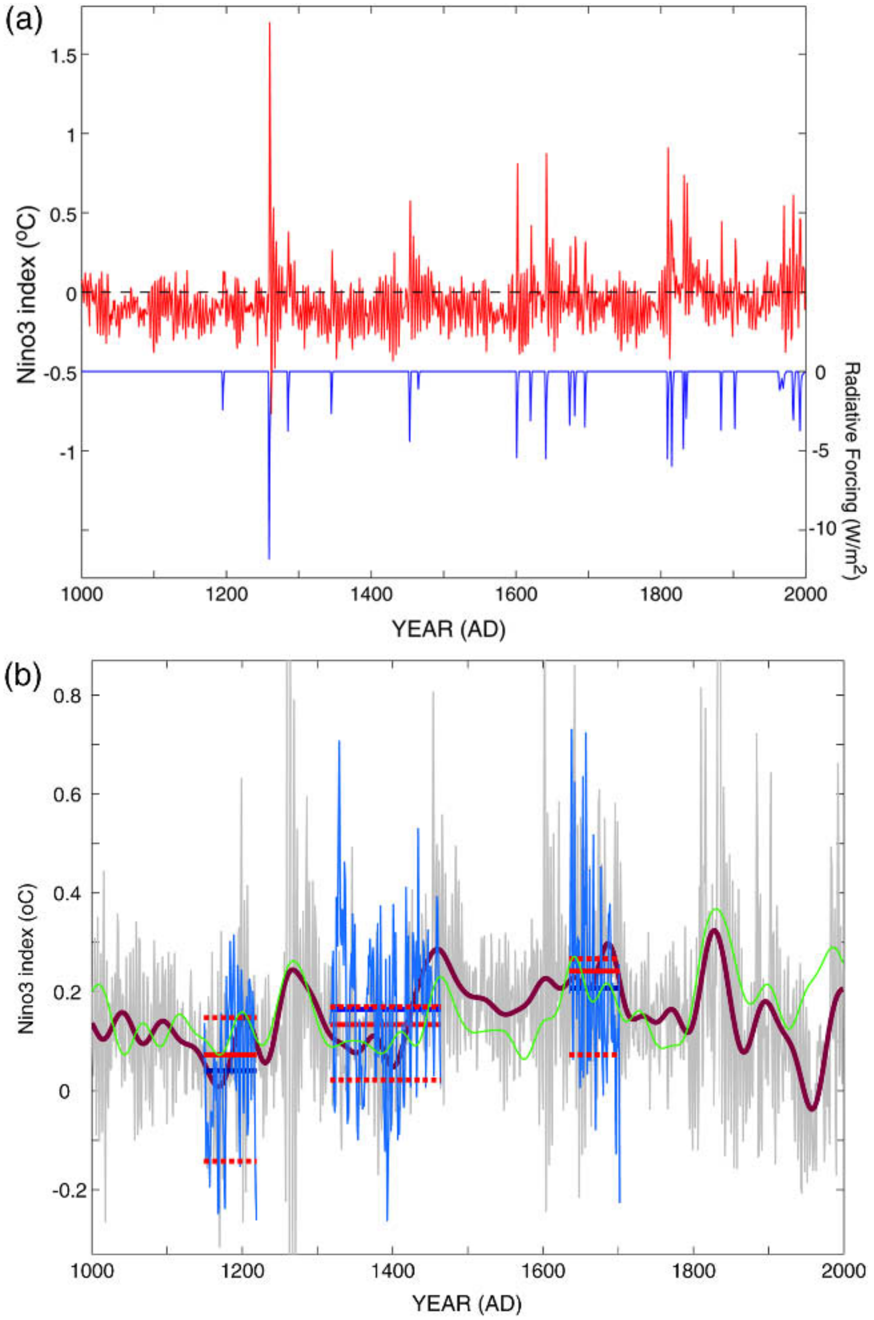

FIG. 3. Comparison of the ensemble annual mean Niño-3 response to the combined natural radiative forcing (volcanic + solar) over the interval A.D. 1000–1999. (a) Response (red; anomaly in °C relative to A.D. 1000–1999 mean) to radiative forcing (blue) based on ensemble of 100 realizations. (b) Comparison of model ensemble-mean Niño-3 (gray; anomaly in °C relative to A.D. 1950–80 reference period; 40-yr smoothed values shown by thick maroon curve) with reconstructions of ENSO behavior from Palmyra coral oxygen isotopes (blue; the annual means of the published monthly isotope data are shown). The coral data are scaled as described in the text, with warm-event (cold event) conditions associated with negative (positive) isotopic departures. Thick horizontal lines indicate averages of the scaled coral data for the three available time segments (blue) and the ensemble-mean averages from the model (red) for the corresponding time intervals. The associated interfourth quartile range for the model means (the interval within which the mean lies for 50% of the model realizations) is also shown (horizontal red dashed lines). The ensemble mean is not at the center of this range, because of the skewed nature of the underlying distribution of the model Niño-3 series. Also shown (green curve) is the 40-yr smoothed model result based on the response to volcanic forcing only, with the mean shifted to match that of the coral segments.

tongue region of the eastern tropical Pacific, a region where the relationship between SST changes and patterns of convection/precipitation might have changed as the mean climate changed. If so, then the quantitative relationship between isotopic departure and indices of ENSO such as the Niño-3 index may not be stationary over time. It is unlikely, however, that the *sign* of the relationship between ENSO indicators and isotopic departures would have changed back in time.

The coral data have been standardized to have the same mean and annual standard deviation as the composite Niño-3 series when averaged over all three overlapping segments. The means and standard deviations of the individual segments are allowed to vary. This imposes an implicit amplitude scale on the Niño-3 history inferred from the isotope data. If, instead, the isotope data are scaled based on the relationship between the twentieth-century coral segment (not shown) and the overlapping instrumental Niño-3 record, the inferred changes in Niño-3 are approximately twice as large. As discussed above, however, it is not clear that such a twentieth-century scaling will precisely hold back in time.

As the coral reconstruction provides only one realization of the history of ENSO in past centuries, it would be quite surprising if the ensemble-mean response of even a perfect model would match the observations exactly, especially at the seasonal to interannual time scale where intrinsic ENSO variability dominates, and where dating uncertainties in the coral records make precise comparisons perilous. However, the agreement between predicted and observed low-frequency changes in mean state, which should be more robust based on statistical sampling considerations, is notable: cold late-twelfth/early-thirteenth-century central/eastern tropical Pacific SSTs, moderate fourteenth/early-fifteenth-century central/eastern tropical Pacific SSTs, and warm late-seventeenth-century central/eastern tropical Pacific SSTs occur in both model and observations. For each of the three available segments the means of the observations and the model ensemble mean are consistent within the sampling distribution from the ensemble. Moreover, the late-seventeenth-century and late-twelfth/early-thirteenth-century means are statistically different in the model simulations (the interfourth quartile range for the mean of the latter period lies entirely above the ensemble average mean of the earlier period, indicating that the mean of the later period would be expected to be higher than that of the earlier period in roughly seven out of every eight realizations). Given the model prediction, we can therefore conclude that the later period would be likely to have a greater mean than the earlier period in the one observed realization (i.e., that provided by the coral data) with a roughly 90% probability. A close similarity is also found in the changes in the amplitude of interannual variability between different time intervals. The numerous large El Niño events of the late seventeenth century and the lack of large El Niño events in the late twelfth/early thirteenth century are similar for both model and observations; in the model, this difference is associated primarily with an abundance and absence, respectively, of large volcanic forcing events at those times. The increase in standard deviation in the seventeenth-century interval relative to the twelfth/thirteenth-century interval is statistically significant for both the coral observations and the model simulations (observations: 0.19 versus 0.15; model: 0.21 versus 0.16; $p < 0.1$ for the difference in both cases). A comparison with the low-frequency changes in Niño-3 due to volcanic forcing only (Fig. 3c) indicates that many of the low-frequency changes in mean and variability arise from volcanic forcing alone, with solar forcing generally playing a secondary role. Thus, the results shown are likely to be qualitatively correct even in the face of relatively large uncertainties in the amplitude of solar radiative forcing in past centuries.

A caveat that should be noted in the comparisons with the coral records is that if the alternative scaling discussed above is used (based on the statistical relationship between the model coral data and instrumental record during the twentieth century), the differences in means between the different coral segments are roughly twice as large, and the differences between the twelfth/thirteenth-century and seventeenth-century intervals fall moderately outside the interfourth quartile range of the model simulations. There are at least four possible reasons for this discrepancy: 1) the model is underestimating the true response of the system to natural radiative forcing changes, 2) the true natural radiative forcing over the tropical Pacific in past centuries is greater than assumed in the radiative forcing estimates used, 3) the actual climate history is, in part, the result of a relatively unusual realization of the internal variability, or 4) long-term changes in mean state have changed the precise relationship between ENSO precipitation and temperature changes in the Palmyra region and thus the quantitative interpretation of the isotope departures in terms of, for example, Niño-3 temperatures. It is difficult to determine, at present, which of these explanations is most viable. As additional fossil coral evidence is recovered from the tropical central Pacific for other time periods, it should be possible to further examine the relationship between natural radiative forcing and past changes in the tropical Pacific. Observations from the mid-thirteenth century following the very large A.D. 1259 eruption, or during the early-nineteenth-century period of relatively intense tropical explosive volcanic activity should, given our simulations, indicate a pronounced tendency toward an El Niño state. Anthropogenic impacts, which are increasingly important subsequent to the mid-nineteenth century, are not considered in this study. Cane et al. (1997) suggest the possibility of a cooling central/eastern equatorial Pacific in response to downward longwave forcing by increasing greenhouse gas concentrations, consistent with the mechanisms discussed in this study. However, we caution the reader that the response to anthropogenic radiative forcing may, as discussed earlier, be more complicated than that associated with the natural radiative forcing changes considered in this study.

4. Conclusions

Our model experiments reproduce the empirical observations of a short-term ENSO response to explosive tropical eruptions, as well as the tendency for an El Niño–like state in the tropical Pacific during the so-called "Little Ice Age" and a La Niña–like state during the so-called Medieval Warm Period. In the modern climate, moderate El Niño conditions are associated with a relative warming on the order of tenths of a degree (degrees Celsius) in global mean temperatures. Moreover, such conditions are associated with a pattern of widespread tropical warming but weaker warming or even cooling in some regions of the extratropics (Seager et al. 2003). The response of the tropical Pacific to radiative forcing isolated in this study thus implies both a decrease in the amplitude of the global or hemispheric-mean warming (cooling) associated with increased (decreased) radiative forcing in past centuries, and a decrease (increase) in the poleward temperature gradient between equator and midlatitudes in response to increased (decreased) radiative forcing. Such a response would argue for somewhat lower amplitude variability in actual hemispheric or global mean temperature in past centuries than is predicted by models that either do not resolve at all, or resolve incompletely, the physics underlying ENSO (e.g., Rind et al. 1999; Crowley 2000; Gonzalez-Rouco et al. 2003). This response would furthermore help to explain apparent evidence that extratropical temperature changes in past centuries (e.g., Esper et al. 2002) have been greater in amplitude than tropical (Hendy et al. 2002) or full hemispheric-scale (e.g., Mann et al. 2003) temperature changes. Future experiments using higher-resolution global coupled ocean–atmosphere models should provide further insights into the response of the tropical Pacific to past radiative forcing changes.

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