EL NIÑO DYNAMICS

Bringer of storms and droughts, the El Niño/Southern Oscillation results from the complex, sometimes chaotic interplay of ocean and atmosphere.

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The El Niño/Southern Oscillation phenomenon (ENSO, for short) is the strongest source of natural variability in Earth's climate system.[1] Although ENSO originates in the tropical latitudes of the Pacific Ocean, its climatic impact is felt globally. Variations in major rainfall systems that are attributed to ENSO range from droughts in Indonesia and Australia to storms and flooding in Ecuador and the US.[2]

The term "El Niño" was originally used by Peruvian fishermen for a warming of coastal waters that begins around Christmas. (*El Niño* is Spanish for "the Christ child.") The term is now used to refer to the large-scale warming of the whole tropical Pacific that takes place every four years on average and alternates with an opposite cold phase, sometimes called La Niña.

The Southern Oscillation was discovered in 1923 by the British climatologist Gilbert Walker, who sought to explain why the Indian monsoon fails in some years. Walker found irregular standing oscillations in atmospheric surface pressure that span the Pacific from east to west. The term "Southern Oscillation" now also applies to the associated large-scale changes in atmospheric circulation.

Climate dynamicists now recognize that El Niño and the Southern Oscillation are simply aspects of the same coupled mode of the ocean–atmosphere system. Observational evidence for this connection is apparent in figure 1, which shows the anticorrelation of variations in sea surface temperature (SST) and surface pressure gradient. Box 1 on page 34 describes the long-term average state of the Pacific climate system, whose interannual variability constitutes ENSO.

The Bjerknes hypothesis

The crucial role of the interaction between the ocean and the atmosphere in the tropical Pacific was first posited in 1969 by Jacob Bjerknes. By the early 1980s, enough was known about the dynamics of the tropical ocean and atmosphere that quantitative models of the feedback between the two fluids could be developed. Over the past decade and a half, such models (see box 2 on page 34) have provided strong evidence that ocean–atmosphere interaction is indeed essential to ENSO, and this notion is referred to (generously, on the part of the many contributors to this work) as the Bjerknes hypothesis.

The essence of the hypothesis, as reinterpreted in light of current research, is that ENSO arises as a coupled cycle in which anomalies in SST (sea surface temperature) in the Pacific cause the trade winds to strengthen or slacken and, in turn, drive the changes in ocean circulation that produce anomalous SSTs. Ocean–atmosphere feedback can amplify perturbations in either the equatorial SST or the Walker Circulation—the thermodynamic circulation of air parallel to the equator (see box 1).

For instance, consider an initial, positive SST anomaly (warmer than the normal SST) in the eastern equatorial Pacific. Such an anomaly reduces the east–west SST gradient, thereby weakening the Walker Circulation, which, in turn, produces weaker trade winds at the equator. In the ocean, weakened winds cause anomalous eastward currents to flow and to deepen the normally shallow thermocline in the eastern basin. A deeper thermocline leads to warmer subsurface temperatures, which are transmitted to the surface by the upwelling in the "cold tongue" region (see box 1), resulting in a warmer SST. This further reduces the SST gradient, giving a positive feedback that can lead to instability in the long-term average state through ocean–atmosphere interactions.

To this chain of interactions must be added a mechanism for moving the system from a phase with warm SST anomalies to a subsequent cold phase. It is now believed that the ocean, by virtue of its slower timescales of adjustment, provides what may be called the memory that carries the oscillation from phase to phase. By "memory," we mean the processes that affect the subsequent evolution of the system. The slow adjustment of the ocean layer between the thermocline and the surface layer causes the depth of the equatorial thermocline to vary slowly, thereby carrying the oscillation between warm and cool phases.

Illustrating these processes, figure 2 shows how the thermal structure of the ocean changed during the onset of the 1997–98 El Niño. The important subsurface observations are now available thanks to a system of moored buoys known as the TAO array.[3]

ENSO models

The foundations of the coupled models—that is, models that incorporate the interaction between ocean and atmosphere—were laid through the study of the individual physical components of the tropical climate system. In the late 1970s and early 1980s a number of groups developed useful models representing the layer above the thermocline—called shallow-water models. These and a more complex model developed by George Philander of Princeton University and his collaborators were used to study the response to wind stress of the thermocline and of the surface and subsurface current systems.

Another advance toward understanding ENSO behavior was made by Mark Cane and Stephen Zebiak of Columbia University, who, in the mid-1980s, combined a modified shallow-water ocean model and a simple atmos-

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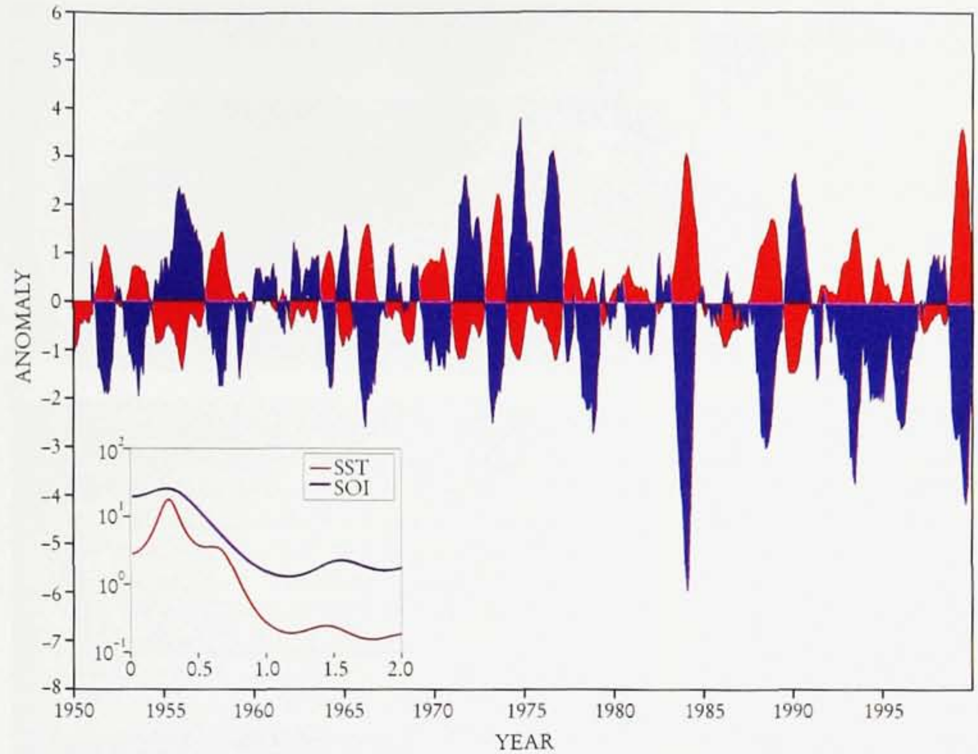


FIGURE 1. COVARYING ATMOSPHERIC AND OCEANIC INDICES. Plotted in red are anomalies (departures from the long-term mean) of sea surface temperature (SST), averaged over the east-central Pacific at the equator for 1950–97. Plotted in blue is the SOI (Southern Oscillation Index), which consists of normalized surface pressure difference between Tahiti, in the mid-Pacific, and Darwin, Australia. The SOI provides a measure of the pressure gradient across the tropical Pacific, and that gradient, in turn, is related to equatorial wind variations. During negative phases of the SOI, the anomalous winds blow eastward from high to low pressure along the equator. The SOI is normalized by the standard deviation, while SST is in degrees C. Power spectra of these time series (inset) exhibit a broad but robust peak centered at approximately four-year period (axis in cycles per year). A smaller (and less statistically robust) peak near two-year period is sometimes noted but is not resolved here.

phere model. Their model yielded sustained oscillations, whose spatial form appeared reasonably close to the observed ENSO—that is, the simulated positive and negative SST anomalies alternated with roughly four-year periods in the western Pacific, while subsurface thermocline depth anomalies carried the signal between phases. The Cane–Zebiak model was also the first coupled model to forecast ENSO with some skill.

Numerical studies of ENSO now benefit from a hierarchy of models of various degrees of complexity. The most complete representation of the system is attempted in coupled general circulation models (CGCMs), which incorporate a detailed representation of the subgrid scale processes and compute a large number of variables at each step. (See box 2.)

Less computer intensive than CGCMs, hybrid coupled models (HCMs) exploit the faster response of the atmosphere to devote computing resources to modeling the more slowly varying ocean. An HCM consists of a full ocean GCM coupled to a simpler atmosphere model.

Models like Cane and Zebiak's, in which both the ocean and atmosphere are treated more simply than in CGCMs, are now known as intermediate coupled models (ICMs).

But regardless of their accuracy or level of detail, simulations alone do not lead directly to a theoretical understanding of the coupled oscillations. Simpler models—in some cases derived by reducing the numerical complexity of ICMs—are also used.[4]

An early and influential such model was developed independently by Paul Schopf and Max Suarez (Goddard Space Flight Center) and David Battisti and Tony Hirst (University of Washington) in the late 1980s. Referred to as the SSBH delayed oscillator model, it was designed to illustrate a regime in which the slower adjustment timescales of the ocean supply the system with the memory essential to the oscillation. A delay term in the SSBH model represents this ocean adjustment time and encapsulates the role of ocean memory in providing the cyclic nature observed. The SSBH model, however, is somewhat limited, since, by presuming that the interaction between the wind stress and the ocean takes a specific form, it cannot explain how this spatial structure arises in ENSO in the first place.

Strong coupling

Given that the ocean has so much more inertia than the atmosphere, you might think that ENSO dynamics could be studied by solving the ocean component and perturbing the solution by weakly coupling it to the atmosphere. Unfortunately, this approach does not provide a realistic picture of ENSO behavior.

Analytical investigations into the balances of the ENSO regime in ICMs show that the timescale and spatial structure of ENSO are set cooperatively by the atmosphere and the ocean. The atmosphere responds quickly to changes in the ocean and, therefore, tends to dominate the spatial structure. Furthermore, the atmosphere's adjustment by fast internal wave motions tends to set large spatial scales. The ocean's slower adjustment provides the memory of the system, but is subject to a spatial structure in wind stress, which is largely determined by the atmosphere. This coupling produces an ENSO timescale that would not have occurred solely based on ocean dynamics, since the ocean alone would not have produced the spatial pattern created by the interaction with the atmosphere.

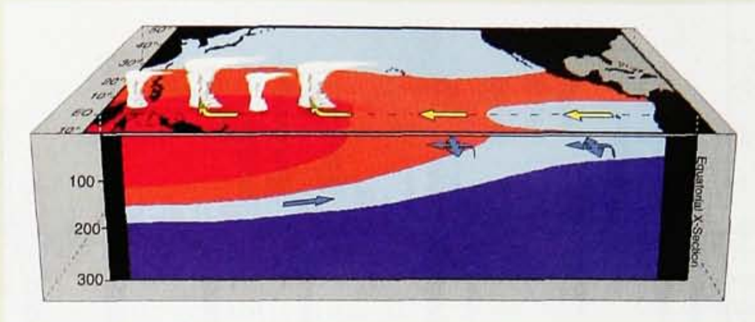
Irregularity, chaos and noise

Although the oscillatory aspect of ENSO behavior is now understood reasonably well, the irregularity of the observed cycle (recall figure 1) is a subject of active research. There are three contending hypotheses for the source of ENSO irregularity—namely, deterministic chaos within the nonlinear dynamics of the slow components of the coupled system, uncoupled atmospheric weather noise and secular variation in the climatic state affecting ENSO. Since ENSO's irregularity limits its predictability, and since these three sources of irregularity affect predictability differently, this particular issue has practical, as well as theoretical, implications.

▷ **Deterministic chaos.** This hypothesis is closely as-

Box 1: The Ocean-Atmosphere System of the Equatorial Pacific

To understand how the ocean-atmosphere system oscillates during an episode of the El Niño/Southern Oscillation (ENSO) phenomenon, we should first consider the system's long-term average state, which is shown schematically in the accompanying figure.



In the tropical latitudes of the Pacific Ocean, a strong equatorial gradient characterizes the long-term average sea surface temperature (SST), which is warmer in the west (red) and cooler in the east (light blue). This gradient causes a thermodynamic circulation parallel to the equator that is known as the Walker Circulation. The warmer SST in the western Pacific produces a "convection zone" (represented as clouds), where moist convection and associated rainfall preferentially occur and air rises on average. Low-altitude, westward winds, known as trade winds, converge on this rising region (yellow arrows).

In the upper layers of the ocean, the effect of the westward wind stress is balanced largely by pressure gradients. Water mass piles up in the west, establishing a sea level gradient of about 40 cm across the Pacific. At a depth of about 200 to 100 m, there is a sharp temperature gradient known as the thermocline between cold deep waters (shown in dark blue) and warmer surface waters. Because the warm water is less dense, increased surface height in the west is compensated by a deeper thermocline, such that pressure gradients in the deep ocean are small.

Pressure gradients due to the slope in the thermocline, which tilts upward toward the east, approximately balance the wind stress. Westward wind stress tends to drive westward surface currents (blue arrows) at the equator. Due to the Coriolis force, which changes sign at the equator, these surface currents diverge north and south just off the equator. This divergence drives a narrow band of upwelling water (tails of blue arrows) along the equator, which brings cooler water up from the thermocline. The combination of upwelling water and shallow thermocline produces the equatorial "cold tongue" (an outcrop of cooler water) in the eastern Pacific, while the deep thermocline in the west is associated with a region warm SST known as the western Pacific warm pool.

sociated with the nonlinear interaction of ENSO with the annual cycle of seasons. Researchers have noticed that when the annual cycle is eliminated from their models, most ICMs have ENSO cycles with an internally determined and regular interannual period. However, when the annual cycle is included in the models, nonlinear interaction with the annual cycle often modifies the period of the ENSO mode to some rational multiple of a year. Such frequency locking is common in nonlinear systems.

Chaotic ENSO behavior has been observed in several models. In ICMs and HCMs, the transition to chaos takes place primarily along the quasi-periodicity route, which is found in periodically forced nonlinear systems. In general, two parameters pave the quasi-periodicity route to chaos. One parameter affects the inherent frequency of the ENSO oscillation relative to the annual cycle, and the other one affects the strength of nonlinearity. As nonlinearity increases in the system, so does the tendency of the ENSO cycle to lock its frequency on rational fractions of the annual frequency. Chaos can ensue as the system jumps between the various subharmonic resonances.

In ICMs, the transition to chaos can occur at very low amplitudes of the ENSO oscillation, which prompts the question as to whether chaos or frequency locking is the more typical behavior. Figure 3 shows an exploration of the parameter regimes of an ICM that suggests that the real system more likely falls into a regime that is frequency locked. In frequency-locked regions, weather noise becomes the default explanation for ENSO irregularity.

▷ **Weather noise.** Much of the atmospheric variability associated with weather has relatively short decorrelation times. Because this variability appears essentially random on the long timescales associated with ENSO, it can be treated as a stochastic noise process, termed "weather noise."

Several recent studies have underlined the importance of weather noise in promoting the irregularity of the ENSO cycle. For instance, adding weather noise to an otherwise periodic coupled model produces irregularity that is generally consistent with observed ENSO signals.

In the ENSO power spectrum, weather noise broadens and flattens the roughly four-year peak. This spectral signature typically differs from that of models whose irregularity is induced purely by chaos. The chaotic models tend to retain fairly sharp dominant spectral peaks.

Box 2: Modeling the Ocean-Atmosphere System

The ocean-atmosphere numerical models that simulate and predict the El Niño/Southern Oscillation (ENSO) are examples of climate models, which are also applied to studies of global warming and other topics in geophysical fluid dynamics. In such models, the fluid motions of atmosphere and ocean are generally represented by discretizing filtered versions of the Navier–Stokes equations.

The models that attempt the most complete representation of the system are known as general circulation models (GCMs). Equations for velocity, temperature and density-related quantities (including water vapor in the atmosphere and salinity in the ocean) are stepped forward in time for roughly one million grid boxes (or an equivalent number of spatial basis functions).

Since numerical stability criteria and the many time-varying phenomena in the climatic system set typical time steps of hours or less, simulations of many years of climatic behavior are computationally intensive. Even on the fastest supercomputers, grid boxes are typically 100 km or more across, which means that the average effects on the grid box of smaller-scale phenomena, such as convective systems and clouds, must be represented approximately. Parameterizing these subgrid scale processes as functions of large-scale climatic variables continually challenges climate modelers.

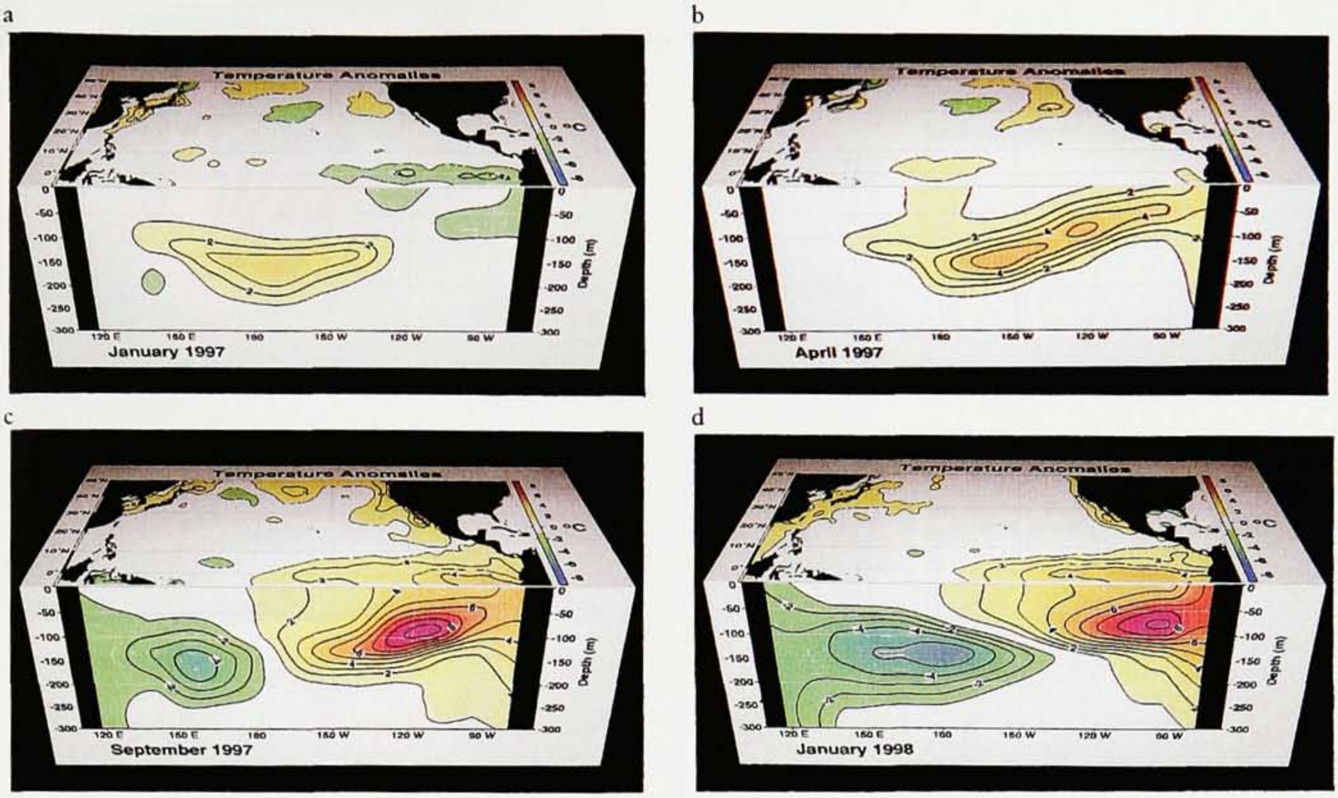


FIGURE 2. THE TRANSITION INTO THE 1997–98 EL NIÑO WARM PHASE, showing evolution of anomalies in sea surface temperatures and subsurface temperatures along the equator. In January 1997 (**a**), the surface temperature in the east was colder than normal, but in the west, the warm subsurface temperature anomalies associated with a lower thermocline had existed for some time, partly due to the movement of warm water from the equator. Because the pressure gradients associated with these anomalies were not in balance with the wind stress, they evolved in time, spreading eastward along the equator. By April 1997 (**b**), the thermocline had deepened in the east, but the effects of subsurface warm anomalies were not seen in surface temperatures. By September 1997 (**c**), the warm anomalies had been communicated to the surface and had set in motion the atmospheric feedback described under the Bjerknes hypothesis. In response to weakened easterly winds, the thermocline slope reduced further, intensifying warm anomalies in the east. In the west, the shallowing of the thermocline produced cold anomalies, which are customarily stronger off the equator. By January 1998 (**d**), this process had produced large anomalies both at and below the surface in the east. The slower adjustment process involving off-equator anomalies in the west produced growing subsurface cold anomalies. Now, in late 1998, the subsequent eastward extension of these anomalies is swinging the system into the predicted cold phase of the cycle. Known as La Niña, this phase develops much like the anomalies shown for El Niño, but with opposite sign. (Figure courtesy of David Pierce, Scripps Institute of Oceanography.)

However, even in the case of noise-driven irregularity, the signature of subharmonic resonances with the annual cycle, as in the transition to chaos, can still be seen in the ENSO power spectrum.

In general, weather noise appears to be a very significant contributor to ENSO irregularity and is, perhaps, the most important factor in setting the fundamental limits to the lead time at which El Niño can be predicted.

Moreover, in some models that successfully match ENSO's cyclic behavior, noise also supplies the energy to maintain the amplitude of the oscillations. However, it is also true that most models that lack weather noise can produce self-sustaining ENSO cycles through the instability of the underlying background state.

▷ **Changing background state.** Climate has strong variations on all timescales. In the study of interannual timescales, it is common to make the approximation that an average over a longer interval can be treated as a fixed background state. Since the period, spatial form and amplitude of the simulated ENSO are sensitive to changes in the basic state—to the mean depth of the thermocline, for instance—variations in the climate system may thus affect the way the ENSO cycle varies on interdecadal and longer timescales. During the 1920s, for example, variations in ENSO indices were relatively weak.

The tropical climate itself is hypothesized to involve a feedback mechanism akin to that at play in ENSO. The long-term average wind pattern depends on the long-term average distribution of SSTs, which, in turn, depends, by means of ocean dynamics, on the winds. How this feedback mechanism—and, by extension, ENSO—might change under global warming is an open and actively investigated question.

ENSO predictions

Because ENSO is based on a low-frequency cycle, there is some degree of inherent predictability. A hierarchy of ENSO prediction models has been developed, ranging from statistical forecast models to fully coupled ocean–atmosphere models.

Information about the evolving subsurface ocean anomalies is introduced either directly, as subsurface temperature data (recently augmented by satellite measurements of sea surface height), or indirectly, for instance, as estimates of the subsurface initial field from an ocean model driven over several previous years by the observed wind stress.

All models can skillfully predict equatorial Pacific SST anomalies at lead times of six to twelve months.[5] Because characteristic atmospheric anomalies are associated with the anomalous SSTs in the Pacific, the prediction of the anomalous SSTs also makes possible the prediction of ENSO-related climate anomalies on a global scale.

The predictability of individual weather phenomena, such as storms, is limited to about two weeks or less. However, low-frequency variations in the lower boundary conditions—SST, for example—can actually make the atmosphere more predictable. Averages over a month or a season, rather than specific weather events, are what can be predicted. More precisely, modelers can forecast changes in the probability density function of weather phenomena, such as an increased probability that, in the presence of an El Niño, Los Angeles will have above-normal winter rainfall. But the regions over which these statistical effects are significant enough to provide useful information cannot be specified arbitrarily.

As was expected from the forecasts, the 1997–98 El Niño resulted in severe drought over Indonesia and the Amazon basin. An enhanced probability of wet conditions was forecast for California and Florida, and, indeed, more storms hit those parts of the US than usual.

In terms of making practical predictions, it is evident that being able to reduce model error, improve observations and make more effective use of observational data would all contribute to achieving better ENSO forecasts. But it is the combined action of weather noise and chaos that sets the fundamental limits on ENSO predictability. Although this limit is not yet clear, current work on the effects of weather noise suggests it is well below the mean ENSO period of four years and is, perhaps, more like two years.

Encouraged by their success with ENSO, climatologists are prospecting for other aspects of Earth's climate system that may be predictable on seasonal-to-interannual timescales. We must bear in mind, however, that only for particular circumstances can we expect that forecasts will push past the limits to predictability set by the internal variability of the atmosphere.

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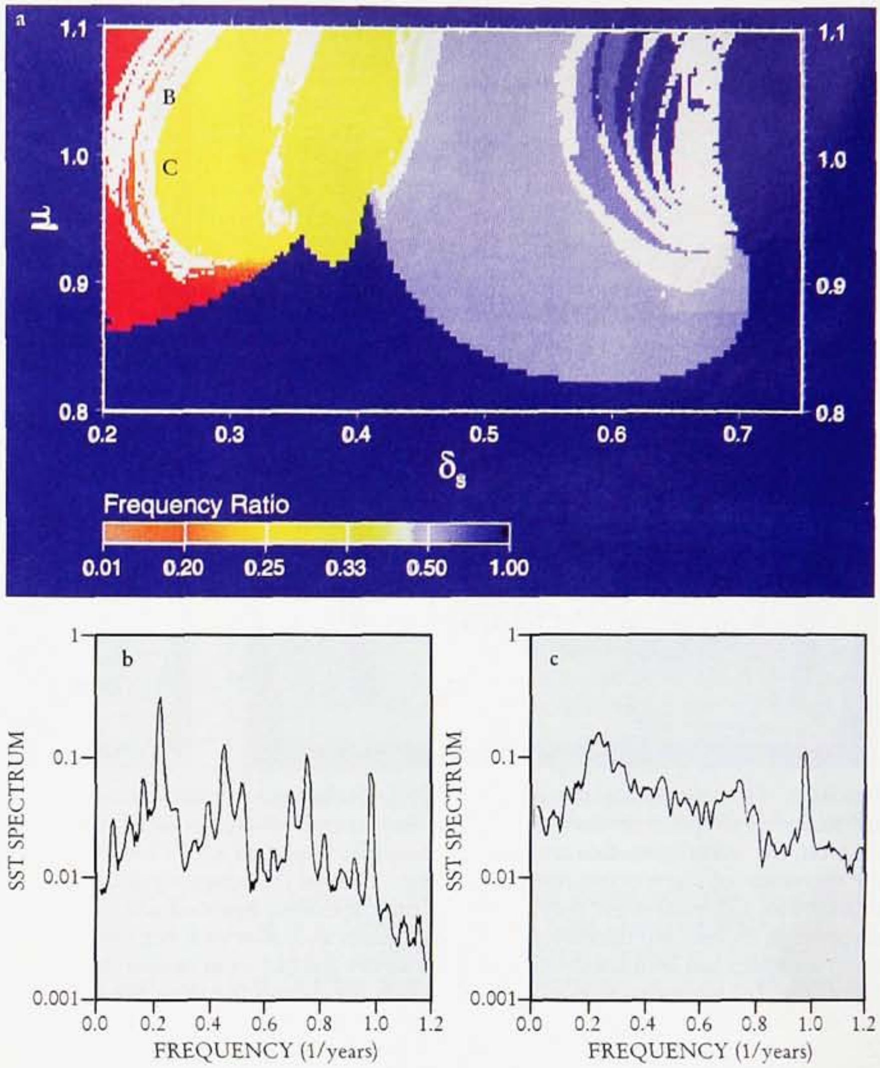

FIGURE 3. DEPENDENCE OF CHAOTIC OR FREQUENCY-LOCKED BEHAVIOR on model parameters for an El Niño model from which weather noise has been excluded. **a:** The vertical axis is a coupling parameter, which affects the amplitude of the simulated El Niño through the strength of atmospheric wind anomalies. The horizontal axis is a surface-layer parameter, inversely related to the strength of momentum mixing between the surface layer and the layer below. The surface-layer parameter affects the length of the simulated cycle, since stronger currents tend to change surface temperature faster. The plot represents the result of about 3000 500-year simulations, with each simulation classified as chaotic (gray) or frequency locked (color). In the frequency-locked case, color represents the frequency ratio of the El Niño oscillation to that of the annual cycle. For example, 0.33 is one El Niño every 3 years, while 0.30 is three El Niños every 10 years. Ratios of integers occur only for frequency-locked solutions. By contrast, the chaotic solutions occur between the strongly frequency locked regions, where the solution tends to lock first on one interval and then on the other. Chaotic solutions yield power spectra that still have spectral peaks, but a broadband background typical of chaotic solutions. **b:** the power spectrum for point B in **a**. **c:** the power spectrum from the point marked C in **a**, but with a representation of weather noise included. It exhibits the broadening of the four-year peak that is comparable to more complex models and to observations (see figure 1). (Adapted from Jin *et al.*, Physica D **98**, 442, 1996.)

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