HTLV-III/LAV directly interacts with the T4 molecule on the target cell (*22*). This also suggests that conserved epitopes of the *env* proteins of these viruses may be critical to virus infection and thus appropriate candidates for vaccine development.

The occurrence of an $STLV\text{-}III_{AGM}$–related virus in healthy Senegalese may provide clues as to how this family of viruses has evolved. It is well recognized that HTLV-III/LAV shares some sequence homology with various ungulate retroviruses, most notably visna (*23*). However, the degree of homology in genes other than *pol* is negligible, suggesting a more ancestral relationship. The similarities and cross-reactivity of $STLV\text{-}III_{AGM}$ with the *env, gag, pol*, and *3'orf* products of HTLV-III/LAV indicate that these are more closely related members of the family of T-lymphotropic viruses. $STLV\text{-}III_{AGM}$ naturally infects only a limited number of primate species, unlike STLV-I, suggesting that $STLV\text{-}III_{AGM}$ may have arisen in more recent times. It is therefore conceivable that $STLV\text{-}III_{AGM}$ or HTLV-IV may have served as the progenitor virus to the human AIDS virus, HTLV-III/LAV; alternatively they may have had a common progenitor. Continued study of the origin of this group of viruses may provide a better understanding of how they acquired their pathogenicity and how we can effectively interfere with HTLV-III/LAV infection.

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El Niño: A Chaotic Dynamical System?

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Most of the principal qualitative features of the El Niño–Southern Oscillation phenomenon can be explained by a simple but physically motivated theory. These features are the occurrence of sea-surface warmings in the eastern equatorial Pacific and the associated trade wind reversal; the aperiodicity of these events; the preferred onset time with respect to the seasonal cycle; and the much weaker events in the Atlantic and Indian oceans. The theory, in its simplest form, is a conceptual model for the interaction of just three variables, namely near-surface temperatures in the east and west equatorial ocean and a wind-driven current advecting the temperature field. For a large range of parameters, the model is naturally chaotic and aperiodically produces El Niño–like events. For a smaller basin, representing a smaller ocean, the events are proportionally less intense.

EL NIÑO MAY BE DEFINED AS THE appearance of anomalously warm water in the eastern equatorial Pacific. Associated with this is a weakening, and sometimes a reversal, of the trade wind field (Fig. 1). Major El Niño–Southern Oscillation events occurred in 1957, 1965, 1972, and 1982, and their occurrence for the past 100 years can be inferred from proxy data (*1*). The various events differ in detail and intensity but appear to have broadly similar overall features (*2–4*). Although occurring aperiodically, the events also appear to be at least partially phase-locked to the seasonal cycle. As well as engendering much purely scientific interest, El Niño has major economic consequences and possibly global climatic effects (*5*). Much observational and modeling effort has therefore been devoted to it, with various degrees of success (*6–12*).

In this report I show that all the broad qualitative features may be explained with a simple but realistic model. Other models for El Niño exist, varying in complexity from relatively elaborate coupled ocean-atmosphere models (*10*) to relatively simple stochastic dynamic or probabilistic models (*12*). To forecast El Niño, a coupled general circulation model is probably needed. However, to understand the phenomenon a simpler theory is needed. The theory, or model, presented here differs from others in that no stochastic or seasonally varying forcing is required to produce the aperiodicity, no explicit wave dynamics are required to explain the time scales, and no mid-latitude influences are needed to explain variations in intensity. Instead, these phenomena arise naturally and deterministically within a simple framework. It has been conjectured (*6, 10, 13*) that El Niños may be generated internally, but no mechanism for the complete cycle of events has been isolated.

Imagine an equatorial ocean to be a box of fluid characterized by temperatures in the east and west (T_e and T_w) and a current u (Fig. 2). The current is driven by a surface wind, which is in part generated by the temperature gradient $(T_e - T_w)/\Delta x$, so describing a parameterized Walker circulation (*14*). A cooler temperature in the east ($T_e < T_w$) produces a westward surface

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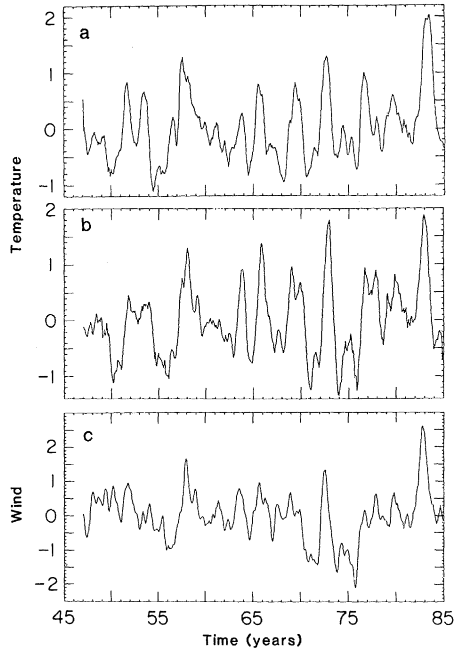
Fig. 1. (a and b) Time series for 1947 to 1985, of average sea-surface temperature anomaly (°C, annual cycle removed) for (a) the eastern equatorial Pacific (10°N to 10°S, 100°W to 80°W) and (b) the central equatorial Pacific (170°W to 120°W, 5°S to 5°N). (c) Time series of eastward surface wind anomaly (m sec^{-1}) in the central equatorial Pacific. Winds are combined averages over regions 150°E to 140°W, 0° to 10°N and 160°E to 160°W, 0° to 10°S. All series are of 5-month running means. The overall similarity of the fields is suggestive of large-scale controlling processes, and thus indicates that a low-order model can capture much of the essential dynamics. [Data courtesy of T. Barnett]



wind across the ocean, because of the convective tendency for air to rise (sink) over warm (cool) water. Thus we write

$$\frac{du}{dt} = B(T_e - T_w)/2\Delta x - C(u - u^*) \quad (1)$$

where B and C are constants. The terms $B(T_e - T_w)/\Delta x + Cu^*$ represent wind-produced stress, $-Cu$ represents mechanical damping, and a negative value for the constant u^* would represent the effect of the mean tropical surface easterlies. (Variations in pressure have been neglected; they do not qualitatively affect the model's behavior.) The temperature field is advected by the current. Assuming a deep ocean of constant temperature $\overline{T}$, the simplest finite difference approximation to the temperature equation of fluid flow is

$$\frac{dT_w}{dt} = \frac{u}{2\Delta x}(\overline{T} - T_e) - A(T_w - T^*) \quad (2)$$

$$\frac{dT_e}{dt} = \frac{u}{2\Delta x}(T_w - \overline{T}) - A(T_e - T^*) \quad (3)$$

The first term on each right-hand side represents horizontal advection and upwelling and the second forcing and thermal damping (A and T^* are constants). T^* is the temperature to which the ocean would relax in the absence of motion, and therefore represents radiative processes and heat exchange with the atmosphere. Equations 1 to 3 constitute the basic model. Obviously some physical processes have been neglected. In particular, small-scale structures, certain types of wave propagation, and the role of absolute temperature (in latent heat release) have not been represented. Kelvin waves may be important in transmitting the influence of a central equatorial wind stress to the eastern ocean (*8–10*). They can be considered a pressure wave whose purpose is to maintain a divergence-free flow. In the model presented here, upwelling is directly related to a horizontal current through the continuity relation, and in this limited sense the need for a Kelvin wave is obviated. Also, the presence of an equatorial wave-guide is implicitly recognized through the restriction of motion to a zonal plane at the equator. Furthermore, the effects of, but no feedback onto, a Hadley circulation (a primarily meridional convective cell in the tropics that produces the mean surface easterlies) are present through the term u^*. Thus, much of the essential physics of large-scale air-sea interactions in the tropics has been preserved.

Without loss of generality, we set $\overline{T} = 0$, so measuring all temperatures with respect to $\overline{T}$. For $u^* = 0$ it is possible to obtain some qualitative insight to the model's behavior, because some mathematical analysis is possible. Steady solutions are found by setting the left-hand sides of Eqs. 1 to 3 equal to zero and solving the resulting equations. For $B' < AC/T^*$ (where $B' = B/2\Delta x^2$), only one real solution exists. Because the influence of the ocean temperature on the wind is so small, the state is stable and has $u = 0$ and $T_e = T_w = T^*$. If we let B increase (keeping other parameters constant), the system will bifurcate when $B' = AC/T^*$ (it is actually a pitchfork bifurcation). The existing solution becomes unstable and two new, real, stable solutions appear. All the solutions become unstable for $B' > (4A + C)C^2/T^*(C - 2A)$. (The system undergoes a subcritical Hopf bifurcation at this point.) However, the system is bounded (meaning that T_w, T_e, and u cannot exceed certain values). Three-dimensional bounded dynamical systems with quadratic nonlinearity can display chaotic, aperiodic behavior (*15*) [whereas systems with two dependent variables (*16*) are restricted to stationary or limit-cycle behavior unless time-dependent forcing is added]. Indeed, with $u^* \neq 0$, Eqs. 1 to 3 have the same structure as the Lorenz equations. The physical system resembles that of ordinary convection in that the velocity of circulation is maintained by a horizontal temperature gradient: this sets up a direct circulation in the atmosphere, which forces the ocean. The unusual aspect here is that the oceanic part of the system is able to overturn with warmer water above the cool deep ocean—a conventionally stable configuration because work must be done on the system. Overturning and instability can occur here because the dominant driving of the ocean is mechanical, namely wind stress.

Thus for constant T^*, C, and A, all stationary solutions become unstable when B, the influence of ocean temperatures on the wind, is sufficiently large. The system can no longer stably reside anywhere and oscillates

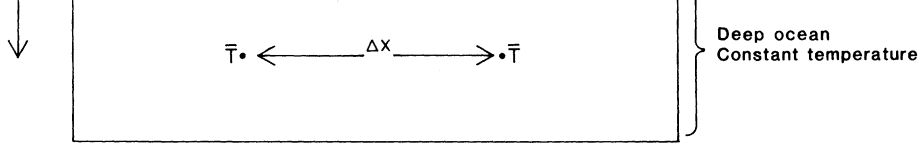
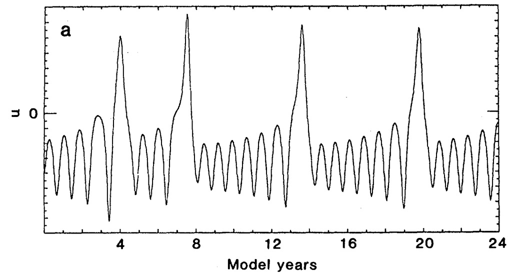


Fig. 2. Schema of model. Below the "thermocline" the temperature is constant, $\overline{T}$. The wind, driven in part by the temperature gradient $(T_e - T_w)$, generates a current which, by mass continuity, generates upwelling or downwelling as well as horizontal advection. Now if $\partial T/\partial t = -(uT)_x - (wT)_z$ and normal velocities are zero at domain boundaries, then $dT_w/dt = [0 - u(T_w + T_e)/2]/\Delta x + [w(\overline{T} + T_w)/2 - 0]/\Delta z = u(\overline{T} - T_e)/2\Delta x$, since $w/\Delta z = u/\Delta x$ by mass conservation. Addition of damping terms gives Eq. 2. Similarly for T_e.



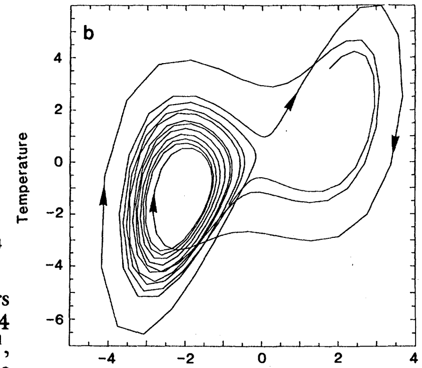
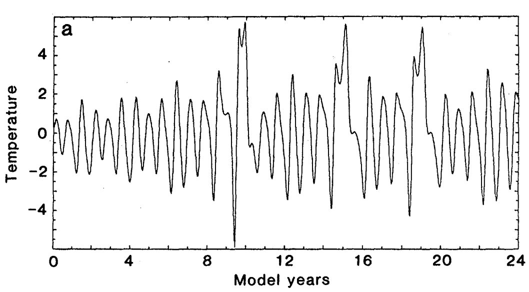


Fig. 3. (a) Typical model time series of u. Parameters chosen correspond to frictional time scales (C) of 1/4 month^{-1}, temperature decay time scale (A) of 1 year^{-1}, mean forcing current (u^*) of -0.45 m sec^{-1}, basin size (Δx) of 7500 km, and T^* of 12°C. A and C are similar to those of many modeling studies (*6, 8*). The parameter u^* has the value of typically observed mean near-surface westward currents (*17*). T^* is a typical temperature difference across the thermocline (*18*). A realistic value of B is difficult to assess. The value used here (2 m^2 sec^{-2} C^{-1}) is approximately equivalent to supposing a current of 35 cm sec^{-1} can be generated in 1 month by a temperature difference ($T_e - T_w$) of 2°C. (b) Trajectory of system projected onto u, ($T_e - T_w$) plane, over a period of 12 years. Arrows indicate direction of flow. Model has previously been integrated for several years, and the initial conditions "forgotten." Time-stepping uses fourth-order Runge-Kutta.



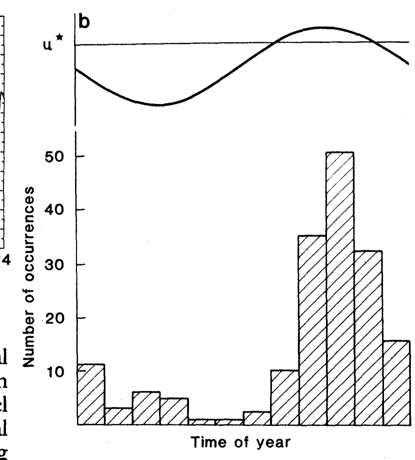


Fig. 4. (a) Model time series of $T_e - T_w$ with seasonal cycle modeled by allowing u^* to vary as u^* (1 + 3 sin ωt). Other parameters are unchanged. Here, the model variability is not completely dominated by the seasonal cycle. However, the onset of El Niño occurs only during part of the annual cycle, as indicated in (b), a histogram of occurrences of model El Niño onset (defined by u becoming positive) over time of year for a 960-year integration. The upper part of (b) illustrates the variability of u^* over the year.

apparently randomly between the two least unstable stationary states (the solution with $u = 0$ is most unstable and is essentially ignored). With $u^* \neq 0$, the symmetry between T_e and T_w is broken. Numerical time integration of the equations then yields aperiodic behavior remarkably evocative of El Niño (Fig. 3). The system stays in the neighborhood of one stationary (but unstable) solution of the equations for many model years before flipping to an El Niño state. El Niño states are orbits around another stationary, but highly unstable, solution to the equations and the system quickly returns to its normal, less unstable state. Model El Niños occur aperiodically, but typically with an interval of a few to several model years. Thus, with neither seasonal cycling nor stochastic forcing, the basic event cycle can plausibly be reproduced. After a large model El Niño, the system returns close to the other stationary solution. It then takes longer before the model breaks away to another El Niño, in accordance with observations (*1*).

A seasonal cycle may be introduced by varying u^*, in order to represent an annual cycle of the trade winds. (The parameter T^* may also be varied, with a similar effect.) Numerical integrations then reveal that the onset of El Niño is partially "phase-locked" to the annual cycle (Fig. 4). Only when the trade winds are weak is the model able to break into an El Niño. This is a well-known feature of the real system. [It may be theoretically possible to produce chaotic behavior with a two-variable model, say with temperature difference ($T_e - T_w$) and u, plus seasonal forcing. However, no such behavior was found.] Finally, the basic size may be altered by varying Δx in Eqs. 1 to 3. The temperature difference between normal and El Niño states is then altered almost in direct proportion. Thus, reducing Δx by a factor of 3 (for the Atlantic Ocean) markedly reduces the El Niño effect although the associated winds are stronger.

In summary, although the model presented here has many limitations (one being that it cannot describe spatial variations in any detail), it does explain many of the qualitative features of El Niño. It transparently demonstrates the underlying dynamics and thereby the possibility of a purely internal mechanism for the phenomenon. It shows that external triggering or stochastic forcing is not necessarily essential, although such effects may have a role in the real system. Verification or falsification of such a theory of El Niño will probably arise through controlled numerical experimentation involving large coupled general circulation models that can be directly compared with observations and used to judge a simpler theory. Until then, the theory presented here should be regarded as untested.

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