

The 1990-1995 El Niño-Southern Oscillation event: Longest on record

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Abstract. The tendency for more frequent El Niño events and fewer La Niña events since the late 1970's has been linked to decadal changes in climate throughout the Pacific basin. Aspects of the most recent warming in the tropical Pacific from 1990 to 1995, which are connected to but not synonymous with El Niño, are unprecedented in the climate record of the past 113 years. There is a distinction between El Niño (EN), the Southern Oscillation (SO) in the atmosphere, and ENSO, where the two are strongly linked, that emerges clearly on decadal time scales. In the traditional El Niño region, sea surface temperature anomalies (SSTAs) have waxed and waned, while SSTAs in the central equatorial Pacific, which are better linked to the SO, remained positive from 1990 to June 1995. We carry out several statistical tests to assess the likelihood that the recent behavior of the SO is part of a natural decadal-timescale variation. One test fits an autoregressive-moving average (ARMA) model to a measure of the SO given by the first hundred years of the pressures at Darwin, Australia, beginning in 1882. Both the recent trend for more ENSO events since 1976 and the prolonged 1990-1995 ENSO event are unexpected given the previous record, with a probability of occurrence about once in 2,000 years. This opens up the possibility that the ENSO changes may be partly caused by the observed increases in greenhouse gases.

Introduction

The recent warm event related to El Niño in the tropical Pacific from 1990 to June 1995, is the longest on record since 1882 by some measures. It occurs in the context of a tendency for more frequent El Niño events and fewer La Niña events since the late 1970's that has been linked to decadal changes in climate throughout the Pacific basin (Trenberth 1990, Trenberth and Hurrell 1994, Kumar et al. 1994, Graham 1995). In assessing how unusual the recent event and the past two decades are, due consideration must be given to which regions of the tropical Pacific sea surface temperatures (SSTs) are most important, their link to the atmospheric circulation component known as the Southern Oscillation (SO), and the integrity and signal-versus-noise ratio of any index or measure of the SO. Given that the changes are unlikely in the context of the natural variability as revealed by the previous record, this may be evidence of climate change rather than simply an unusually long fluctuation.

El Niño (EN) refers to the occasional "anomalous" warming of the eastern tropical Pacific Ocean but is commonly linked to a basin-scale warming extending from the coast of South

America to the International Dateline. It is the basin-scale phenomenon, however, that is linked to global atmospheric circulation and associated weather anomalies. The primary response in the atmosphere coupled to EN is the SO and, together, the tropical Pacific warm events are often referred to as ENSO events.

The Southern Oscillation

The SO has a time scale of 2-7 years and consists of a global-scale, predominantly standing wave with centers of action in surface pressure over Indonesia and the tropical South Pacific (see Fig. 1 of Trenberth and Shea 1987). The nature of the oscillation can be seen from the inverse variations in pressures at Darwin (12.4°S 130.9°E) in northern Australia and Tahiti (17.5°S 149.6°W) in the South Pacific whose annual mean pressures are correlated at -0.79 (Trenberth 1984). These two stations can be optimally combined into a SO index, $SOI = T_N - D_N$ where T and D refer to the departure from the long-term monthly mean sea level pressures at Tahiti and Darwin, respectively, and the subscript N refers to an appropriate normalization.

Because there are many small scale and high frequency phenomena in the atmosphere that can influence the pressures at Tahiti and Darwin, such an index contains noise that does not reflect the global-scale SO. A primary source of high frequency variability arises from the 30-60 day intraseasonal oscillation (Madden and Julian 1994). A measure of noise $SON = T_N + D_N$ (Trenberth 1984) indicates times when Tahiti and Darwin are not varying in opposition as observed in the SO (Fig. 1). Taking account of the signal-to-noise ratio and the coherence of the Darwin and Tahiti time series, the SOI is optimized as an indicator of the SO by applying a low-pass 11 term filter that eliminates fluctuations of less than 8 months period but mostly retains periods exceeding 24 months (Trenberth 1984). The ratio of the variances of these two series changes from 2.0 for monthly data to 6.4 with the filtering, and the filtered SOI retains 56% of the monthly variance. Accordingly, an appropriate normalization is the annual mean standard deviation of each time series (Trenberth 1984).

The Tahiti record is less reliable and contains missing data prior to 1935. Tahiti and Darwin monthly (annual) pressure anomalies are correlated -0.35 (-0.77) for 1935 to 1995 but -0.19 (-0.36) for 1882 to 1934 yet the SO was strongly in evidence from other stations during the earlier period (Trenberth and Shea 1987). The only long-term homogeneous record of the SO is given by the appropriately filtered pressures at Darwin (Fig. 2). This record is used to judge the degree to which the behavior in recent years is anomalous.

El Niño-Southern Oscillation

To explore the coupling between the atmosphere and the ocean in ENSO events, we make use of the "Niño" regions

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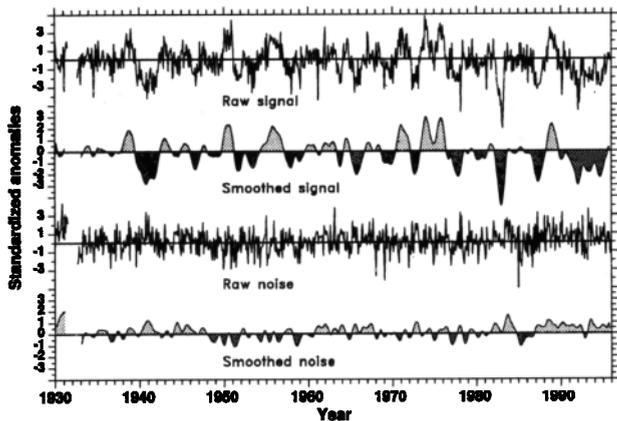


Figure 1. Time series of the SOI (normalized Tahiti minus Darwin sea level pressure anomalies) signal and a measure of noise in the SOI given by SON (normalized Tahiti plus Darwin) with base period 1950-1979. The top two show the SOI, monthly and filtered, the lower two show the SON. The filtered series reveal the interannual fluctuations; note the different scalings on the ordinate.

from the *Climate Diagnostics Bulletin* and SSTs from the Climate Analysis Center. In the traditional El Niño region, Niño [1+2] SST anomalies (SSTAs) have waxed and waned, while Niño 4 SSTAs, like the SOI, have remained persistently anomalous in recent years (Fig. 3).

Correlation coefficients for 1951 to April 1995 between the smoothed (raw monthly) SOI and the monthly SSTAs (Fig. 3) are -0.61 (-0.48), -0.81 (-0.65) and -0.84 (-0.68) for Niño [1+2], Niño 3 and Niño 4, respectively, demonstrating highly statistically significant correlations that are strongest in the central equatorial Pacific. Niño 4 and Niño [1+2] SSTAs are correlated 0.49 over the same period. Commonly, SST increases occurred almost simultaneously from South America to the Dateline, so the distinction between which region most influences the atmosphere has not been easy to make. In recent years, this has not been the case (Fig. 3). The correlations between the smoothed SOI and monthly SST anomalies from 1950 to 1994 (45 years) (Fig. 4) are strongest, exceeding -0.8, in the region 120°W to 180, 5°N to 10°S, which straddles part of the Niño 3 and Niño 4 regions and extends farther into the Southern Hemisphere. If only one value per year is conserva-

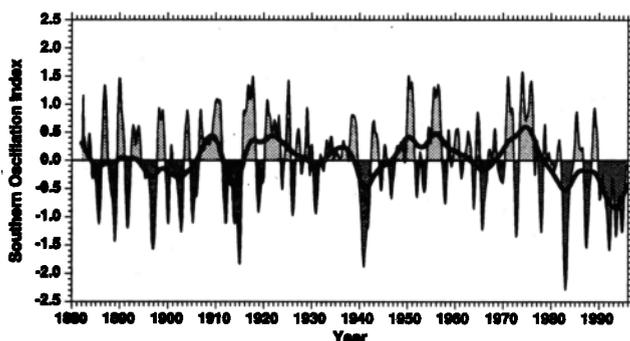


Figure 2. Time series of the monthly normalized Southern Oscillation Index (minus Darwin sea level pressure anomalies) smoothed with the 11-term filter and with a low pass smoothing spline filter (45 years) that removes periods less than 10 years. A 1-2-1 filter is used on the end points and the last value is September 1995.

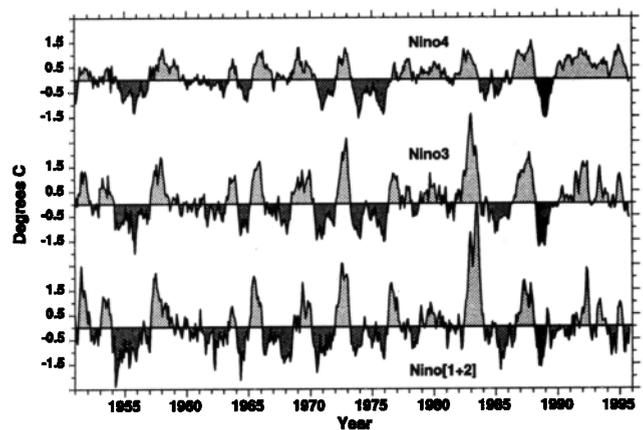


Figure 3. Time series of Niño areas SST anomalies from 1950 through September 1995. The areas covered are Niño [1+2]: 0°-10°S 90°W-80°W, Niño 3: 5°N-5°S, 150°W-90°W, and Niño 4: 5°N-5°S, 160°E-150°W.

tively regarded as independent then the 5% significance level is 0.30. Also apparent (Fig. 4) is the striking boomerang-shaped opposite SST anomalies extending into the extratropics of each hemisphere and the coastal influence along the Americas with the same sign as the tropical Pacific. Therefore, the SSTs most involved in ENSO are in the central Pacific, not in the coastal waters off of Peru and Ecuador (Trenberth and Shea 1987, Deser and Wallace 1987, Ropelewski et al. 1992).

The importance of the SO has varied in the past hundred years: strong variations from 1880 to the 1920s and after about 1950 and, except for strong event during 1939-1942, weaker variations from the mid-1920s to 1950 (Trenberth and Shea 1987) (Fig. 2). Note the lack of decadal or longer-term variability until recent years. The trend for a negative SOI after 1976 is apparent (Figs. 1 and 2) and sets the stage for the very persistent warming over the past five years in the vicinity of the equator and the Dateline (Fig. 3). It is important to distinguish this phenomenon from the coastal El Niño.

Using the smoothed SOI time series in Fig. 2, the previous longest continuous ENSO event, from early-1911 to mid-1915, lasted 4.1 years. The longest interval of opposite sign lasted 5.0 years, from May 1906 to April 1911. The current event, by this measure, began in October 1989 and continued through June 1995, 5 years 8 months. When the Niño 4 SSTAs are used as a measure, positive values began in September 1989 and continued through July 1995; values exceeded 0.3°C from January 1990 through July 1995 except for a short break from February to April 1994 (relative to a 1950-79 mean).

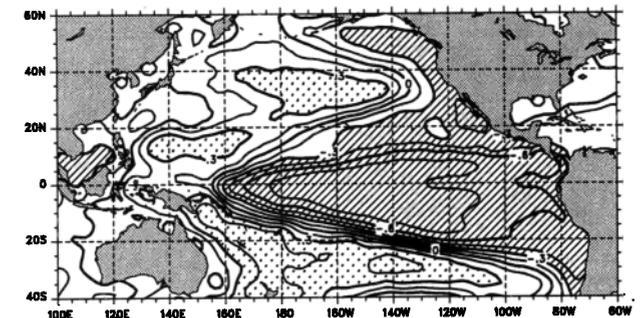


Figure 4. Correlations of the smoothed SOI with monthly SST anomalies for January 1950 to December 1994 (540 months). Magnitudes exceeding 0.3 are shaded or stippled.

Statistical tests

To test whether the recent SO behavior is statistically unlikely, a number of tests are performed. We identify the seasons as December-January-February, DJF, and so on. The 22 seasonal mean anomalies at Darwin from DJF 1989 to MAM 1995 are all positive relative to the 1882-1981 mean. The next longest positive runs observed are 15 seasons from MAM 1894 to SON 1897, 12 from DJF 1981-82 to SON 1984, and 11 from SON 1939 to MAM 1942. The longest run of opposite sign lasted 13 seasons from MAM 1973 to MAM 1976.

We first use a t test for the difference between the means of two periods under the null hypothesis that they are the same, modified to account for the strong persistence in the SO time series. In determining the standard error of the mean for the SOI, the time needed to gain an extra degree of freedom or, effectively the time between independent observations, is 6 months (Trenberth 1984). For December 1989 to May 1995 (66 months) versus January 1882 to November 1989 (1295 months), the result is $t = 2.82$ with an estimated 225 degrees of freedom, significant at 0.5% with a two-tailed test.

Similarly, for March 1977-May 1995 (219 months), the t statistic is 2.68; significantly different from the mean for the 1142 months in the rest of the series at <1%.

These tests provide a ballpark indication, but are confounded somewhat by the persistence in the time series. A more comprehensive test fits an autoregressive (AR) moving average (MA) or ARMA model to the time series of seasonal Darwin pressure anomalies for the first hundred years of record (1882 to 1981). The model is then used to generate synthetic time series for testing.

The ARMA model for Darwin can be compared with one based on a much shorter period for the SOI Tahiti minus Darwin by Chu and Katz (1985) who found a best fit with an AR(3) process for seasonal values. Our best fit model was found using a maximum likelihood fitting procedure (Jones 1980) and Akaike's Information Criterion (AIC) (Akaike 1974) which invokes a performance and penalty function related to the number of parameters in the model; the most parsimonious model is one with a minimum in the AIC. The model selected is an ARMA (3,1) (of order 3 for the AR process and 1 for the MA), given by

$$y_t = 1.278y_{t-1} - 0.318y_{t-2} - 0.136y_{t-3} + a_t - 0.712a_{t-1}$$

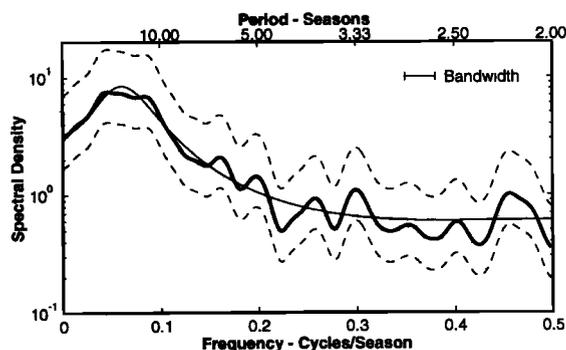


Figure 5. Estimated power spectra for Darwin seasonal anomalies from 1882-1981 (heavy) and the corresponding spectra of the ARMA(3,1) best fit model (thin). A logarithmic vertical scale is used so that the 95% confidence band (dashed) is constant in width, while the abscissa is linear in frequency. The bandwidth of the Parzen window (with 60 lags) is plotted.

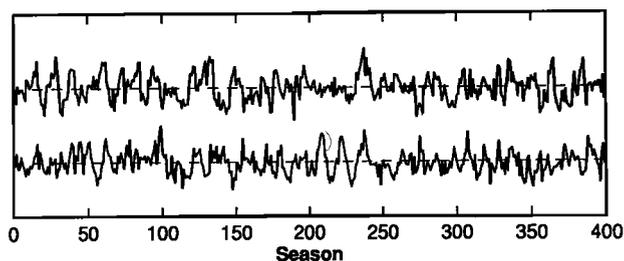


Figure 6. Observed (top) from 1882 to 1981 and simulated (bottom) 100 year sequences of Darwin seasonal pressure anomalies. Note the additional noise compared with the filtered values in Fig. 2.

where the a_t is a Gaussian white noise process at time t with zero mean and variance $\sigma_a^2 = 0.435 \text{ mb}^2$, and the y is the synthetic Darwin series of seasonal anomalies, t is in units of seasons, and all units are in mb.

The estimated power spectrum of the Darwin seasonal anomalies for 1882-1981 (Fig. 5), which reveals a broad spectral peak from 3 to 7 years period in the SOI, is seen to have a very good fit with the theoretical ARMA spectrum (c.f. Chu and Katz 1989), which features a broad peak at 4.2 years periodicity. Of particular note for the current exercise, is the excellent agreement in power at very low frequencies. This model is used to generate over 1,000,000 years of synthetic record and the first 1,000 years are discarded because of possible spinup effects. The remainder is used to estimate the probability of events such as those recently observed. A comparison of 100 years of model output with the observed first 100 years of Darwin (Fig. 6) reveals the similar character of the variations; note three sequential strong simulated "ENSO events" 3.5 years apart between seasons 200 and 250, quite similar to the observed 1939-42 event (near season 240, top curve).

Because the results indicated we were dealing with rare events, we tested the sensitivity of the results to variants in the model. Minor changes arising from different initial states in the search for the ARMA coefficients made insignificant differences. Somewhat larger differences were produced when the model was based on either the first 95 or 105 years of record instead of the first 100. In both cases, the spectrum of the ARMA best-fit model had slightly more power at periods longer than 20 years. The 105-year model is based on data through 1986 which includes the 1982-83 ENSO event, the largest on record. Because it overlaps considerably with the 1977-1995 period that we wish to test, it is considered less reliable.

The longest run of simulated values of one sign was 31 seasons and 113 runs of either sign equalled or exceeded 22 seasons, indicating an incidence of 1 "observed" event in about 8,850 years. From this standpoint, the model suggests that the continuous positive run for the most recent 22 seasons is extremely rare. In the alternate models, the numbers of runs of 22 seasons or more were 144 and 154, so that the most conservative estimate is for one such run about every 6,500 years.

The mean Darwin anomaly relative to 1882-1981 for the last 22 seasons is 0.94 mb. From the model, it was determined that the median 1 in 1000 year threshold for 22-season events of either sign was 0.88 mb, and the 1 in 10,000 year threshold was 0.99 mb, indicating a frequency of occurrence of the observed value of 1 in 3,000 years; or about 1 in 545

22-season intervals (0.18%). Given 100 trials of 10,000 years, the sampling for 1,000 year events indicates an interquartile range of 0.86 to 0.91 mb, and the range is 0.80 to 0.99 mb. The median return periods of the observed value in the alternate models were 1,648 and 1,137 years.

For the last 73 seasons from MAM 1977 to MAM 1995, the observed mean anomaly is 0.50 mb. From 73-season sequences in the model, values of 0.48 mb and 0.52 mb are reached once every 1,000 and 10,000 years, respectively, and the observed value is obtained about once every 2,000 years or about 1 in 110 such sequences (0.9%). The results from the alternative models give return periods of 2,400 and 1,390 years.

In all cases, the shortest return periods occur for the model based upon 1882-1986, as expected. For the 73-season case, the longest return period is for the model based upon 1882-1976, the only model that was not based on part of the period of interest.

Discussion

The results from the t tests indicate that the low frequency variability and the negative trend in the SOI in recent decades are quite unusual; the recent sequence would be expected only about once in 1,100 years. The ARMA modeling refines this estimate and indicates that the likelihood of occurrence of the 1990-95 ENSO, given the first hundred years of record, is about once in 1,500 to 3,000 years. The change beginning about 1976 toward more frequent ENSO events is also unlikely, about a once in 2,000 year expectation. Clearly the two are not independent and the results suggest a non-stationary influence such as would arise from a change in climate.

Several aspects of the decadal change beginning around 1976 have been simulated with atmospheric models using specified SSTs (Kumar et al. 1994, Graham 1995) including patterns of surface temperature change observed in recent years over land. These and other studies confirm that the atmospheric changes are tied to the changes in SSTs and, further, that the changes over the North Pacific and surrounding areas are substantially controlled by the anomalous SST forcing from the tropical Pacific, and thus linked to the changes in ENSO. Accordingly, the key question is why the SSTs, and especially the tropical Pacific SSTs, have changed in the way they have?

No current coupled global climate model provides a fully realistic simulation of ENSO events although some models reproduce aspects of the observed behavior but with reduced amplitude. Thus there is little basis for expecting that there will be an increase in the number and/or length of ENSO events from coupled atmosphere-ocean models, although models do predict SST warming with increased greenhouse gases (Knutson and Manabe 1995), so that the background mean is changed. In more limited models designed specifically for simulating ENSO in the Pacific, the prolonged ENSO has not been well predicted by models which have otherwise demonstrated skill in predicting ENSO events (see recent issues of NOAA's *Experimental long-lead Forecast Bulletin* and *Climate Diagnostics Bulletin*).

These results raise questions about the role of climate change. Is this pattern of change a manifestation of the global warming and related climate change associated with increases

in greenhouse gases in the atmosphere? Or is this pattern a natural decadal-timescale variation? We have shown that the latter is highly unlikely.

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References

- Akaike, H., A new look at the statistical model identification. *IEEE Trans. Auto. Control*, **19**, 716-723, 1974.
- Chu, P-S., and R. W. Katz, Modeling and forecasting the Southern Oscillation: A time-domain approach. *Mon. Wea. Rev.* **113** 1876-1888, 1985.
- Chu, P-S., and R. W. Katz, Spectral estimation from time series models with relevance to the Southern Oscillation. *J. Climate* **2**, 86-90, 1989.
- Deser C., and J. M. Wallace, El Niño events and their relation to the Southern Oscillation. *J. Geophys. Res.*, **92**, 14189-14196, 1987.
- Graham, N. E., Simulation of recent global temperature trends. *Science*, **267**, 666-671, 1995.
- Jones, R. H., Maximum likelihood fitting of ARMA models to time series with missing observations. *Technometrics*, **22**, 389-395, 1980.
- Knutson, T. R., and S. Manabe, Time-mean response over the tropical Pacific to increased CO₂ in a coupled ocean-atmosphere model. *J. Climate* **8**, 2181-2199, 1995.
- Kumar, A., A. Leetmaa and M. Ji, Simulations of atmospheric variability induced by sea surface temperatures and implications for global warming. *Science*, **266**, 632-634, 1994.
- Madden, R. A., and P. R. Julian, Observations of the 40-50 day tropical oscillation - A review. *Mon. Wea. Rev.* **122**, 814-837, 1994.
- Ropelewski, C. F., M. S. Halpert, and X. Wang, Observed tropospheric biennial variability and its relationship to the Southern Oscillation. *J. Climate* **5**, 594-614, 1992.
- Trenberth, K. E., Signal versus noise in the Southern Oscillation. *Mon. Wea. Rev.*, **112**, 326-332, 1984.
- Trenberth, K. E., Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.*, **71**, 988-993, 1990.
- Trenberth, K. E., and J. W. Hurrell, Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.*, **9**, 303-319, 1994.
- Trenberth, K. E., and D. J. Shea, On the evolution of the Southern Oscillation. *Mon. Wea. Rev.*, **115**, 3078-3096, 1987.

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