



Frontiers

The evolution of El Niño, past and future

Mark A. Cane*

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964-8000, United States

Received 16 July 2004; received in revised form 3 December 2004; accepted 8 December 2004

Available online 13 January 2005

Editor: A.N. Halliday

Abstract

We review forecasts of the future of El Niño and the Southern Oscillation (ENSO), a coupled instability of the ocean–atmosphere system in the tropical Pacific with global impacts. ENSO in the modern world is briefly described, and the physics of the ENSO cycle is discussed. Particular attention is given to the Bjerknes feedback, the instability mechanism which figures prominently in ENSO past and future. Our knowledge of ENSO in the paleoclimate record has expanded rapidly within the last 5 yr. The ENSO cycle is present in all relevant records, going back 130 kyr. It was systematically weaker during the early and middle Holocene, and model studies indicate that this results from reduced amplification in the late summer and early fall, a consequence of the altered mean climate in response to boreal summer perihelion. Data from corals shows substantial decadal and longer variations in the strength of the ENSO cycle within the past 1000 yr; it is suggested that this may be due to solar and volcanic variations in solar insolation, amplified by the Bjerknes feedback. There is some evidence that this feedback has operated in the 20th century and some model results indicate that it will hold sway in the greenhouse future, but it is very far from conclusive. The comprehensive general circulation models used for future climate projections leave us with an indeterminate picture of ENSO's future. Some predict more ENSO activity, some less, with the highly uncertain consensus forecast indicating little change.

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Keywords: El Niño; ENSO; paleoclimate; greenhouse warming

1. Introduction

Given time, we are a very adaptable species. Humans survive, and even flourish, in climates ranging from tropical to arctic, from arid to rain

forest. In common with most species, however, we are troubled by rapid changes in climate. A few years of well below average rainfall in some normally well-watered farmlands may fairly be described as “a devastating drought”, although the same level of rainfall might mean a bountiful harvest in a savannah.

Within our lifetimes, the most dramatic, most energetic, and best-defined pattern of climate changes

* Tel.: +1 845 365 8344; fax: +1 845 365 8736.

E-mail address: mcane@ldeo.columbia.edu.

has been the global set of anomalies¹ referred to as ENSO (El Niño and the Southern Oscillation). The very strong and very heavily reported event in 1997–98 brought El Niño worldwide notoriety. It is implicated in catastrophic flooding in coastal Peru and Ecuador, drought in the Altiplano of Peru and Bolivia, the Nordeste region of Brazil, and Indonesia, New Guinea, and Australia. Huge forest fires on Kalimantan spread a thick cloud of smoke over Southeast Asia and crippled air travel by shutting down airports in Singapore, Malaysia, and Indonesia.

While there is a tendency to hold El Niño responsible for just about anything unusual that happened anywhere, the listed climate impacts are ones that investigations of events in the past century have shown to be strongly correlated with El Niño. Of course, every year there are droughts and floods somewhere. Goddard and Dilley [1] point out that, paradoxically, El Niño years may come to be the least costly. Unlike the seemingly random set of climate hazards in a typical year, those associated with El Niño are predictable a year or more ahead [2,3]. This could allow preparations that would mitigate the impacts of El Niño related climate anomalies. For example, given prior warning of the 1997–98 El Niño, in anticipation of heavy rains, the city of Los Angeles cleared storm drains to prevent flooding. Even without good predictions of particular events, there can be adaptive advantages just in knowing the longer-term patterns. Farmers in Queensland now understand that as a consequence of the ENSO cycle, it is likely that they will make money only 3 yr out of 10, and plan accordingly. In *Guns, Germs and Steel*, Jared Diamond argues that since agriculture was doomed to fail so often, aboriginal Australians were correct to remain as hunter–gatherers, a choice with the most profound cultural consequences.

All of us now anticipate a change in climate brought about by human activity. Among other things, we will have to adjust to a change in the year-to-year variations in climate. Will there be more El Niños, or more powerful El Niños? Will the impacts of the ENSO cycle change? Over the past century, the period for which we have instrumental data, there is a

statistically significant association between poor monsoons in India and El Niño events. This relationship seemingly broke down in the 1990s [4]; monsoon rainfall was near normal during the powerful 1997 event. In contrast during the very strong 1877 El Niño, there was severe drought in India leading to widespread famine. Kumar et al. [4] speculated that the change in the monsoon–ENSO relationship might be a consequence of global warming. However, the “normal” association seemingly has returned, as the moderate 2001–02 El Niño was accompanied by a weak monsoon.

So, how will El Niño change in a greenhouse world? The short answer, to be expanded upon in Section 4, is that the best estimate is that it will not change much at all, but we have very low confidence in this answer. We begin in Section 2 with a brief review of salient features of ENSO observed in the modern, instrumental record. We touch on ideas about the physics of ENSO, ideas that are useful in considering how ENSO behavior can change. ENSO’s past is reviewed in Section 3. The last few years have seen a great increase in our knowledge of ENSO in the Holocene and late Pleistocene. The changes over this time, and our ability to explain them, offer some guidance for the future.

2. ENSO in the present

Fig. 1 shows two widely used indices for ENSO over the past century and a half. The term “El Niño” was used long ago by Peruvian fishermen for the annual warming of coastal waters that occurs around Christmas time. Scientists now reserve the term for a warming of the eastern equatorial Pacific, though there is no widely accepted definition of how much of a warming over exactly what region it takes to qualify as an “El Niño”. NINO3, which refers to the sea surface temperature (SST) anomaly in the NINO3 region (90W–150W, 5S–5N) of the eastern equatorial Pacific, is a commonly used index of El Niño. The “Southern Oscillation” is a seesawing of atmospheric mass, and hence of sea level pressure (SLP), between the eastern and western Pacific. It is most often indexed by the Southern Oscillation Index (SOI), a normalized SLP difference between Darwin, Australia and Tahiti. In Fig. 1, we simply use SLP at Darwin,

¹ In this paper, “anomalies” mean departures from the seasonally varying climatological mean state.

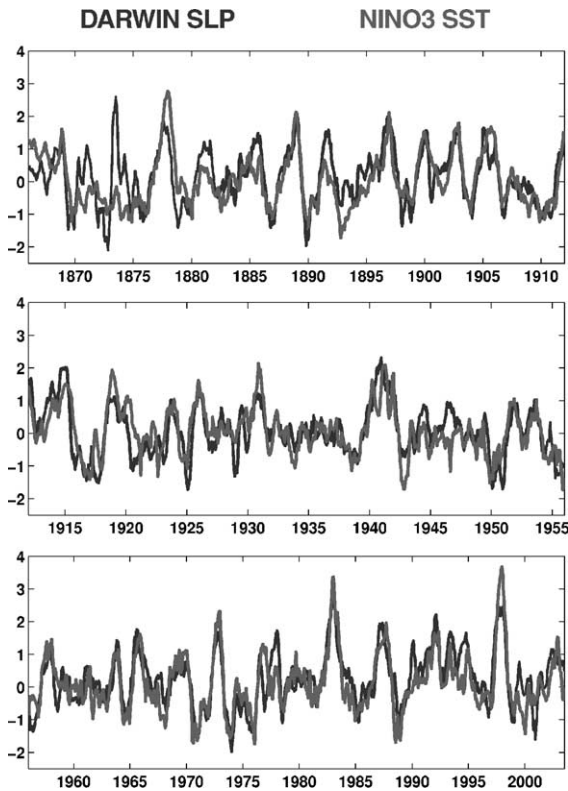


Fig. 1. Measures of El Niño and of the Southern Oscillation, 1866–2003. The grey curve is a commonly used index of El Niño, the sea surface temperature (SST) anomaly in the NINO3 region of the eastern equatorial Pacific (90°W–150°W, 5°S–5°N). The black curve is the sea level pressure (SLP) at Darwin, Australia, an index of the atmospheric Southern Oscillation. The close relationship between the two indices is evident. (Departures in the earliest part of the record are more likely due to data quality problems than to real structural changes in ENSO.)

which is almost the same because the anti-correlation between Tahiti and Darwin is so high. There is a striking similarity between the two measures, one atmospheric and one oceanic, widely separated in space. Clearly, they index the same phenomenon.

The most obvious features of the records in Fig. 1 are the irregular oscillations occurring about every 4 yr (2–7 yr is usually taken as defining the ENSO band). Some time periods such as the late 19th or 20th centuries are marked by numerous high amplitude oscillations, while others (e.g., the 1930s) are rather quiet.

There is now a widely accepted explanation for the oscillation, built upon Jacob Bjerknes' [5] masterpiece

of physical reasoning from observational data (see [6] for a more detailed historical account of ENSO theory). Bjerknes marked the peculiar character of the “normal” equatorial Pacific: although the equatorial oceans all receive about the same solar insolation, the Pacific is 4–10 °C colder in the east than in the west (see Fig. 2). The east is cold because of equatorial upwelling, the raising of the thermocline exposing colder waters, and the transport of cold water from the South Pacific. All of these are dynamical features driven by the easterly trade winds. But the winds are due, in part, to the temperature contrast in the ocean, which results in higher pressures in the east than the west. The surface air flows down this gradient. Thus, the state of the tropical Pacific is maintained by a coupled positive feedback: colder temperatures in the east drive stronger easterlies which in turn drive greater upwelling, pull the thermocline up more strongly, and transport cold waters faster, making the temperatures colder still. Bjerknes, writing in the heyday of atomic energy, referred to it as a “chain reaction”. We now prefer “positive feedback” or “instability”.

Bjerknes went on to explain the El Niño state with the same mechanism. Suppose the east starts to warm; for example, because the thermocline is depressed. Then the east–west SST contrast is reduced so the pressure gradient and the winds weaken. The weaker winds bring weaker upwelling, a sinking thermocline, and slower transports of cold water. The positive feedback between ocean and atmosphere is operating in the opposite sense (see Fig. 2). Note that this explanation locks together the eastern Pacific SST and the pressure gradient—the Southern Oscillation—into a single mode of the ocean–atmosphere system, ENSO.

Bjerknes' mechanism explains why the system has two favored states but not why it oscillates between them. That part of the story relies on the understanding of equatorial ocean dynamics that developed in the two decades after he wrote. The key variable is the depth of the thermocline, or, equivalently, the amount of warm water above the thermocline. The depth changes in this warm layer associated with ENSO are much too large to be due to exchanges of heat with the atmosphere; they are a consequence of wind driven ocean dynamics. While the wind and SST changes in the ENSO cycle are tightly locked together, the sluggish thermocline changes are not in

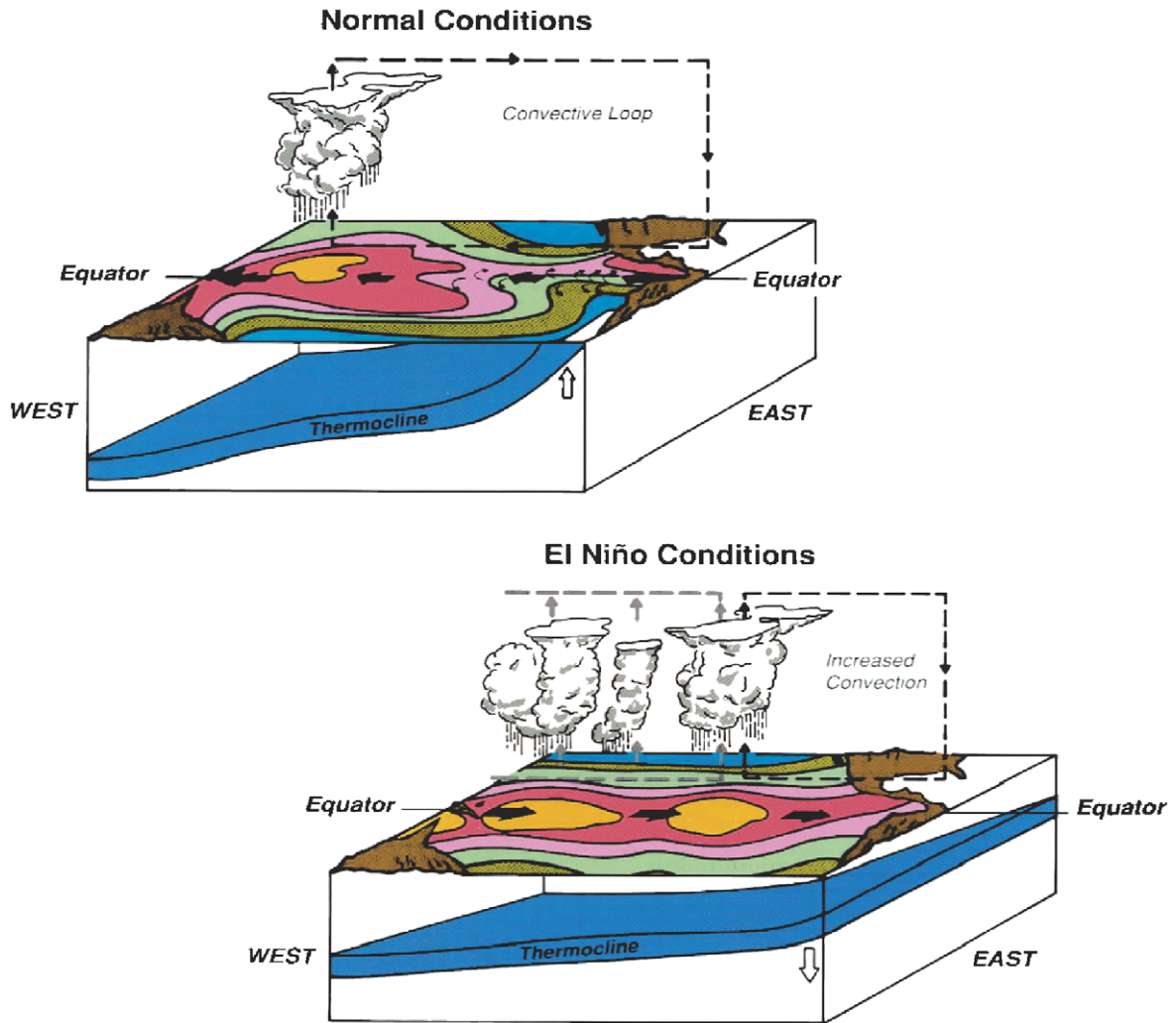


Fig. 2. Schematics of Normal Conditions and El Niño Conditions in the equatorial Pacific Ocean and atmosphere to illustrate the Bjerknes feedback. In the “normal” state, the thermocline is near the surface in the east and temperatures there are cold. The easterly trades are strong. The stronger winds pull the thermocline up and increase upwelling; the stronger east–west sea surface temperature (SST) gradient creates a stronger east west sea level pressure (SLP) gradient (a more positive Southern Oscillation), that drives stronger winds. In the El Niño state, the winds relax, the thermocline deepens in the east and the temperatures there warm. The SST and SLP gradients decrease, weakening the trade winds, and the warm state is reinforced.

phase with the winds driving them. Every oscillation must contain some element that is not perfectly in phase with the other; for ENSO it is the tropical thermocline. In particular, it is the mean depth of the thermocline—equivalently, the heat content—in the equatorial region. The most widely accepted account of the underlying dynamics emphasizes wave propagation and is referred to as the “delayed oscillator”. Some authors regard the recharge–discharge of the

equatorial ocean heat content as the essence of the oscillation. Others emphasize the role of ocean–atmosphere interactions in the western Pacific. One point of view (that of the author) is that these are different descriptions of what is the same essential physics. For another view and a summary of these ideas with numerous references, see [7].

There are two elements in this story: the coupled Bjerknes feedback and the (linear) ocean dynamics,

which introduces the out-of-phase element required to make an oscillator. If the coupling were strong enough, then the direct link from westerly wind anomaly to deeper eastern thermocline to warmer SST and back to increased westerly anomaly would build too quickly for the out-of-phase signals to ever catch up. There would be no oscillation. The “coupling strength” is determined by a host of physical factors. Among the most important: how strong the mean wind is, which influences how much wind stress is realized from a wind anomaly; how much atmospheric heating is generated by a given SST change, which will depend on mean atmospheric temperature and humidity; how sharp and deep the climatological thermocline is, which together determine how big a change in the temperature of upwelled water is realized from a given wind-driven change in the thermocline depth. The impact on ENSO frequency and amplitude of these and other factors have been discussed from the beginnings of ENSO modeling (e.g., [8]), but Federov and Philander [9,10] have recently provided a far more comprehensive study.

In simple linear analyses, the ENSO period is determined more by the coupling strength than the time for waves to travel back and forth across the Pacific. In more realistic nonlinear models, this general statement still holds, but in contrast to the linear case, the periods tend to stay within the 2–7 yr band. There is no satisfactory theory explaining why this is so, or more generally, what sets the average period of the ENSO cycle. There is broad disagreement as to why the cycle is irregular; some attribute it to low-order chaotic dynamics, some to noise–weather systems and intraseasonal oscillations—shaking what is essentially a linear, damped system. We will return to these issues as we consider ENSO past and future.

3. ENSO in the paleoclimate record

There is good evidence that the ENSO cycle has been a feature of the earth’s climate for at least the past 130,000 yr [11,12]. Fig. 3 shows records from fossil corals collected on the Huon Peninsula, a location in ENSO’s “heartland”. The oxygen isotope signal primarily reflects variations in rainfall, which has much greater range there than temperature. In any

case, since greater precipitation and warmer temperatures occur together there, we can take $\delta^{18}\text{O}$ as an index of ENSO without troubling to disentangle the temperature and salinity signals. Every record shows oscillations in the 2–7 yr band characteristic of ENSO. The records cover only a small fraction of the time since the last interglacial, so the possibility of some period without oscillations or with markedly different oscillations cannot be ruled out. However, there are enough records to be able to say that if there are such periods they cannot be common. It is interesting to note that an ENSO model [13] shows ENSO stopping only twice in the past 500,000 yr: during the Younger Dryas, and about 400 kyr earlier when the orbital configuration was most similar to the Younger Dryas.

An earlier study of a laminated core from a lake in Ecuador ([14], also see [15]) was often interpreted as showing an absence of ENSO in the early and middle Holocene [9,10,14]. The proxy for ENSO is the clastic sediment washed into the lake during the heavy rains that occur almost exclusively during El Niño events. It is consistent with the Tudhope et al. [11] record to suppose that although the ENSO cycle continues, there were few El Niño events during this period strong enough to wash material into the lake. In this view, ENSO does not start circa 5000 BP, but merely picks up strength. Because ENSO amplitudes can vary so much over a century (e.g., Fig. 1), the fossil coral records are too short and too few to allow a confident statement that the early and middle Holocene were surely marked by a weakened ENSO cycle. The lake record, however, covers the whole period, and shows a systematic difference between the early–middle Holocene and the last 5000 yr. The fossil coral records strongly suggest that the ENSO cycle was also weaker than at present during the glacial era, and of comparable amplitude to the modern during the last interglacial. More records are needed to establish that this description is indeed correct.

It is still not clear what changes in the mean state of the tropical Pacific (SST, SST gradients, upper ocean temperature structure; location and abundance of rainfall; wind patterns) accompanied these marked changes in ENSO variance through the Holocene. In particular, a continuing middle Holocene controversy is whether the mean state of the eastern equatorial Pacific was warmer or colder than today. On the basis

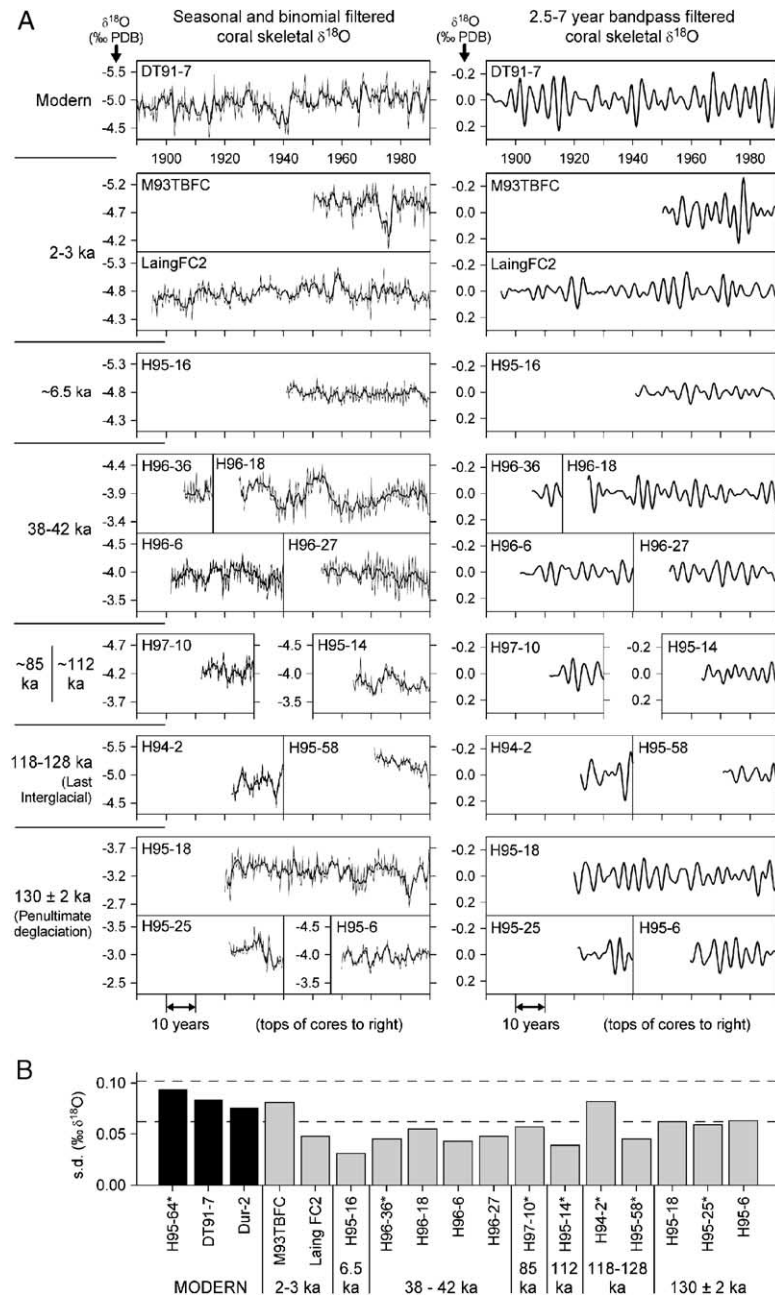


Fig. 3. Paleo-ENSO variability from fossil corals. From Tudhope et al. [11]. (A) Left-hand side: Seasonal resolution (thin lines) and 2.25 yr binomial filtered (thick lines) skeletal ^{18}O records from fossil corals from the Huon Peninsula, with the record from modern coral DT91-7 shown for comparison. Right-hand side: 2.5–7 yr (ENSO) bandpass filtered coral ^{18}O timeseries. (B) Standard deviation of the 2.5–7 yr (ENSO) bandpass filtered timeseries of all modern and fossil corals shown in (A). An asterisk after the coral label indicates that the timeseries is <30 yr long. The horizontal dashed lines indicate maximum and minimum values of standard deviation for sliding 30-yr increments in the modern coral records.

of warm water mollusk shells found on the coast of Peru at latitudes where they are not present today, Sandweiss et al. [16] inferred that the mean temperatures were warmer—a persistent El Niño state. This is not consistent with other geological evidence or the proxy temperature record of Koutavas et al. [17]. Moreover, if an El Niño-like state prevailed, there should have been more rain at the lake sites in Ecuador. A possible resolution of this apparent discrepancy was provided by Clement et al. [18] who suggest that the warm water mollusks survive not because of a permanent warm (El Niño) state, but because the cold (La Niña) phase of ENSO was also weaker at this time of reduced variability.

Why was the behavior of ENSO so different in the early and middle Holocene? Clement et al. [18] show that the likely cause is the difference in the earth's orbital configuration at that time. Using the ENSO model of Zebiak and Cane [8], they impose the perturbation heating due to orbital changes to an otherwise modern state. The model simulation has a weaker ENSO cycle during the early and middle Holocene. The average period between events is not greatly different, but strong events are rare. In both the model and real versions of the modern climate, ENSO events amplify through a “growing season” that runs through the boreal summer and into the autumn, after which growth ceases and anomalies begin to decay. (Thus El Niño and La Niña events peak around the end of the calendar year, when the rate of change is zero.) The growth is a consequence of the Bjerknes feedback; there is a positive feedback for only part of the year. In the model simulations of the early Holocene, the growth of anomalies ends around August, before the summer is over. This shorter growing season means that anomalies do not reach the peak values of today.

The equatorial oceans received about the same annual solar radiation but its seasonal distribution is quite different. Northern Hemisphere insolation was stronger in the late summer and fall, so the Intertropical Convergence Zone,² which tends to lie over the warmest water, was held in place in the higher

tropical latitudes. A key link in the Bjerknes feedback is from SST to enhanced heating to changes in the winds, but the heating is associated with low level convergence, and if the convergence cannot be moved on to the equator the link is broken and the ENSO anomalies do not grow. This analysis is based on a model of intermediate complexity, one that omits mechanisms that might alter the outcome, such as the advection of subsurface temperature anomalies. However, a comprehensive coupled general circulation model has also been shown to have a weak amplitude ENSO cycle at 9 kyr BP and 6 kyr BP [19].

Thus, orbital changes alter the mean climate and this in turn changes ENSO behavior markedly. The Tudhope et al. [11] records also suggest that ENSO was weakened by glacial conditions at times when the model, which sees only orbital changes, maintains its strength. The changes in orbital forcing and from modern to glacial are both strong perturbations. Very recent studies of ENSO over the last millennium provide examples of shifts in ENSO behavior without strong forcing. These are shifts in ENSO variance, typically associated with changes in mean temperatures in the eastern equatorial Pacific, with timescales of decades to perhaps centuries. They could be a consequence of unforced natural variability, but, as discussed below, are more likely a response to the variations in radiation forcing due to volcanic activity and changes in solar output. These forcings are not only much weaker than the orbital changes, but they have far less seasonal and latitudinal structure, so they provide more direct lessons for the greenhouse climate.

Decadal variations in ENSO are intertwined with Pacific-wide decadal variations in SST, sea level pressure, and winds. The Pacific Decadal Variation (PDO) has a pattern much like ENSO in the tropical Pacific, but broader; it has its largest amplitude in the mid-latitude North Pacific [20,21]. Recent work has shown that there are decadal variations in the South Pacific, strongly expressed in the movement of the South Pacific Convergence Zone, and that these are linked to the PDO [21–23]. Power et al. [23], noting that “PDO” is usually taken to be centered in the North Pacific, use “Interdecadal Pacific Oscillation” (IPO) to emphasize the basin wide nature of Pacific variability. Having the signal appear in both hemispheres implicates the tropics as a likely source, and

² The Intertropical Convergence Zone is the region where the northern and southern trades converge. The consequent upward motion makes this a zone of strong rainfall.

some of this work shows a direct connection in the data (see especially [21]). How much of the basin wide decadal variability is driven from coupled interactions in the tropical Pacific similar to ENSO, and how much is attributable to mid-latitude sources is an area of active research. The IPO (or PDO) has been shown to affect the connections between ENSO and rainfall in Australia [23] and North America [24]. It appears that the total SST perturbation in (at least) the tropical Pacific must be considered to capture global impacts; ENSO alone is insufficient.

It is difficult to reach firm conclusions about decadal variations from the instrumental record, since it is only long enough to provide half a dozen or so instances. The principal proxies able to resolve decadal variations are tree rings and isotopic analyses of corals. Both are at annual resolution and also resolve ENSO. The relevant tree rings are primarily proxies for precipitation in places where the influence of ENSO and the IPO are strong. They are thus indirect proxies for ENSO, subject to other large-scale climate influences as well as the usual local and biological effects. This problem can be overcome by using multiple sites to extract the signal that corresponds to ENSO or the IPO; see Mann [25], for a broad discussion. This approach has been used by a number of investigators to construct indices of the IPO going back several centuries, primarily using tree rings, [26–29], but also using both tree ring and coral data ([30–32]) and corals alone [33].

The corals from a given site used in these reconstructions have been a single coral head, allowing records of a few hundred years or less. Cobb et al. [34] overlapped shorter segments of fossil coral in a manner similar to the way tree ring time series have been spliced together from individual trees. The result is displayed in Fig. 5. Palmyra (6°N, 162°W) is in a prime location to provide an ENSO proxy, and Cobb et al.'s $\delta^{18}\text{O}$ record from modern corals correlates with the NINO3.4 (120°W to 170°W, 5°S to 5°N) SST at $r=-0.84$ in the ENSO band. In other words, this coral proxy series correlates as well or better as any two commonly used ENSO indices (e.g., SOI, NINO3, NINO3.4) correlate with each other. It is likely that the $\delta^{18}\text{O}$ signal primarily reflects rainfall and so correlates better with NINO3.4 (and NINO3) than with local SST (see [33]).

Fig. 4 also displays the results [35] of a 100-member ensemble calculated by forcing the Zebiak–Cane model with a slightly updated version of the Crowley [36] solar and volcanic forcing. Given the $\sim 1^\circ\text{C}$ variance in a single model run, one would expect the variance of the mean of a 100-member ensemble to be $\sim 0.1^\circ\text{C}$ if the variance in each member is independent, but if some of the variability is forced, then the variance of the mean will be higher. Regardless of whether it is noise-driven or a consequence of chaos, the variability of ENSO makes it impossible that even a perfect model would agree in detail with the single realization present in the observational record. If the ENSO variability is

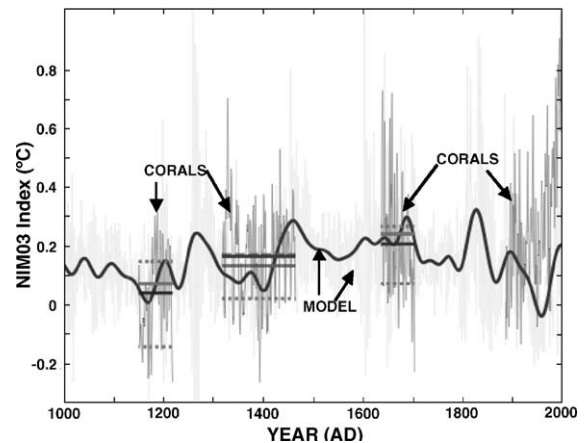


Fig. 4. After Mann et al. [35]. The annual mean NINO3 response of the Zebiak–Cane model to the combined volcanic and solar radiative forcing is compared with reconstructions of ENSO behavior from Palmyra coral oxygen isotopes. The model is run over the interval AD 1000–1999; the coral reconstruction, shown as darker grey curves, is available only for the 4 intervals shown. The continuous faint grey curve is the annual mean model NINO3 anomaly (in $^\circ\text{C}$ relative to the AD 1950–1980 reference period) averaged over a 100-member ensemble. Despite the averaging considerable variability remains, largely due to the influence of volcanic eruptions. The heavy black line shows 40-yr smoothed values of model NINO3. The coral data (darker grey curves) are scaled so that the mean agrees with the model (see [35] for details). Thick grey lines indicate averages of the scaled coral data for the three available time segments; the thick black lines are the ensemble-mean averages from the model for the corresponding time intervals. The associated inter-fourth quartile range for the model means (the interval within which the mean lies for 50% of the model realizations) is also shown (dashed grey lines). The ensemble mean is not at the center of this range, due to the skewed nature of the underlying distribution of the model NINO3 series.

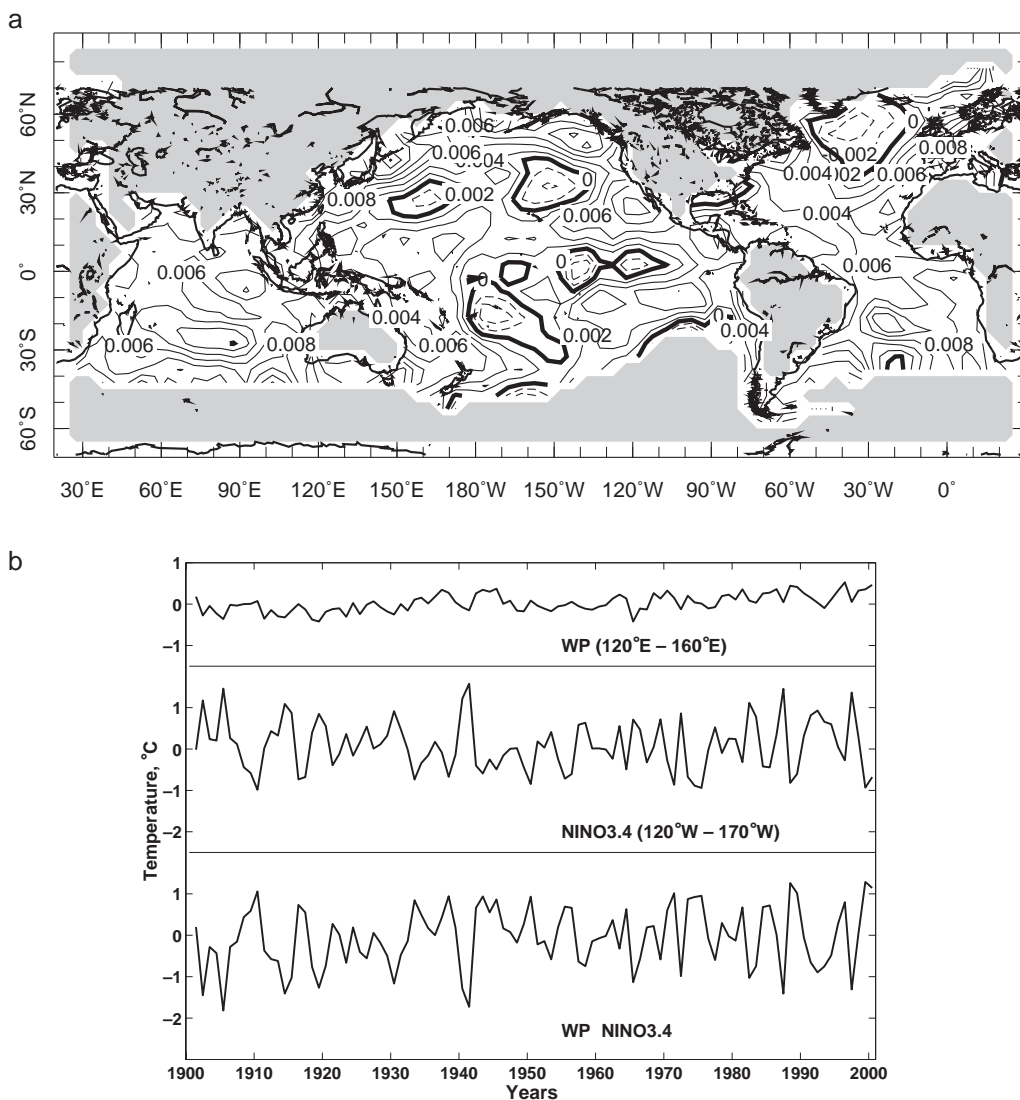


Fig. 5. (a) The trend in monthly mean SST anomalies from 1900 to 2000 in $^{\circ}\text{C}$ per yr. Updated from Cane et al. [42]. Regions that cool, such as the eastern equatorial Pacific, are significantly different from the mean global SST warming of 0.4°C per yr. (b) Time series of: (top) the average SST anomaly in the WP region (120°E to 160°E ; 5°N to 5°S); (middle) average SST anomaly in the NINO3.4 region (120°W to 170°W ; 5°N to 5°S); (bottom) the difference WP-NINO3.4, a measure of the zonal SST gradient. The least squares estimate of the linear trends in the 3 time series ($^{\circ}\text{C}$ per yr) are 0.41 ± 0.06 , -0.08 ± 0.25 , and 0.50 ± 0.25 , respectively.

forced, then it is possible for values averaged over a number of ENSO events to agree. Indeed, Fig. 5 shows, for both model and data, cold SSTs in the mean in the late 12th–early 13th centuries, moderate SSTs in the 14th–early 15th centuries, and warm SSTs in the late 17th century. In all three cases, the means of the observations and the model ensemble

are consistent within the ensemble sampling distribution (dashed lines on Fig. 4). Moreover, the late 17th century warmth and the 12–13th century cold are well separated within the distribution of states from the model ensemble runs: one would expect the later period to be warmer than the earlier one in roughly 7 out of every 8 realizations. Applying these

statistics to reality, we would expect nature's single realization to be warmer in the later period with close to a 90% probability. In both data and model, there is also a systematic difference in the strength of the ENSO cycle in the two periods. There are numerous large El Niño events in the late 17th century and very few in the 12th to early 13th century period. (This difference is statistically significant at the 0.1 level for both model and data.) Thus, both data and model show that for the last millennium more (less) ENSO variability goes with a warmer (colder) mean SST in the eastern equatorial Pacific.

The differences—in the model run, at least—are a consequence of the Bjerknes mechanism. The result is, at first, counterintuitive: the warmer tropical Pacific temperatures occur at a time of increased volcanic activity and global cooling [36,37] and vice versa. If there is a cooling over the entire tropics, then the Pacific will change more in the west than in the east because the strong upwelling in the east holds the temperature closer to the pre-existing value. Hence, the east–west temperature gradient will weaken, so the winds will slacken, so the temperature gradient will decrease further—the Bjerknes feedback, leading to a more El Niño-like state. This chain of physical reasoning is certainly correct as far as it goes, and the agreement between the data and the simulation with the simplified Zebiak–Cane model is evidence for the idea that the Bjerknes feedback holds sway in response to a change in radiation forcing. But the climate system is complex and processes not considered in this argument, such as cloud feedbacks, might be controlling.

4. ENSO in the future

Before turning to model projections of the future, we briefly consider what can be learned from the changes since the rise of CO₂ began in earnest in the late 19th century. Trenberth and Hoar [38], noting that greenhouse gas concentrations rose sharply in the past few decades, argued that the increase in the frequency and amplitude of ENSO events in the 1980s and 1990s was highly unusual, significantly different from the behavior in the preceding century, and thus attributable to anthropogenic causes. Rajagopalan et al. [39] used a different statistical model to

formulate their null hypothesis and concluded that the behavior was not significantly different from that in the earlier part of the instrumental record (also see [40]). The arguments are technical and inconclusive; the reader is invited to compare the last quarter of the 20th century with the last quarter of the 19th century in Fig. 1 and decide if the level of ENSO activity in the two eras is strikingly different. By some measures, the 1877 El Niño was more powerful than any of the events in the 20th century. Record drought in India, as well as severe droughts in Ethiopia, China, Northeast Brazil, and elsewhere, all contributed to what is fairly described as a global holocaust [41].

We noted that the data of Cobb et al. [34] showed cooling in the eastern equatorial Pacific at times in the past when the global climate warmed due to increased solar radiation or reduced volcanism, a result reproduced in the modeling study of Mann et al. [35] and explained by the Bjerknes feedback. However, this same relation does not seem to hold for the 20th century, when radiative forcing and global temperatures increase. (Crowley [36], found the greatest disagreement between global mean temperature and a model forced by solar, volcanic, and greenhouse gas variations in the early 20th century.) Perhaps this change in behavior is due to the impact of atmospheric aerosol or perhaps there is something missed in our argument when the radiative increase is due to increased greenhouse gases. Another possibility is suggested by the result of Cane et al. [42], whose plots of temperature trends from 1900 to 1991 are updated to 2000 in Fig. 5. Fig. 5 shows essentially no change in the eastern central Pacific. (Cane et al. found a slight cooling, but it was not significantly different from zero in the NINO3.4 region.) However, the data in this region are quite sparse, so this conclusion is not robust. But the east–west SST gradient does become significantly stronger over the century—as would be expected from the Bjerknes feedback (Fig. 5, bottom panel).

If we are to trust a model to predict ENSO in the greenhouse world, it is necessary that it reproduces the changes in prior centuries, but it may not be sufficient. In addition to simulating changes, it greatly increases our confidence if the model can simulate the defining features of the ENSO cycle with some skill. Is the mean frequency close to 4 yr? Is the largest

warm anomaly where it is observed in the eastern equatorial Pacific? Does the model's cold tongue extend too far to the west, into the warm pool region? Unfortunately, few of the comprehensive Coupled General Circulation Models (CGCMs) get these features right. AchutaRao and Sperber [43] reviewed the simulations of ENSO in 17 CGCMs that were part of the Coupled Model Intercomparison Project (CMIP). Most of the model El Niños were too weak and markedly in the wrong location. Five of the models were judged to “represent well the Walker circulation anomalies, the warming and enhanced rainfall in the central/east Pacific”. Some of these model ENSOs had most of their power at a higher frequency (~ 2 yr) than observed, and most did not have the correct phase with respect to the annual cycle.

Collins et al. [44] investigated the predictions from 20 CMIP CGCMs of changes in ENSO due to 1% per year increases in greenhouse gases. Fig. 6 summarizes the results. The top panel shows the histogram over the 20 model results of a measure of whether the mean state becomes more El Niño-like or more La Niña-like. The most probable outcome is no large trend in either direction. The middle panel is the histogram weighted by how well the model simulates ENSO in the present climate. The measure of quality used is obviously somewhat arbitrary, but the results are not very different from the unweighted histogram and would be qualitatively the same for any sensible measure. As the bottom panel shows, the models that do the best simulations predict small changes.

The ENSO cycle depends on the seasonal cycle, as is obvious from its tendency to have a pattern of evolution locked to the calendar. Few CGCMs are capable of realistic simulations of the climatology of

the real world. This problem can be “fixed” with “flux corrections”, empirical terms added to push the model away from its own climatology toward the observed one. Such a fix raises questions as to whether or not the flux-corrected model will have the correct variability or the correct sensitivities to

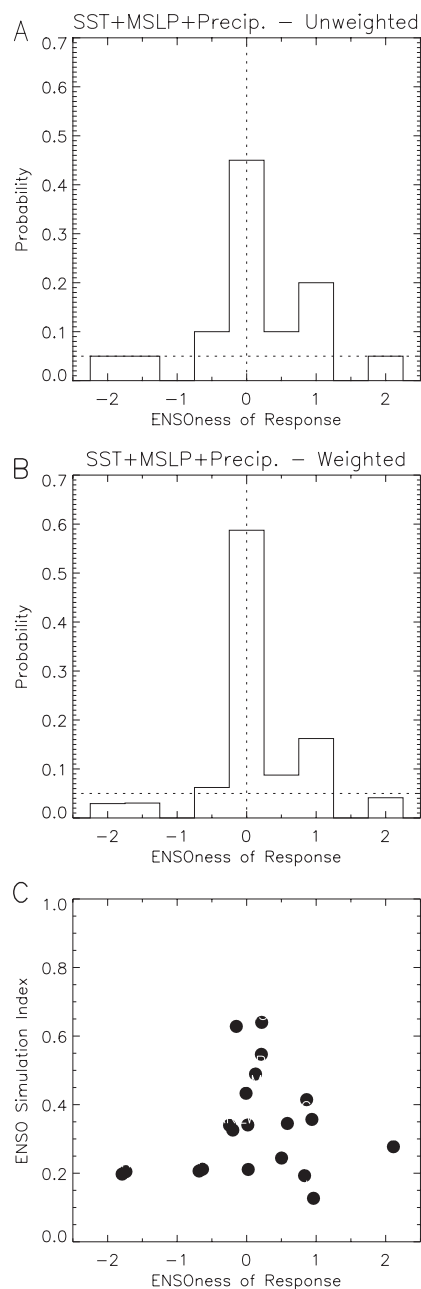


Fig. 6. (A) Un-weighted histogram of a measure of ENSO (called “ENSOness” in Collins et al. [44]) of the pattern of climate change in the CMIP 1%/yr increase of greenhouse gas experiments. The histogram is normalized to give probability values. A bin size of 0.5 is used with bins centered on 0, ± 0.5 , ± 1 , etc. (B) Histogram of “ENSOness” weighted by the ENSO Simulation Index (ESI), a measure of the realism of the model control run ENSO cycle. Bin sizes, etc., as in (A). (C) ENSOness measure against ESI for the CMIP models. Those models with the more realistic ENSO cycle tend to have a smaller amplitude trend towards either El Niño-like or La Niña-like change. From Collins et al. [44].

greenhouse gases. Strenuous efforts are now made to avoid flux corrections. Much of the difficulty models have with ENSO variability is a consequence of their poor tropical Pacific mean climates. Rather small changes have great consequence, as succinctly illustrated in Collins [45]. In simulations of a $4\times\text{CO}_2$ world, the HADCM2 model, which was flux corrected, had a stronger ENSO at a higher frequency than in a control simulation. A $4\times\text{CO}_2$ simulation with HADCM3, an improved version of HADCM2 (no flux correction, higher resolution, improved process parameterizations), showed no change in ENSO. The two models have different mean states in the control runs, and different changes in the $4\times\text{CO}_2$ world. These differences in the mean, which are primarily due to subtle differences in the parameterization of low cloud, account for the differences in ENSO response.

Doherty and Hulme [46] looked at the simulations from 12 CGCMs of changes in the SOI and tropical precipitation from 1900 to 2099. (Data from these 12 are available at the IPCC Data Distribution Centre; many are also in the CMIP set.) They report that changes in SOI variability are not coherent among the models, broadly consistent with Collins et al. [44]. They do find an overall tendency toward a more positive SOI—a more La Niña-like state. Specifically, 6 of the simulations showed a statistically significant positive trend and 2 a statistically significant negative (El Niño-like) trend, while the remaining 4 showed no significant trends.

The positive trend is in keeping with expectations based on the Bjerknes feedback, but was surprising because two of the earliest studies of ENSO in the greenhouse with this generation of models reported a positive (more El Niño-like) trend in NINO3 [47,48]. Moreover, the models used in these studies, ECHAM4 and CSIRO, are among the ones found to have positive trends in the SOI. One possible reason for the discrepancy between the two measures of ENSO is that a trend toward more La Niña-like SSTs in the eastern Pacific is overridden by the overall global warming; it would be revealed by looking at east–west temperature gradients instead of NINO3, as is the case for the 20th century observations in Fig. 5. Or, it might be that the overall pattern of the ENSO events is altered in the greenhouse world; for example, a shift to the southeast as observed in the late 20th century by

Kumar et al. [4]. Doherty and Hulme [46] found pattern changes in a minority of the 12 simulations they considered, with HADCM2 and ECHAM4 showing eastward shifts.

5. Conclusions

Glendower: *I can summon spirits from the vasty deep.*
Hotspur: *why, so can I, or so can any man; but will they come when you do call for them?*

Henry IV, Part 1, Act 3 Scene 1

ENSO variations impact climate worldwide because the changes in the heating of the tropical atmosphere they create alter the global atmospheric circulation. Changes in the mean state of the tropical Pacific would have similar impacts. Since societies and ecosystems are profoundly affected, we would like to know how ENSO and the mean state of the tropical Pacific will change in our greenhouse future. We must rely on models to make such predictions, since the past does not provide a true analogue of the new climate we are creating. Our comprehensive coupled general circulation models are impressive achievements, now able to simulate many features of the climate with striking verisimilitude. The ENSO cycle, however, is not their forte. Present attempts to summon the ENSO of the future bring forth a motley and uncertain set of responses. The paleoclimate record shows us that ENSO behavior is quite sensitive to climatological conditions, so it stands to reason that ENSO will behave differently in the future. But we can't say how it will differ with any confidence. Indeed, the models' consensus estimate is that it won't change much at all.

There are reasons for optimism. The quality of ENSO simulations has improved dramatically in the past decade, and further progress is likely if computing power grows adequately. The paleoclimate record, almost devoid of information about ENSO only 5 yr ago, is expanding rapidly and even now provides enough information to test models under conditions substantially different from modern. Thus there is hope that we can soon increase our confidence in forecasts of future variability. But for the present, the

future of ENSO lies in depths of vast uncertainty, beyond our summons.

Acknowledgements

Thanks to Alexey Kaplan, Naomi Naik, Amy Clement, Sandy Tudhope, and Matt Collins for valuable discussions, and to Naomi Naik and Alexey Kaplan for help with figures and Virginia DiBlasi for help with ms preparation. The constructive reviews of Sandy Tudhope, Chunzai Wang, and Sune Nielsen improved the text. This work was supported by NOAA grants NA03OAR4310064 and NA03OAR4320179 and NSF grant ATM0347009.

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Mark Cane is the G. Unger Vetlesen Professor of Earth and Climate Sciences at Columbia University. With Lamont colleague Stephen Zebiak, he devised the first numerical model able to simulate El Niño. In 1985, this model was used to make the first physically based forecasts of El Niño. Over the years, the Zebiak–Cane model has been the primary tool used by many investigators to enhance understanding of ENSO. Dr. Cane has also worked extensively on the impact of El Niño on human activity, especially agriculture. His recent research includes paleoclimate problems from the Pliocene to the last millennium.