GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 23, PAGES 3057-3060, DECEMBER 1, 1997

El Niño and climate change

Kevin E. Trenberth and Timothy J. Hoar

National Center for Atmospheric Research, Boulder, Colorado

Abstract. A comprehensive statistical analysis of how an index of the Southern Oscillation changed from 1882 to 1995 was given by *Trenberth and Hoar* [1996], with a focus on the unusual nature of the 1990-1995 El Niño-Southern Oscillation (ENSO) warm event in the context of an observed trend for more El Niño and fewer La Niña events after the late 1970s. The conclusions of that study have been challenged by two studies which deal with only the part of our results pertaining to the length of runs of anomalies of one sign in the Southern Oscillation Index. They therefore neglect the essence of Trenberth and Hoar, which focussed on the magnitude of anomalies for certain periods and showed that anomalies during both the post-1976 and 1990–mid-1995 periods were highly unlikely given the previous record. With updated data through mid 1997, we have performed additional tests using a regression model with autoregressive-moving average (ARMA) errors that simultaneously estimates the appropriate ARMA model to fit the data and assesses the statistical significance of how unusual the two periods of interest are. The mean SOI for the post-1976 period is statistically different from the overall mean at $< 0.05\%$ and so is the 1990–mid-1995 period. The recent evolution of ENSO, with a major new El Niño event underway in 1997, reinforces the evidence that the tendency for more El Niño and fewer La Niña events since the late 1970s is highly unusual and very unlikely to be accounted for solely by natural variability.

Introduction

A detailed statistical analysis of how an index of the Southern Oscillation (SOI) (as represented by sea level pressures at Darwin, Australia) changed from 1882 to 1995 was given by *Trenberth and Hoar* [1996]. The focus of the study was how unusual the 1990-1995 El Niño-Southern Oscillation (ENSO) warm event was in the context of the warming trend in the tropical Pacific after about 1976 when there have been more El Niño and fewer La Niña events.

Two papers have since commented on the *Trenberth and Hoar* [1996] (henceforth TH) paper. *Harrison and Larkin* [1997] do not consider the size of the anomalies of the SOI for specific periods, which was the main basis of TH, and instead with some questionable assumptions examine the length of runs of one sign in the time series, which was a minor part of TH. *Rajagopalan et al.* [1997] (henceforth RLC) has also tested the length of runs in the Darwin pressures to alternative statistical models and noted the sensitivity of results for runs of a given length to the statistical model fitted. However, unlike TH, they did not demonstrate the fit or appropriateness of their models and, once again, considered only the length of runs of one sign. An advantage of their approach is that they can address different behavior for positive versus negative anomalies in Darwin pressure (El Niño versus La Niña events) which are not symmetrical about the average [see *Trenberth*, 1997]. These papers are discussed and the appropriateness of the conclusions reviewed. Further we use a new statistical test, which directly addresses the main concern of *Harrison and Larkin* [1997] of how to estimate the number of degrees of freedom, to assess how unusual recent behavior has been. We also briefly consider more recent evidence which is in support of the original conclusions, and discuss the potential for paleodata to help to resolve the issues.

Paper number 97GL03092.
0094-8534/97/97GL-03092$05.00

Southern Oscillation Index analysis

In TH we observed that aspects of the recent warming of the tropical Pacific from 1990 to mid 1995 were unprecedented in the observational record of the previous 113 years. Moreover, we noted that this behavior was in the context of the tendency for more El Niño and fewer La Niña events since the late 1970s. We described the difficulty in finding reliable homogeneous measurements or indices of what has happened in ENSO and concluded that the best such continuous record was the sea level pressures from Darwin, which is near one center of the Southern Oscillation, and thus can be used as a Southern Oscillation index. We then carried out several statistical tests to assess the likelihood that both the trends after the late 1970s and the behavior from 1990 to mid 1995 was consistent with the earlier record and thus could be considered part of a natural decadal variation. We used a null hypothesis of no change relative to the first hundred years of record from 1882 to 1981. The tests reinforced one another to indicate that both the recent trend for more warm ENSO events and fewer cold events since 1976, and the prolonged 1990-1995 warm event are unexpected, given the previous record, with an overall probability of occurrence about once in 2000 years for both. We concluded, therefore, that changes in climate were probably influencing ENSO behavior.

One aspect of the confusion over the 1990-1995 warm ENSO phase has been the different character of the sequences in different parts of the tropical Pacific. Sea surface temperature (SST) anomalies did wax and wane in the traditional El Niño region along the coast of South America but stayed continuously above average in the central equatorial Pacific. An objective definition of El Niño that matches the El Niño events identified historically is for SSTs in the Niño 3.4 region (120°-170°W 5°N-5°S) to exceed 0.4°C for 6 months or more *Trenberth* [1997]. Relative to the 1950-79 mean, this definition identifies three El Niños from 1990 to 1995 (see Fig. 1) from March 1991 to July 1992, February to September 1993, and June 1994 to March 1995. However, these peak phases are clearly linked, as conditions do not return to average in between. It therefore remains ambiguous as to whether these should be regarded as one long El Niño or three events in

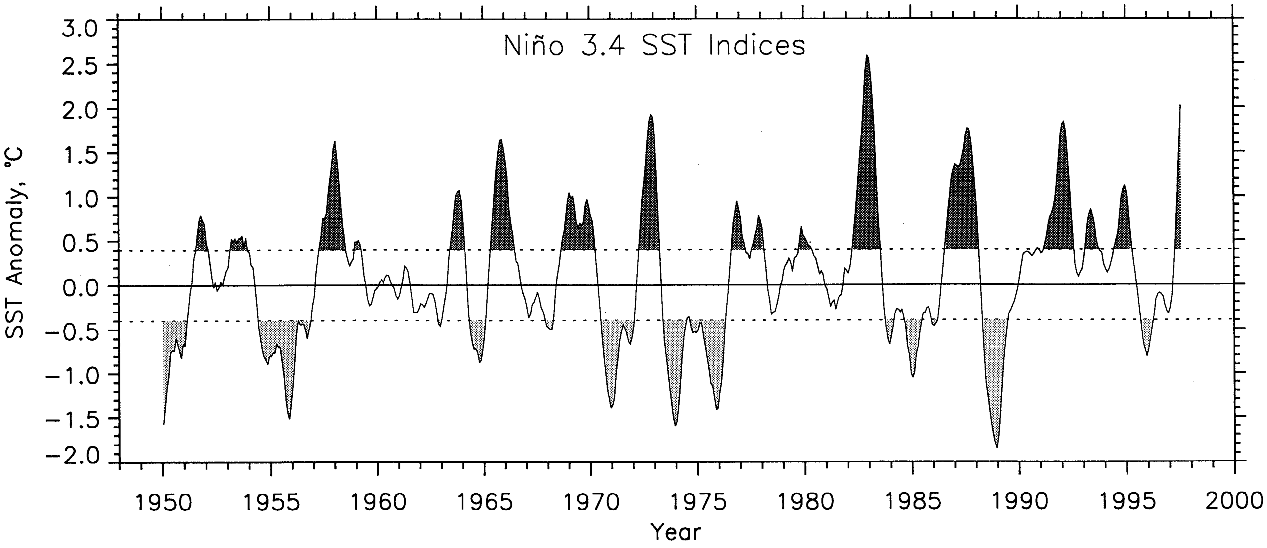

Figure 1. Time series plots of the Niño 3.4 SST indices as five month running means using data from NOAA and relative to a base period climatology from 1950-79. Values exceeding threshold ± 0.4°C for Niño 3.4 are stippled to indicate ENSO events.

close succession, and above we referred to it as a warm phase of ENSO.

One test used by TH was to note that the 22 seasons from December-January-February (DJF) 1989-90 to March-April-May (MAM) 1995 had an SOI continually below zero (Darwin pressure anomalies positive), and that this was an unprecedented run of the SOI of one sign since 1882, when the record began. Statistical testing which fitted an autoregressive moving average (ARMA) model of order (3,1) to the Darwin record showed the 22 season run of one sign was a very rare event. This was challenged by *Harrison and Larkin* [1997] who note that *monthly* Darwin pressures did go below normal during this period. Because a run of one sign is very dependent on noise that might, for a short time, cause the run to be broken, not much weight was placed on this test in TH. TH recognized the noise in monthly data and noted that time averaging was necessary and appropriate to provide a better indication of SO behavior [*Trenberth*, 1984a]. An appropriately filtered SOI is shown in Fig. 2, where the baseline is the 1882-1981 mean. A low pass spline filter is also applied to the SOI and it reveals more clearly the decadal timescales and how the period after about 1976 has been exceptionally low. Note, in particular, that the period after 1976 has featured 5 El Niño events (1976-77-78, 1982-83, 1986-87-88, 1990-1995, 1997-present) but only three La Niña events (1984-85, 1988-89, 1995-96). Also, the 1982-83 event has the biggest magnitude on record and the 1990-95 event is the longest on record (or else it counts as three events), whereas for La Niñas only the 1988-89 event was strong (Fig. 1).

Harrison and Larkin [1997] go on to show that with other assumptions about the persistence in the data, which imply a longer time between effectively independent values (T_o) than the observed value of 6 months [*Trenberth*, 1984a], then return periods of long runs are indeed much reduced. This argument hinges on compution of T_o which involves a weighted sum of the lagged correlations [their Eq. (4)]. We note that the autocorrelations at various lags are not independent, and that the variance of a linear combination of correlated random variables cannot be calculated from the variances of the individual variables (it depends on the covariances as well) (R. Jones personal communication). The Harrison-Larkin assumptions in computing confidence limits on T_o are wrong, therefore, and the values they use are not correct. Moreover the way they use T_o is questionable because it is strictly the time required to gain an extra degree of freedom for estimating the standard error of the mean [*Trenberth*, 1984b]. Other uses of T_o may not be valid, and an example is Harrison and Larkin's use in a Bootstrap/Monte Carlo test to find the probability of flipping a weighted coin to test for runs in a series. In addition, as this test fails to take into account the quasi-periodicity in the Southern Oscillation, it cannot be considered relevant.

The second paper commenting on TH by RLC also tested the the length of runs to alternative statistical models and noted the sensitivity of results for runs of a given length to the statistical model fitted. Our awareness of this point was the reason why the run length results were not emphasized (and not included in our conclusions or abstract). RLC use lower order models which are not shown to be good fits to the data or its power spectra, as was done for the ARMA model fitted by TH. Moreover the RLC models are fitted to a transformed Darwin pressure anomaly time series in which positive anomalies (PA) are replaced by 1 and negative anomalies (NA) by 0. Apparently this introduces extra spectral power at interdecadal frequencies compared with the original series. RLC use a broad window of length 17.5 years (70 seasons) to fit a Markov Chain model and thus can only deal with results to 1988, which does not fully cover the recent warm ENSO event. Markov Chain models of order 1 and 2 are used, whereas TH found the best fit model to be an autoregressive moving average (ARMA) model of order (3,1), and that any lower order model would seriously misrepresent the low frequency behavior of the time series. It is not surprising then that the return periods of runs of anomalies of one sign for these low order models are shorter than estimated in TH.

In discussing their results, RLC first state that "The rate of occurrence of PA at the turn of the century is similar to that in recent times." Yet the figure (their Fig. 3) shows a rate of 0.75 at the end of the series in 1988, compared with

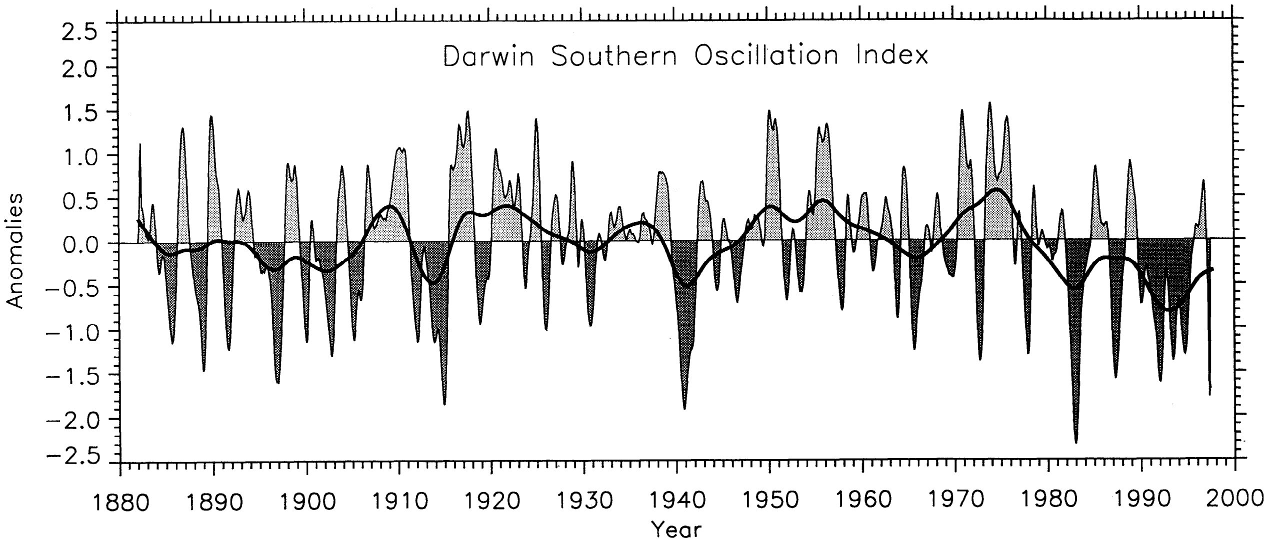

Figure 2. Time series of the monthly normalized Southern Oscillation Index (minus Darwin sea level pressure anomalies) smoothed with the 11-term filter and with a low pass smoothing spline filter that removes periods less than 10 years. The base period is 1882 to 1981. A 1-2-1 filter is used on the end points and the last value is July 1997.

a mean of 0.5, and a value which is much higher than any other time (previous peak of 0.65 about 1900). After fitting a nonhomogeneous first order Markov Chain model to the data, they find that the likelihood of continuing positive anomalies is high in recent years but comparable to earlier in the century. However, they also find that the transition probability of a negative anomaly following a negative anomaly is the lowest in the entire record at the end of the series. This aspect is down played in their discussion and conclusions, yet it is perhaps most pertinent to our conclusions.

The main tests that TH used were not based on runs of one sign. Instead they were based on the magnitude of anomalies over (i) the 22 seasons from DJF 1989-90 to MAM 1995 for which Darwin was +0.94 mb and (ii) the last 73 seasons from MAM 1977 to MAM 1995 for which Darwin was +0.50 mb. A standard t test which allowed for persistence in the data gave return periods of over 1000 years and indicated that, for both intervals under consideration, the mean anomalies of Darwin pressures were statistically different from zero at $< 1\%$ with a two tailed test. To better incorporate the quasi-periodicity in the SOI, extensive tests were made of the distribution of magnitudes of anomalies for the specified periods using the ARMA (3,1) model fitted to the first 100 years of Darwin record, and also with variants based on the previous 95 or 105 years instead of 100. The conclusions were robust and indicated about once in 2000 year return periods for both the post-1976 Darwin anomalies and those for the 1990–mid-1995 warm ENSO event. These results are untouched by either of papers which comment on TH.

To further bolster these results, we have run some extra statistical tests using updated data through July 1997. The test used simultaneously fits an ARMA model to the whole time series while allowing for indicator variables of breakpoints. The process is sometimes called dynamic regression. Specifically, we used the Statistical Analysis System (SAS) Economic Time Series (ETS) package with Autoregresssive Integrated Moving Average (ARIMA) processing (SAS/ETS V6.11 Proc ARIMA) to fit a regression model with ARMA errors. The model parameters are estimated using all of the data, so all of the energy gets partitioned at once. The process produces random residuals and estimates of the various parameters of the model along with standard errors of their fit. As in previous results, the model used is an ARMA(3,1). The coefficients are all statistically significant but differ slightly ($< 8\%$) from those in TH as the entire series is now being fitted. We included a "continuing intervention" variable to allow for step functions in the model. The data used are Darwin seasonal anomalies, where the last season of June-July-August 1997 was approximated by the mean of the anomalies for June and July. Thus, beginning in 1882, 463 seasons were used and 6 parameters were fitted leaving 457 degrees of freedom. In testing for a break point beginning March 1977, so that a different mean is permitted for the period from March 1977 to July 1997, the result is highly statistically significant with $t = 3.61$ at $< 0.05\%$ with a 2-tailed test and for which Darwin is +0.49 mb above the 100 year average. Similarly, for the extended 1990 to 1995 El Niño (DJF 1989 to MAM 1995) period $t = 3.79$, which is statistically significantly different from the mean of the rest of the series at $< 0.02\%$ with a 2-tailed test. These results confirm the very unusual behavior of the recent SOI.

Another approach to determining how unusual recent ENSO behavior has been is to try to put it in the context of much longer records using paleoclimate data, especially from cores of coral in the tropical Pacific. Examples include the analyses from Galapagos [*Dunbar et al.*, 1994] and Tarawa [*Cole et al.*, 1993]. However, while oxygen isotope records from corals can provide excellent records of interannual variability, the decadal and lower frequency variability has not been validated. For instance, the decadal variability in the isotopic record is larger and not coherent with the instrumental record at Tarawa [*Cole et al.*, 1993]. Moreover, it is known that low frequencies can be contaminated by biological and growth effects in the coral and other non-climatic influences on the record (Rob Dunbar, personal communication). The paleo-records of isotopic and chemical tracers have great potential, however, for clarifying what the natural variability of ENSO has been over several centuries. The reproducible signals from multiple cores of adjacent coral colonies presumably represent climate variations while aspects unique to a single core are attributable to growth and other factors. Using this assumption, it will be possible to ensure that the record does represent climate variations when sufficient reconstructions have been completed. It is also important to recognize that on century time scales, the climate has changed (for instance, the Little Ice Age) and conditions external to the climate system have also changed (notably solar and volcanic activity), and hence interpretation of the record may not be straightforward in terms of deducing how much decadal variability there should be in ENSO in an unchanging climate. Nevertheless, coral records have great potential for clarifying the natural variability of ENSO on various time scales.

Recent evidence

At the time TH was written (submitted in August 1995), the future evolution of ENSO was quite uncertain, so it is worthwhile examining the more recent evidence. Conditions in the tropical Pacific returned to about average in mid-1995 and were followed by a weak La Niña event from September 1995 to March 1996 (Fig. 1). However, beginning in April 1997 a major El Niño event has emerged and is still developing at this time. The amplitude of SST anomalies in the eastern tropical Pacific have already exceeded 4°C and the event is challenging the 1982-83 event as the largest on record (Figs. 1 and 2). This current behavior reinforces the view that recent ENSO behavior is very unusual.

Our results depend upon the assumption that we have a representative sample and that the SOI based upon Darwin alone is an adequate measure; unfortunately all other pertinent data that we are aware of have problems with homogeneity and continuity of record which are critical for detecting change. Our interpretation of the result is that at least part of what is happening in ENSO can not be accounted for solely by natural variability. But the existence of decadal variability in the Pacific [e.g., *Zhang et al.,* 1997] makes it difficult to distinguish which part. Another observational study reveals changes in the rainfall and temperatures associated with ENSO over Australia since the 1970s [*Nicholls et al.*, 1996].

Our results add further to the need to determine whether the anomalous behavior of ENSO is linked to or a consequence of the global warming arising from anthropogenic increases in greenhouse gases in the atmosphere. Several climate models do indicate a more El Niño-like climate (greater warming in the tropical east Pacific Ocean and an eastward shift in convective activity in the Pacific) with increased greenhouse gases [e.g., *Meehl and Washington*, 1996; *Knutson et al.*, 1995, 1997]. However, at present it is not possible to make such an attribution definitively because the global climate models have trouble simulating ENSO with sufficient fidelity to have confidence in the results. But that the recent observed behavior is very unusual is well established.

Acknowledgments. NCAR is sponsored by the National Science Foundation. We thank David Stepaniak for generating the figures. This research was sponsored by NOAA Office of Global Programs under grant NA56GP0247 and by the Geophysical Statistics Project at NCAR under grant NSF DMS9312686.

References

Cole, J. E., R. G. Fairbanks and G. T. Shen, 1993: Recent variability in the Southern Oscillation: Isotopic results from a Tarawa atoll coral. *Science*, **260**, 1790–1793.

Dunbar, R. B., G. M. Wellington, M. W. Colgan, and P. W. Glynn, 1994: Eastern Pacific sea surface temperature since 1600 A.D.: The δ^{18}O record of climate variability in Galapagos corals. *Paleoceanogr.*, **9**, 291–315.

Harrison, D. E., and N. K. Larkin, 1997: Darwin sea level pressure, 1876-1996: Evidence for climate change? *Geophys. Res. Lttrs*, **24**, 1779–1782.

Knutson, T. R., and S. Manabe, 1995: Time-mean response over the tropical Pacific to increased CO_2 in a coupled ocean-atmosphere model. *J. Climate*, **8**, 2181–2199.

Knutson, T. R., S. Manabe and D. Gu, 1997: Simulated ENSO in a global coupled ocean-atmosphere model: multidecadal ampitude modulation and CO_2 sensitivity. *J. Climate*, **10**, 138–161.

Meehl, G. A. and W. M. Washington, 1996: El Niño-like climate change in a model with increased atmospheric CO_2 concentrations. *Nature*, **382**, 56–60.

Nicholls, N., B. Lavery, C. Frederiksen and W. Drosdowsky, 1996: Recent apparent changes in relationships between the El Niño-Southern Oscillation and Australian rainfall and temperature. *Geophys. Res. Lttrs*, **23**, 3357-3360.

Rajagopalan, B., U. Lall and M. A. Cane, 1997: Anomalous ENSO occurrences: An alternative view. *J. Climate*, **10**, 2351–2357.

Trenberth, K. E., 1984: Some effects of finite sample size and persistence on meteorological statistics. Pt. I: Autocorrelations. *Mon. Wea. Rev.*, **112**, 2359–2368.

Trenberth, K. E., 1984: Signal versus noise in the Southern Oscillation. *Mon. Wea. Rev.*, **112**, 326–332.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Met. Soc.*, (in press).

Trenberth, K. E., and T. J. Hoar, 1996: The 1990–1995 El Niño-Southern Oscillation Event: Longest on record. *Geophys. Res. Lttrs*, **23**, 57–60.

Zhang, Y., J. M. Wallace and D. S. Battisti, 1997: ENSO-like interdecadal variability: 1900–93. *J. Climate*, **10**, 1004–1020.

K. E. Trenberth and T. J. Hoar, Climate and Global Dynamics Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000. (e-mail: trenbert@ncar.ucar.edu)

(Received August 26, 1997; accepted October 22, 1997.)