The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1849-30

Conference and School on Predictability of Natural Disasters for our Planet in Danger. A System View; Theory, Models, Data Analysis

25 June - 6 July, 2007

Predictability of ENSO
Part I: A Brief Review of ENSO Theory and its Predictability

Ping Chang

Texas A&M University (TAMU)
College Station
U.S.A.

Predictability of ENSO

Part I: A Brief Review of ENSO Theory and its Predictability

Ping Chang

TAMU

A Presentation Given at the Conference & School on Predictability of Natural Disasters for our Planet in Danger. A System View: Theory, Model, Data Analysis

ICTP, Trieste, Italy, July, 2007

Irregular oscillation

Phase Locking

Broad Spectrum

What is ENSO?

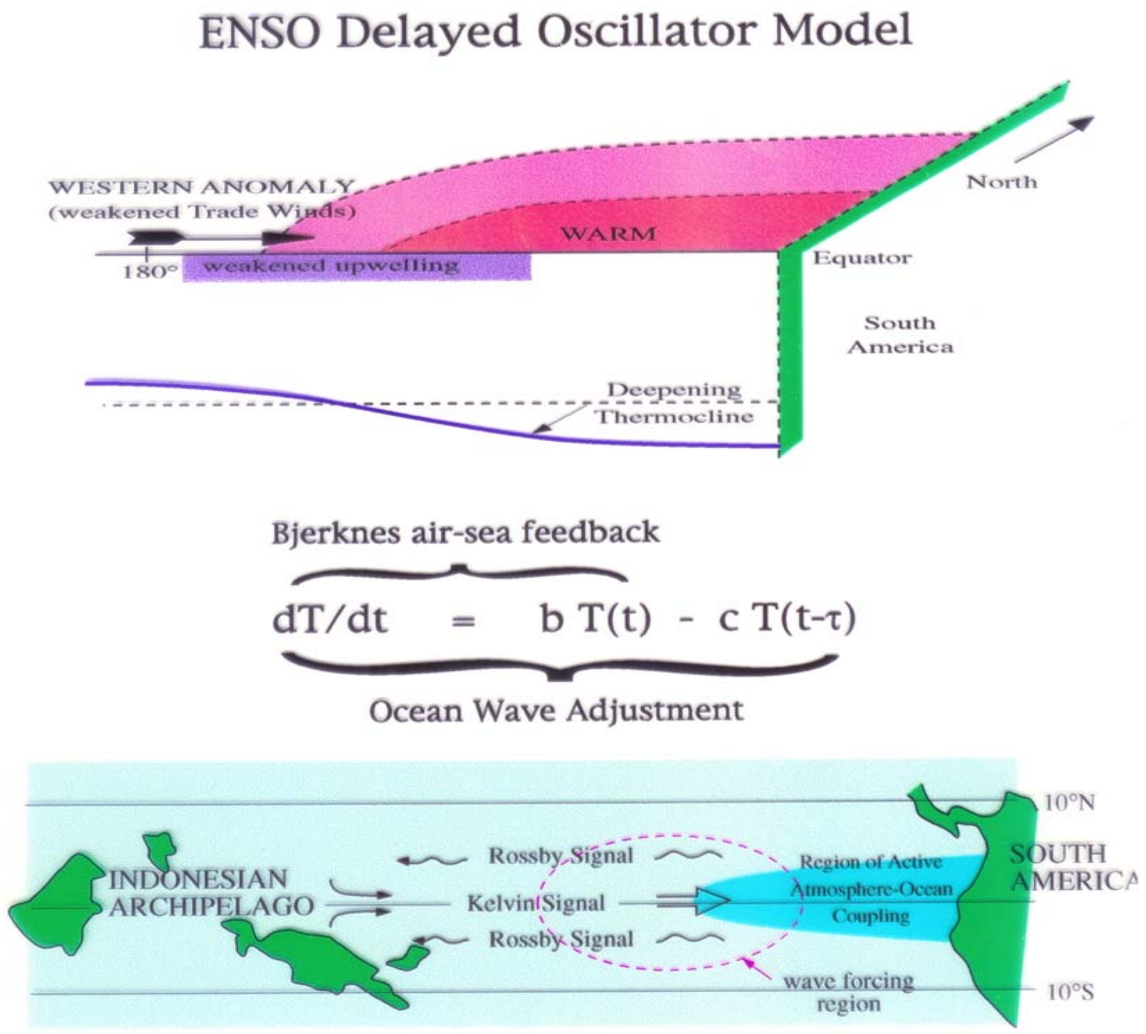
The El Niño Southern Oscillation is a spectacular, planetary-scale climate phenomenon that is inherently caused by interactions between the atmosphere and the ocean. Historically, El Niño refers to unusually warm ocean temperatures that occur every 2–7 years around Christmas time along Peruvian coast, extending into equatorial eastern and central Pacific Ocean. The Southern Oscillation, named by its discoverer – Sir Gilbert Walker – on the other hand, refers to a "seesaw" of the atmospheric pressure between the Pacific and Indian Oceans. It was not until the seminal work of Jacob Bjerknes in the late 1960s that scientists realized that these two phenomena are intimately linked. The acronym ENSO (El Niño Southern Oscillation) has now been widely used to describe this fascinating interannual climate fluctuation, emphasizing the inherent ocean – atmosphere coupling.

(from Chang and Zebiak, 2003)

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Why Does ENSO Oscillate?

- The delayed-oscillator theory forms an earlier theoretical basis for ENSO prediction.
- The recognition of the importance of subsurface ocean memory mechanism led to the TAO array.
- The theory does not address ENSO predictability limit issue.



The delayed oscillator model offers an explanation for the turnabout between warm and cold phase of the ENSO cycle. The period of ENSO is determined by a competition between the Bjerknes positive air-sea feedback and the negative feedback due to subsurface ocean adjustment. The theory points to the importance of subsurface ocean memory, particularly in the western Pacific Ocean.

ENSO Theory & Predictability

Nonlinear vs. Linear ENSO Theory :

1. ENSO Chaos Theory
2. Stochastic ENSO Theory

ENSO Predictability :

1. Factors that Limit Predictability
2. Predictability Measure
3. Predictability Analysis

Summary :

1. What Is Known
2. What Lies Ahead

ENSO Chaos Theory

Assumptions :

1. The ENSO system is unstable, so that ENSO evolution is dominated by the most unstable coupled mode, e.g., the delayed oscillator mode.

2. The most unstable mode interacts nonlinearly with the annual cycle or other modes.

How Does It Work ?

1. One parameter controlling relative strength of ENSO and annual cycle.

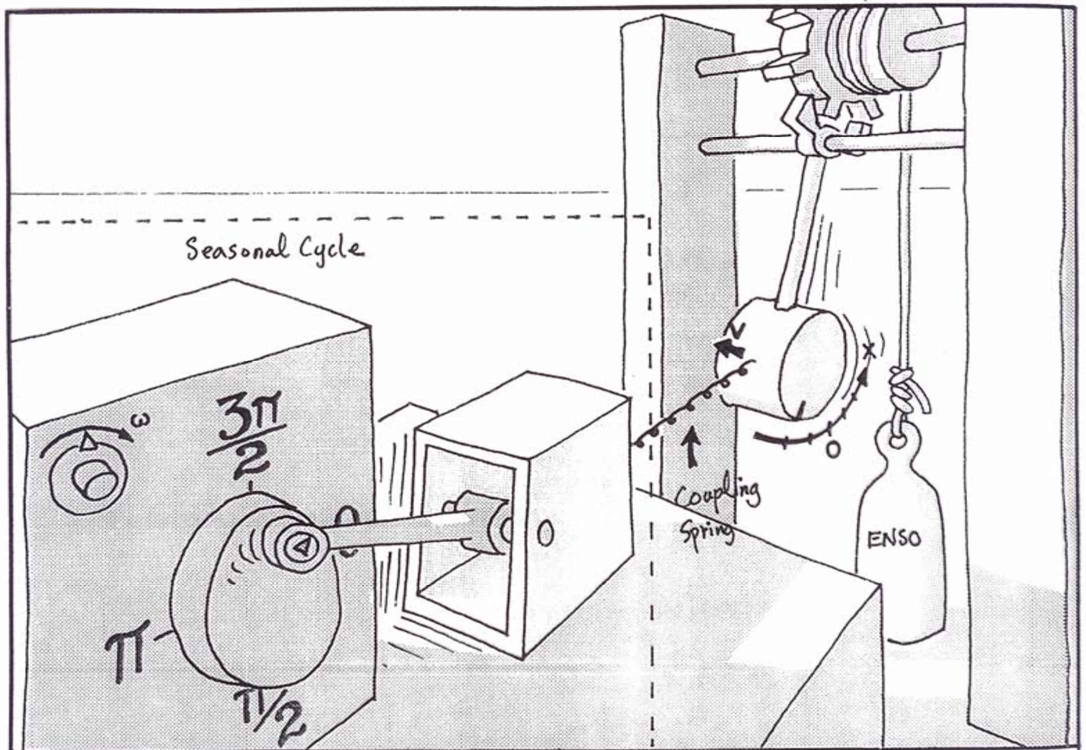
2. Other parameter controlling the nonlinearity.

What Does the Theory Predict ?

1. The tendancy of the ENSO cycle to frequency lock to rational fractions of the annual cycle.

2. The system behaves chaotically when one frequency locking regime overlaps the other, as the system jumps between the two neighboring frequency locking regimes.

Van der Pol Oscillator



5.3.1. The turntable motor is so well regulated that its speed, once set with the control knob, is unaffected by the load. The forcing oscillation is coupled to the clock pendulum by a light spring. The stiffer the spring, the greater the effect of the driving oscillation on the periodic motion of the clock pendulum.

from Abraham & Shaw (1992)

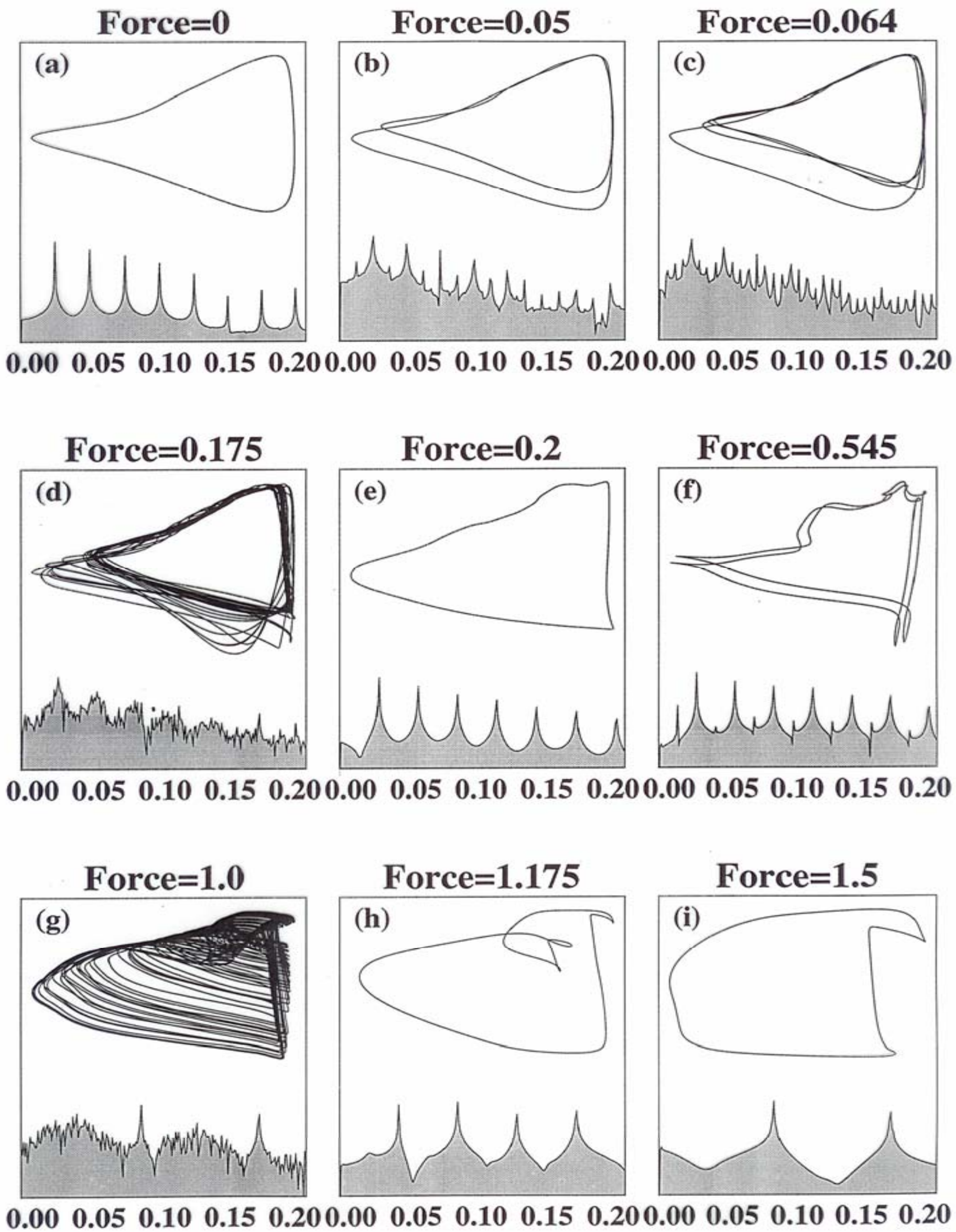


Figure 1. Phase portraits (upper) and power spectra (lower) of the model SST in the eastern equatorial Pacific (0°, 120°W) for various values of the seasonal heat flux forcing amplitude A. The phase portraits are reconstructed using the method of time delay. The delayed time is determined by auto-correlation analysis. The power spectra are shown in log-linear plots and the frequency is in units of $months^{-1}$.

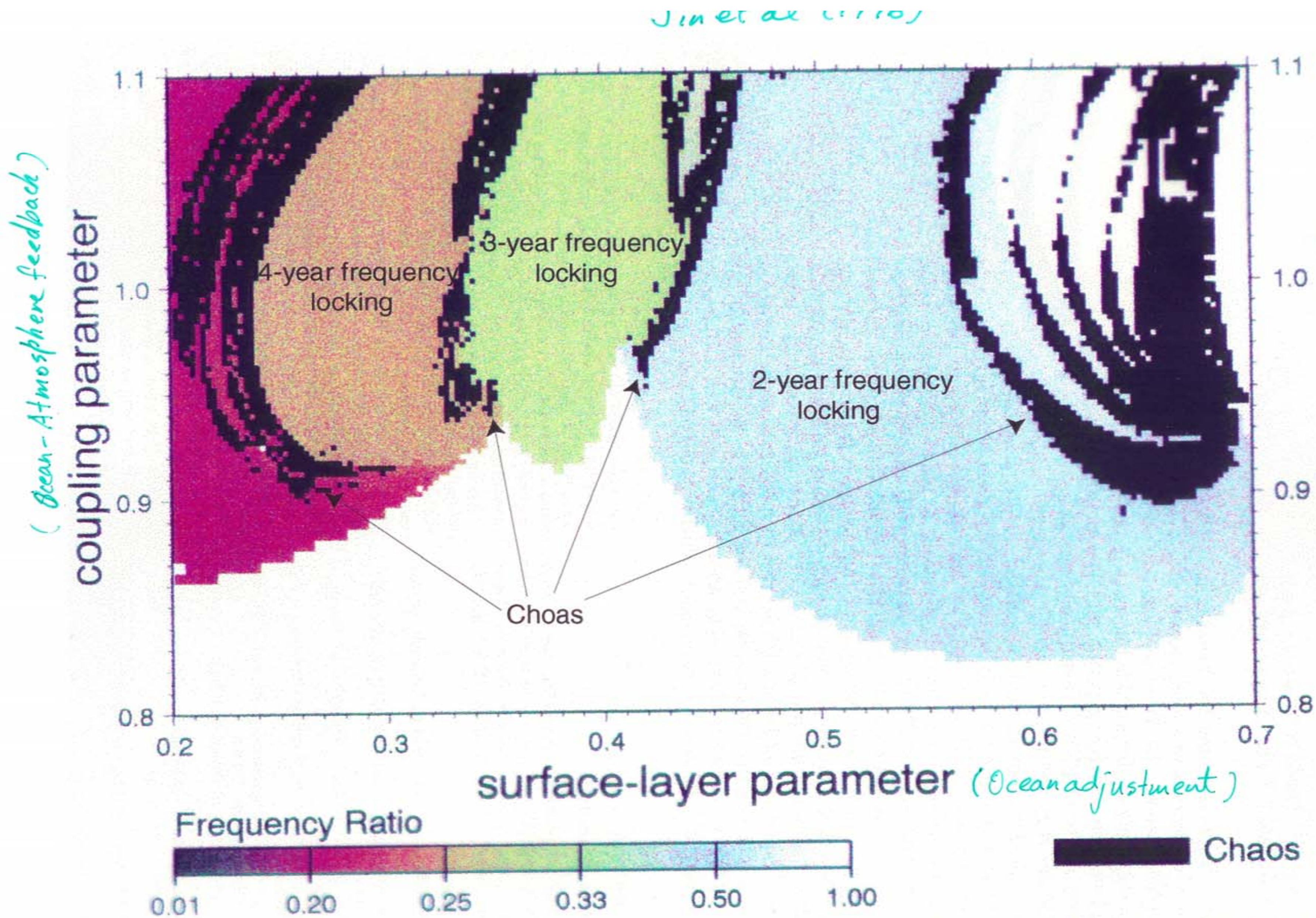


Plate 1. Chaotic versus frequency-locked behavior in an intermediate coupled model as a function of parameters. The coupling coefficient, μ, affects the amplitude of the oscillation and thus the strength of nonlinearity. The surface-layer coefficient, δ_s, affects the inherent ENSO period. Frequency ratio of the ENSO frequency to the annual frequency is shown by the color scale, with 0.25 corresponding to one El Niño every 4 years, etc. Chaotic regions are shown in black. The blank region at low coupling is below the primary bifurcation so the ENSO mode is stable. After *Jin et al.* [1996].

Linear Stochastic ENSO Theory

Assumptions :

1. The ENSO system is stable, so that ENSO evolution is not dominated by a single normal mode.

2. The internal variability of the atmosphere acts as an external (spatially coherent) white-noise forcing to maintain ENSO variability.

How Does It Work ?

1. A group of damped normal modes interferes constructively or destructively, depending on their excitation by the stochastic forcing, to give SST growth or decay.

What Does the Theory Predict ?

1. Broad band spectrum.

2. The existence of optimal initial condition and optimal stochastic forcing.

Thompson & Battisti (1999)

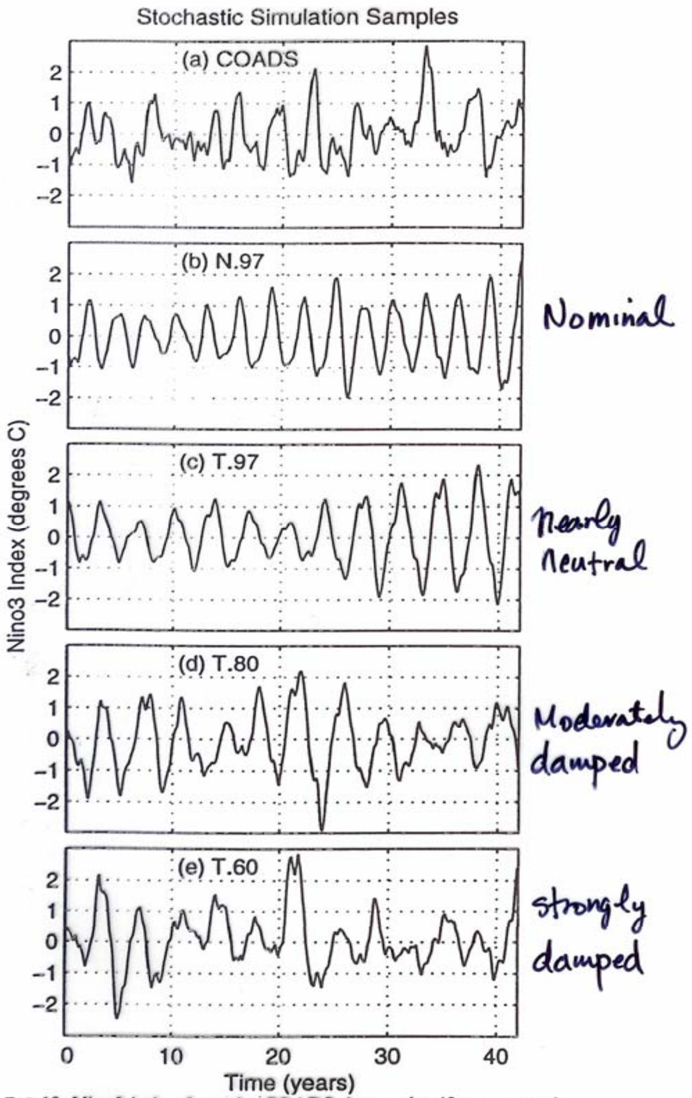


FIG 13. Nino3 index from the COADS data and a 42 year sample

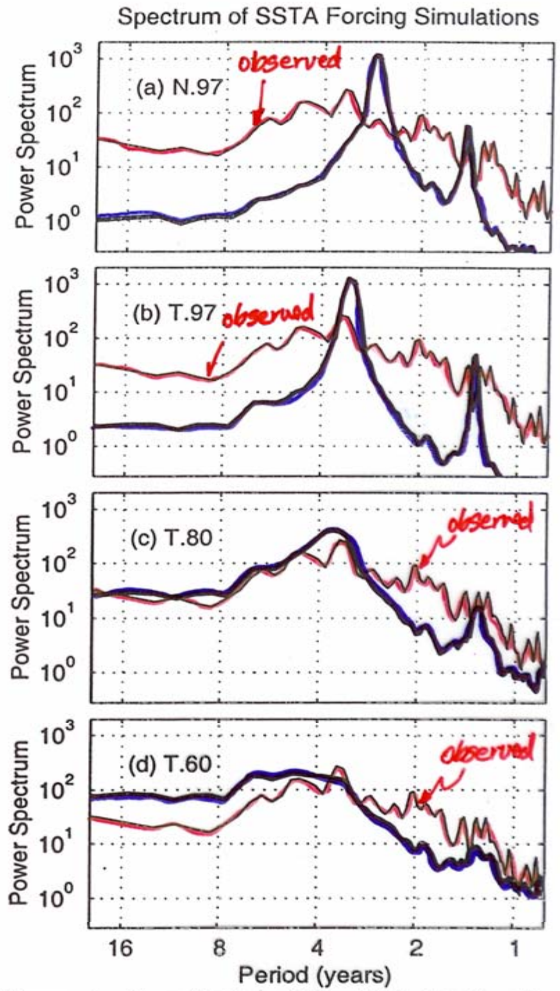
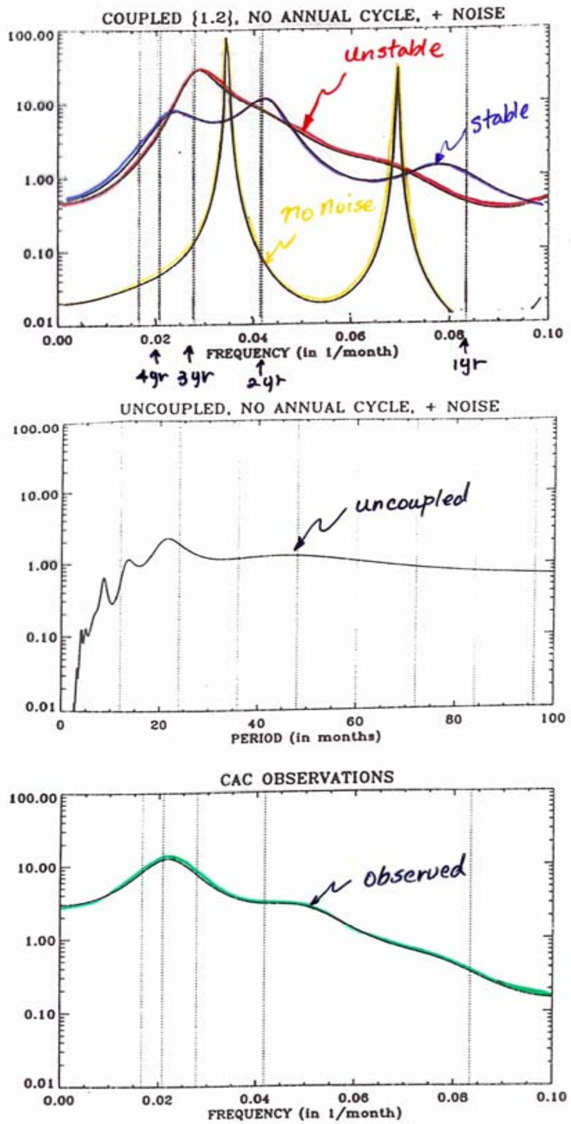


Figure 4. Power Spectra of Candidate Models. The thick lines in panels (a) through (d) show the spectrum of the Nino3 index for the N.97, T.97, T.80, and T.60, respectively. The thin line repeated in all four panels shows the COADS spectrum for comparison.

Blanke, Neelin & Gutzler (1997)



ENSO = Unstable+N.

FIG. 4. Power spectrum of the Niño3 SST anomaly time series: (a) as a function of the period, for a 112-yr simulation with the OGCM only (uncoupled mode) forced by the empirically estimated stochastic wind stress product added to the mean annual observed stress; (b) as a function of the frequency, for the observations (period 1950–93). Spectra from the maximum entropy method (MEM) of order 30.

Implication to ENSO Predictability

Deterministic Chaos Theory :

1. Initial condition error limits the predictability.
2. Predictability limit is set by the largest Lyaponov exponent.
3. ENSO is predictable well beyond one year.

Stochastic Theory :

1. Stochastic processes in the atmosphere limits the predictability.
2. Predictability limit depends on both the deterministic dynamics and stochastic forcing.
3. ENSO predictability may be quite limited.

Predictability Analysis

Given a multivariate linear stochastic system,

$$\frac{d\vec{\theta}}{dt} = \mathbf{A}\vec{\theta} + \mathbf{F}\vec{\eta}, \tag{1}$$

the optimal forecast model under the "perfect initial condition scenario" is

$$\vec{\theta}_s(\tau; t_0) = e^{\mathbf{A}\tau}\vec{\theta}_0(t_0) \tag{2}$$

with

$$\vec{\theta}_0(t_0) = \int_0^{t_0} e^{\mathbf{A}(t_0-s)}\mathbf{F}\vec{\eta}_0(s)ds$$

where $\tau = t - t_0$ is called lead time of the prediction. Prediction error is

$$\vec{\theta}_e = \int_{t_0}^{t} e^{\mathbf{A}(t-s)}\mathbf{F}\vec{\eta}(s)ds. \tag{3}$$

The normalized error error variance

$$\epsilon^2(\tau) = \frac{\sigma_e^2(\tau)}{\sigma_\infty^2} = \frac{tr(\mathbf{C}(\tau))}{tr(\mathbf{C}(\infty))} \tag{4}$$

gives a predictability meassure, where $\mathbf{C}(\tau)$ and $\mathbf{C}(\infty)$ are error and climatological covariance matrices.

Penland, Flügel and Chang (1999) Global Error Variance <$\vec{e}^* \vec{e}$>

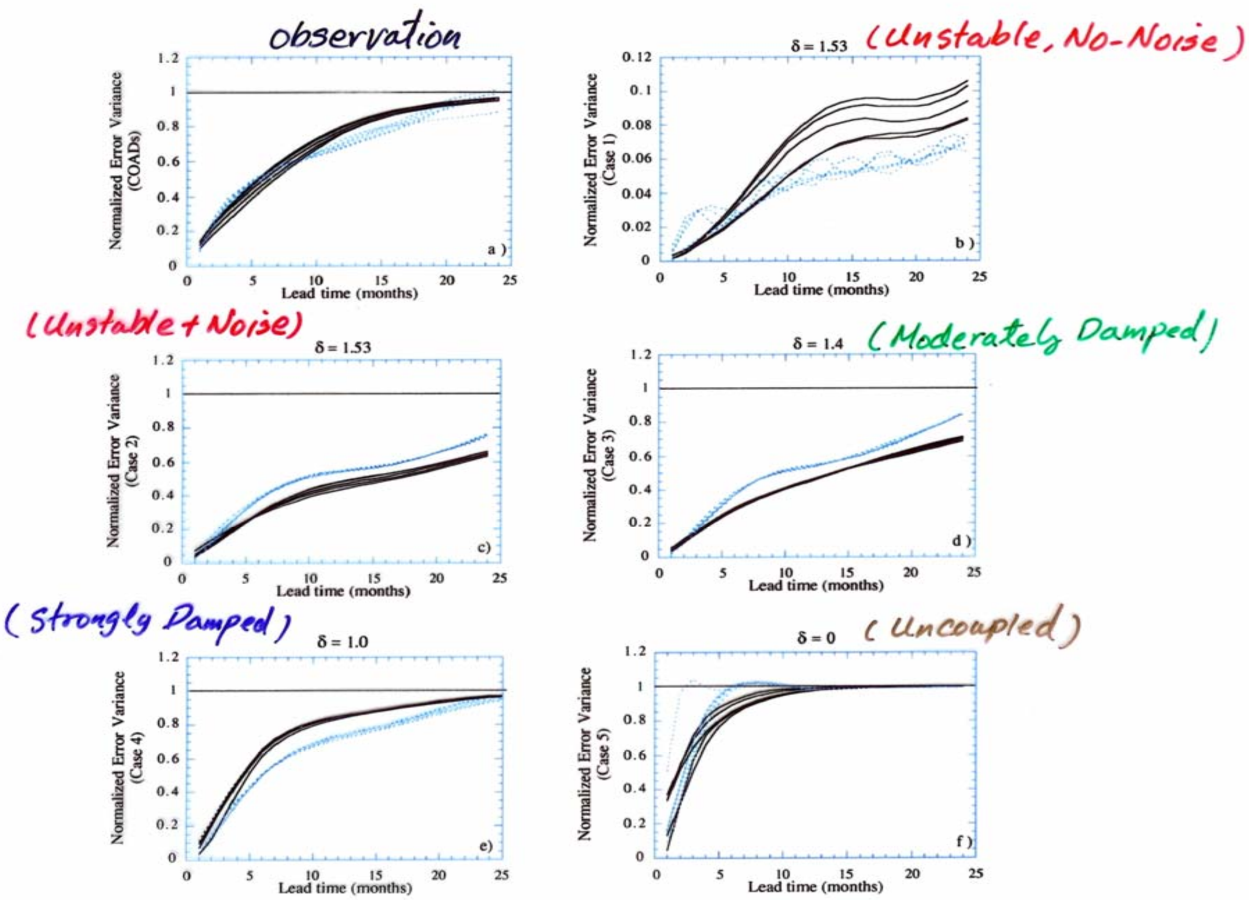


Fig.3) Normalized error variance as a function of lead time. Solid lines: Theoretically-expected error curves for $\tau_0 = 3,4,5,6,7$ months. Dotted lines: Corresponding observed error curves. a) COADS data as analyzed by PS95. b-f) Error curves for Cases 1 through 5, respectively.

Thompson & Battisti (1999)

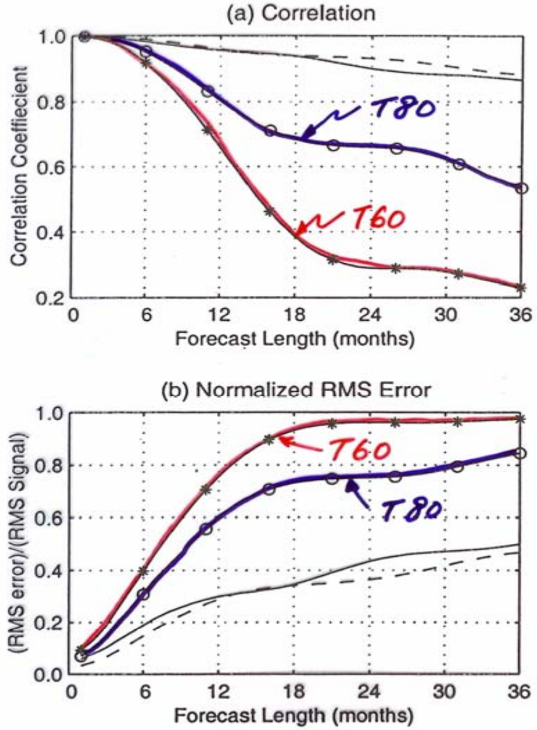


Figure 13. Averaged Potential Predictability Limit. Panel (a) shows the correlation of the Nino3 index from a simulation with the Nino3 index which is forecast using the same model with perfect initialization, but without knowledge of future noise forcing. Panel (b) shows the average normalized RMS error for the same forecasts. The key for both panels is as follows: the solid line is N.97; the dashed line is T.97; the circles are T.80; the asterisks are T.60.

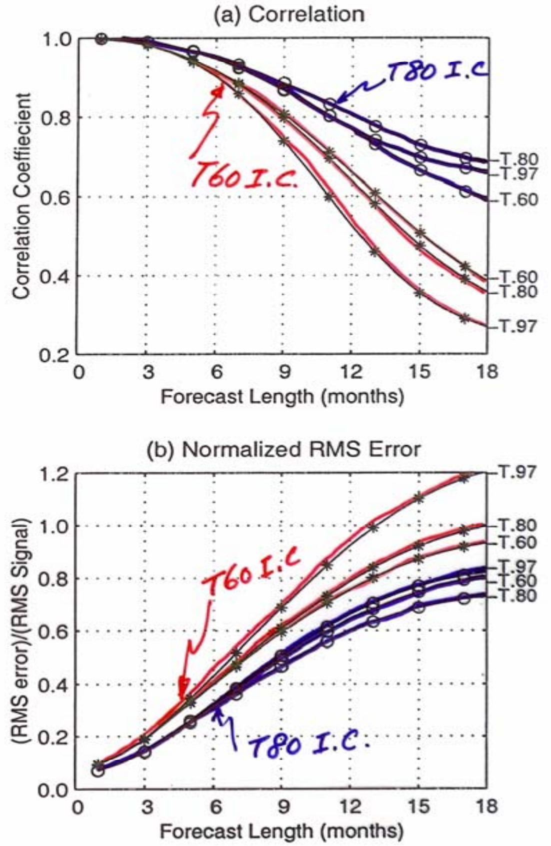


Figure 14. Imperfect Model Predictions. These graphs show the results of using one model to forecast the simulated data produced by a different model. The Nino3 index has been used at the metric to evaluate skill. Panel (a) shows the correlation for forecasts of the T.80 simulated data (circles) using the T.97, T.80 and T.60, models. Perfect initial conditions were used to start the forecasts, and hence the two sources of error are (i) errors due to the inherently unpredictable future noise and (ii) error due to differences between the forecast model and the simulation model. The forecasts are repeated using the T.60 model to simulate the data (curves marked with asterisks). Panel (b) is the same as panel (a) except the RMS error is measured instead of correlation.

Latest ENSO Predictability Studies

Retrospective ENSO Forecasts: Sensitivity to Atmospheric Model and Ocean Resolution

EDWIN K. SCHNEIDER,* DAVID G. DEWITT,+ ANTHONY ROSATI,# BEN P. KIRTMAN,* LINK JI,@ AND JOSEPH J. TRIBBIA&

*George Mason University, Fairfax, Virginia, and Center for Ocean–Land–Atmosphere Studies, Calverton, Maryland
+International Research Institute for Climate Prediction, Palisades, New York
#NOAA, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey
@Department of Oceanography, Texas A&M University, College Station, Texas
&National Center for Atmospheric Research, Boulder, Colorado

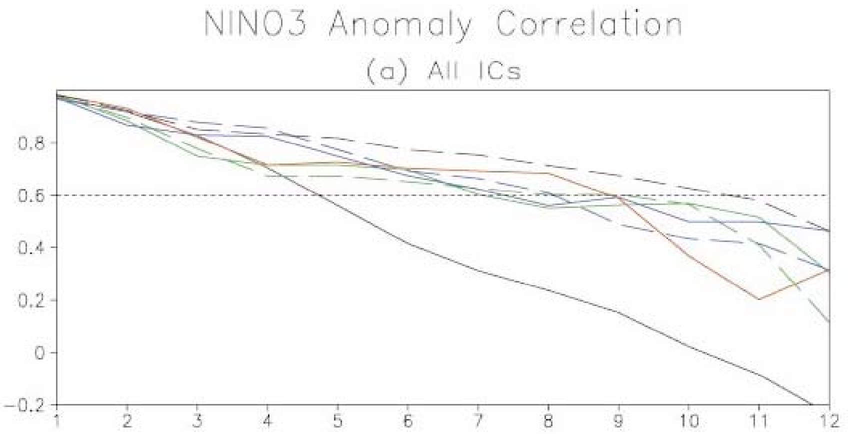
(Manuscript received 19 September 2002, in final form 16 June 2003)

ABSTRACT

Results are described from a series of 40 retrospective forecasts of tropical Pacific SST, starting 1 January and 1 July 1980–99, performed with several coupled ocean–atmosphere general circulation models sharing the same ocean model—the Modular Ocean Model version 3 (MOM3) OGCM—and the same initial conditions. The atmospheric components of the coupled models were the Center for Ocean–Land–Atmosphere Studies (COLA), ECHAM, and Community Climate Model version 3 (CCM3) models at T42 horizontal resolution, and no empirical corrections were applied to the coupling. Additionally, the retrospective forecasts using the COLA and ECHAM atmospheric models were carried out with two resolutions of the OGCM. The high-resolution version of the OGCM had 1° horizontal resolution (1/3° meridional resolution near the equator) and 40 levels in the vertical, while the lower-resolution version had 1.5° horizontal resolution (1/2° meridional resolution near the equator) and 25 levels. The initial states were taken from an ocean data assimilation performed by the Geophysical Fluid Dynamics Laboratory (GFDL) using the high-resolution OGCM. Initial conditions for the lower-resolution retrospective forecasts were obtained by interpolation from the GFDL ocean data assimilation.

The systematic errors of the mean evolution in the coupled models depend strongly on the atmospheric model, with the COLA versions having a warm bias in tropical Pacific SST, the CCM3 version a cold bias, and the ECHAM versions a smaller cold bias. Each of the models exhibits similar levels of skill, although some statistically significant differences are identified. The models have better retrospective forecast performance from the 1 July initial conditions, suggesting a spring prediction barrier. A consensus retrospective forecast produced by taking the ensemble average of the retrospective forecasts from all of the models is generally superior to any of the individual retrospective forecasts. One reason that averaging across models appears to be successful is that the averaging reduces the effects of systematic errors in the structure of the ENSO variability of the different models. The effect of reducing noise by averaging ensembles of forecasts made with the same model is compared to the effects from multimodel ensembling for a subset of the cases; however, the sample size is not large enough to clearly distinguish between the multimodel consensus and the single-model ensembles.

There are obvious problems with the retrospective forecasts that can be connected to the various systematic errors of the coupled models in simulation mode, and which are ultimately due to model error (errors in the physical parameterizations and numerical truncation). These errors lead to initial shock and a "spring variability barrier" that degrade the retrospective forecasts.



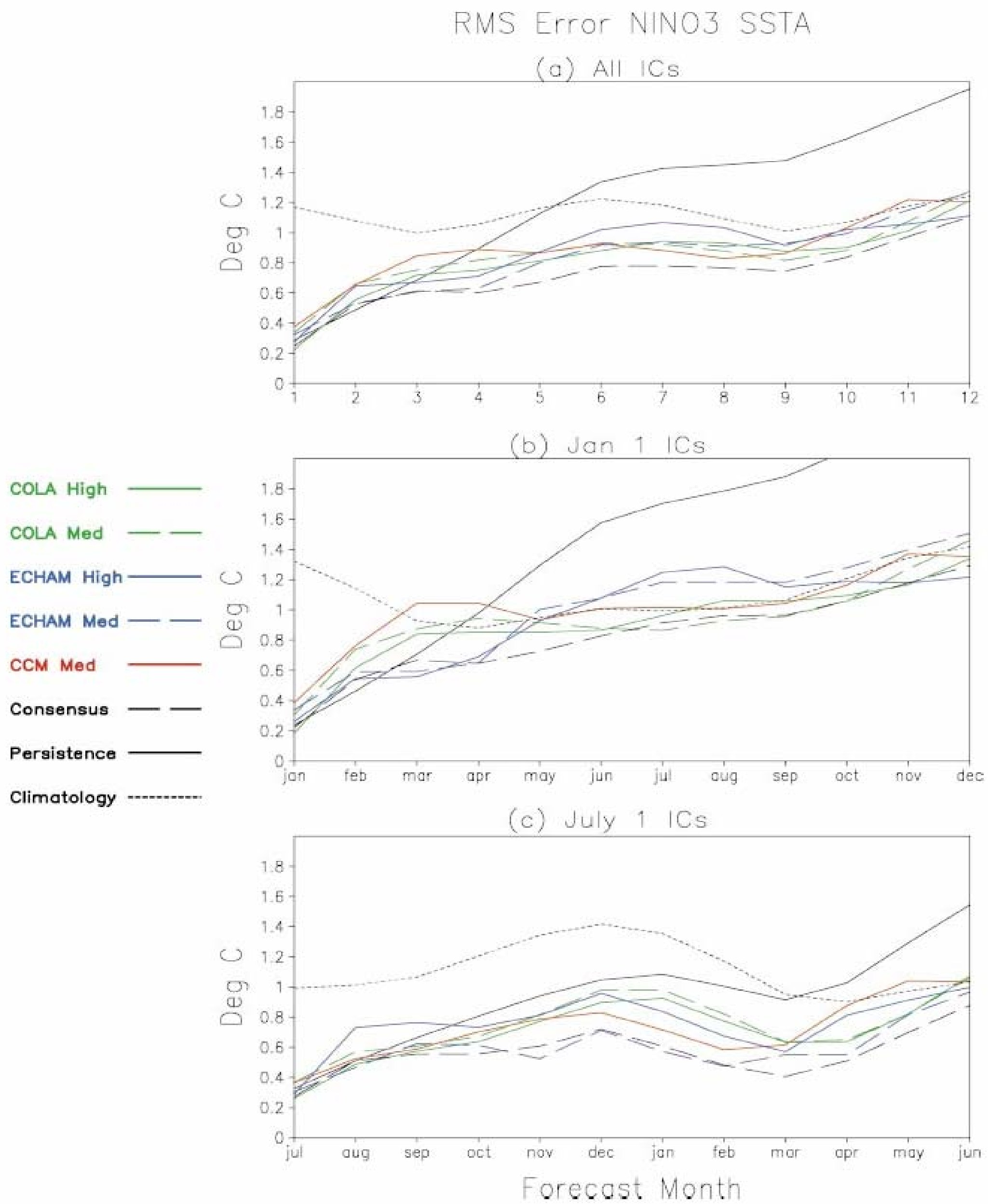


FIG. 3. Rms errors of retrospective forecasts of Niño-3 SSTAs for the models, Consensus, Persistence, and Climatology (zero-anomaly retrospective forecast), as a function of lead time: (a) All initial conditions combined, (b) 1 Jan initial conditions, and (c) 1 Jul initial conditions.

Seasonal Climate Predictability in a Coupled OAGCM Using a Different Approach for Ensemble Forecasts

JING-JIA LUO, SEBASTIEN MASSON, AND SWADHIN BEHERA

Frontier Research Center for Global Change, JAMSTEC, Yokohama, Japan

SATORU SHINGU

NEC System Technologies, Ltd., Tokyo, Japan

TOSHIO YAMAGATA*

Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan

(Manuscript received 11 November 2004, in final form 9 March 2005)

ABSTRACT

Predictabilities of tropical climate signals are investigated using a relatively high resolution Scale Interaction Experiment–Frontier Research Center for Global Change (FRCGC) coupled GCM (SINTEX-F). Five ensemble forecast members are generated by perturbing the model's coupling physics, which accounts for the uncertainties of both initial conditions and model physics. Because of the model's good performance in simulating the climatology and ENSO in the tropical Pacific, a simple coupled SST-nudging scheme generates realistic thermocline and surface wind variations in the equatorial Pacific. Several westerly and easterly wind bursts in the western Pacific are also captured.

Hindcast results for the period 1982–2001 show a high predictability of ENSO. All past El Niño and La Niña events, including the strongest 1997/98 warm episode, are successfully predicted with the anomaly correlation coefficient (ACC) skill scores above 0.7 at the 12-month lead time. The predicted signals of some particular events, however, become weak with a delay in the phase at mid and long lead times. This is found to be related to the intraseasonal wind bursts that are unpredicted beyond a few months of lead time. The model forecasts also show a "spring prediction barrier" similar to that in observations. Spatial SST anomalies, teleconnection, and global drought/flood during three different phases of ENSO are successfully predicted at 9–12-month lead times.

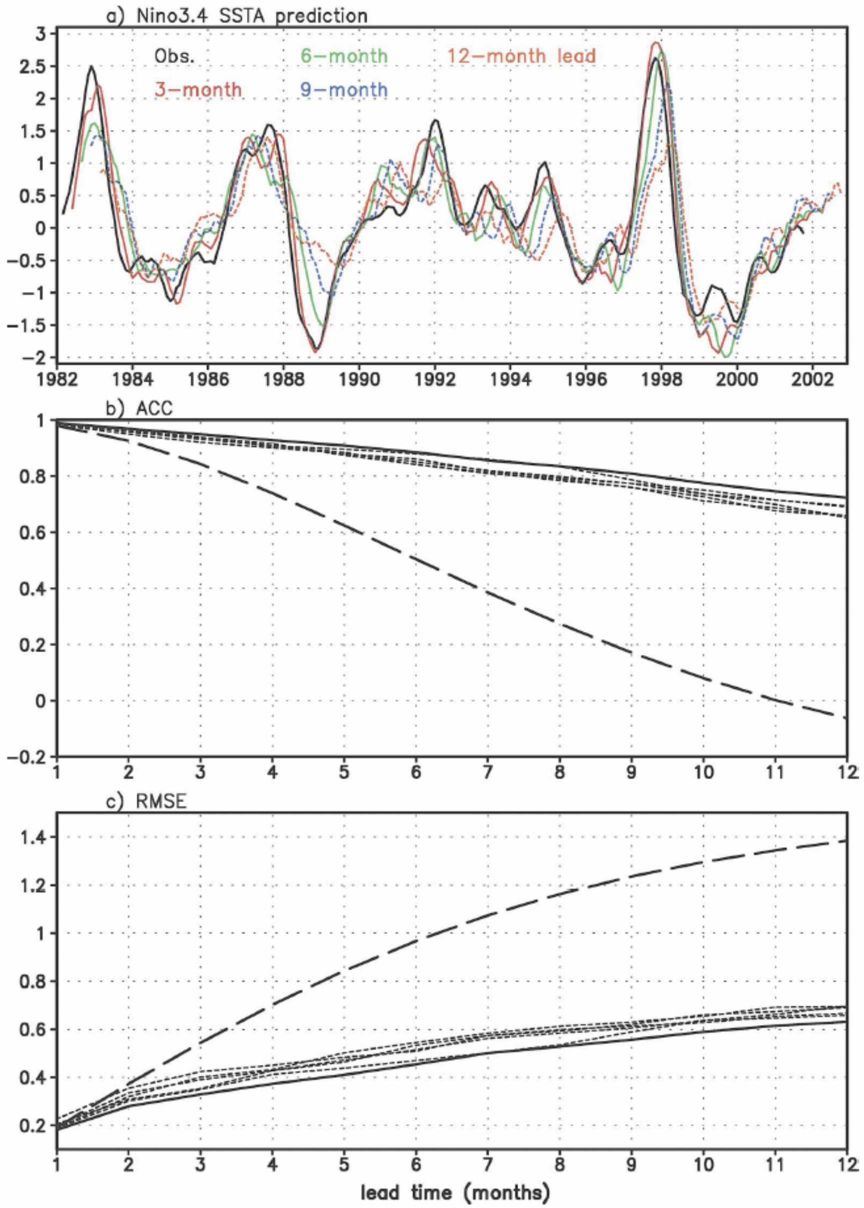


FIG. 5. (a) Niño-3.4 SST anomalies (5°S–5°N, 170°–120°W) based on the NOAA/CDC observations (solid line) and model predictions at 3- (red line), 6- (green line), 9- (blue line), and 12-month (yellow line) lead times. Results have been smoothed with 5-month running mean. (b), (c) ACC scores and rmses of the persistence (long dashed lines), ensemble mean (solid lines), and individual member forecasts (short dashed lines).

What Is Known

- ENSO is a coupled phenomenon where the dynamic feedback between trade winds and SST is fundamental.

- ENSO resides in a dynamic regime where the time scales associated with air-sea feedback and oceanic adjustment are comparable. Neither these time scales alone determine the period of ENSO.

- The turnabout between warm and cold phases of ENSO cycle is attributed to subsurface ocean adjustment off the equator.

- Evidence at hand suggests that ENSO is probably weakly nonlinear.

- It is increasingly evident that stochastic processes play an important role in ENSO evolution.

Unresolved Issues

What limits ENSO predictability ?

- Spring predictability barrier
- Stochastic processes
- Decadal modulation of ENSO

How does ENSO interact with other modes ?

- Annual cycle $\Leftrightarrow$ ENSO
- Tropics $\Leftrightarrow$ extratropics
- Monsoon, TAV $\Leftrightarrow$ ENSO

How does global climate change affect ENSO ?