GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO.14, PAGES 1779-1782, JULY 15, 1997

Darwin sea level pressure, 1876-1996: Evidence for climate change?

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Abstract. It has been argued that there was a period of prolonged ENSO conditions between 1990–95 so anomalous that it is "highly unlikely" to be due to "natural decadal-timescale variation" [*Trenberth and Hoar*, 1996]. This conclusion follows from their study of the Darwin sea level pressure anomaly record, which found that the 1990–95 period would occur randomly about once every 1100–3000 yrs. Taking into account the uncertainty in number of degrees of freedom in the Darwin time series, we find that conditions like those of 1990–95 may be expected as often as every 150–200 yrs at the 95% confidence level. Student's-*t*, ARMA, and Bootstrap/Monte Carlo tests of the time series all yield similar results. We therefore suggest that the 1990–95 period may plausibly be an aspect of the natural variability of the tropical Pacific.

Introduction

The early 1990s was a period of unusual conditions in the tropical Pacific. Slightly warmer than normal sea surface temperatures in 1990 led into the ENSO event of 1991–92, which was followed by several years with a western Pacific tendency toward warmer than normal conditions and westerly wind anomalies. Also of note was a tendency for Darwin, Australia sea level pressure anomaly (SLPA) to be higher than usual. Low-pass filtered Darwin SLPA is a useful but imperfect measure of ENSO conditions [*Deser and Wallace*, 1987; *Harrison and Larkin*, 1996]. It has often been used instead of the conventional Southern Oscillation Index because it is a long (1876–) and homogeneous record [e.g. *Trenberth and Shea*, 1987; *Wright et al.*, 1988]. On the basis of the behavior of seasonally averaged Darwin SLPA, *Trenberth and Hoar* [1996] (hereafter TH96) argue that the period 1990–95 is "unprecedented" and "highly unlikely" to be due to "natural decadal-timescale variation," and they ask if it may be a "manifestation of the global warming and related climate change associated with increases in greenhouse gases" (p. 57, 60).

The conventional view of ENSO is that it represents a phenomenon of 18–24 months duration, which occurs sporadically with a mean time between events of 4–7 years [e.g., *Rasmusson and Carpenter*, 1982]. Noting that 22 consecutive seasons (DJF 1989–MAM 95) of positive Darwin SLPA had not occurred previously in the historical record, TH96 undertook to estimate the likelihood that such a period would be expected to occur by chance, based on the statistics of the Darwin record between 1882 and 1981. Using a time between independent samples of 6 months from *Trenberth* [1984] (hereafter T84), TH96 computed a Student's-*t* result that the 22-season mean was different from zero at the 99.5% level, and would therefore be expected to occur randomly only every 1100 yrs (22 seasons/0.005).They also fitted the Darwin record with moving-average autoregressive models (ARMA(3,1)) and generated synthetic time series for frequency-of-occurrence statistics. The ARMA results indicated such a period would occur by chance every 1500–3000+ yrs, depending upon particular choices in the model. The implausibility of randomly getting this 22-season interval of same-sign values led to their comments cited above.

The TH96 statistical results were puzzling to us, because other periods of sustained values of one sign are evident in the Darwin record (Figure 1) [*Halpert et al.*, 1996]. We have re-examined the Darwin SLPA record, and reach a different conclusion about the likelihood that the 1990–95 period may have occurred by chance.

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Paper number 97GL01789.

Darwin Sea Level Pressure Anomaly (SLPA)

First let us examine the robustness of the 22-season interval of positive values, with mean of 0.94 mb. This span of positive values is idiosyncratic to their seasonal binning (DJF, MAM, etc.). Alternate seasonal binnings (NDJ, etc. or JFM, etc.) result in 20 or 21 positive seasons out of the 22. A 3-month (mo) running average filter (Figure 1) avoids the issue of which seasonal binning to prefer. The use of filters with longer half-power periods is common in SOI studies. The T84 filter, developed specifically to highlight ENSO variability in the Darwin and Tahiti time series, is similar in effect to a 13-mo triangle filter (Figure 1). Use of the 13-mo triangle or T84 filter produces a 73-month period of positive Darwin SLPA values in the early 90s, as well a 50-mo period of positive and 60-mo period of negative SLPA earlier in the record (Table 1). Figure 2 overlays these three periods for comparison; the recent period differs only in length. How does it come about that the TH96 results indicate that the recent positive period is so unusual?

Their result has its foundation in the assumption that effectively independent points in the Darwin SLPA record are 6 months apart (T_0 = 6 mo). It is useful to use the TH96 result to compare the estimated frequency of occurrence of the 50- and 60-mo intervals with the observed rates of occurrence. Using T_0 = 6 mo, these intervals are 23/6 and 13/6 independent points shorter than the recent 73-mo interval which TH96 expect to occur every 1100–3000 yrs. We therefore expect them to occur ~$2^{23/6}$ and $2^{13/6}$ times as often, or every 75–210 and 245–670 yrs, respectively. Since all of these periods occurred within a single 121-yr span, the TH96 analysis seems to be underestimating the frequency of occurrence of such periods.

Statistical Testing

The foundation of any parametric test of statistical significance is the number of degrees of freedom (ν) in the test. Estimation of ν (= record length/T_0) is often based on examination of the auto-correlation function (ACF) [e.g., T84]. How-

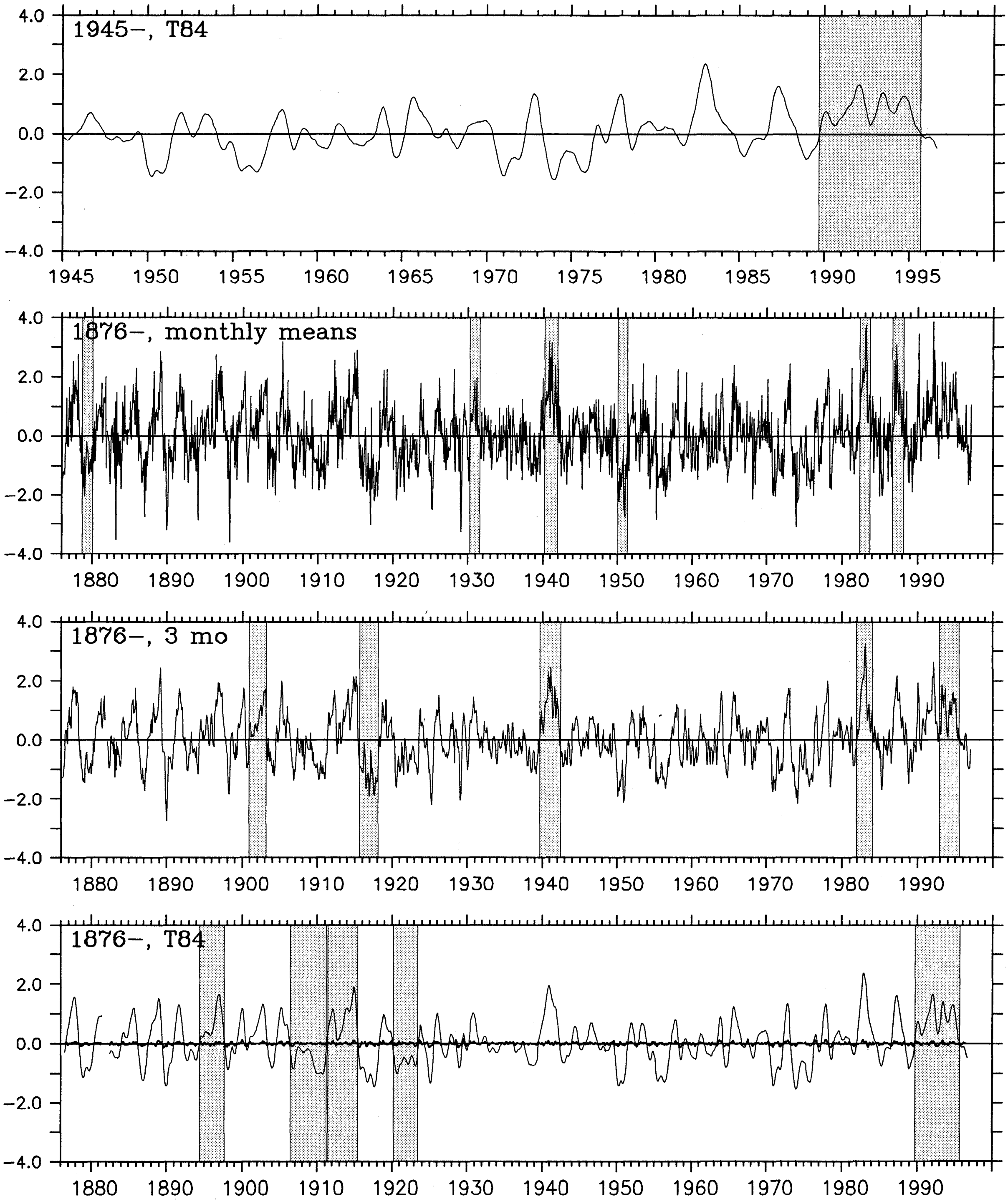

Figure 1. Darwin sea level pressure (SLP) anomaly time series in mb. (A) Post WWII period, 1945–present, filtered with the *Trenberth* [1984] 11-term filter (T84). (B) 1876–present, unfiltered monthly means. (C) 1876–present, filtered with a 3-month running mean (3 mo). (D) 1876–present, filtered with the T84 filter (light line). The difference between the T84 filter and a 13-month triangle filter (heavy line). In each panel, the five longest continuous intervals of either positive or negative anomalies are indicated by shading (Table 1).

ever, the ACF for any finite record is itself uncertain, and any estimate of ν should include a range of values. The Appendix describes how to make this uncertainty estimate. Appropriate treatment of the uncertainty in ν reconciles the conflict between the observed and TH96-expected frequency of occurrence of intervals of sustained same-sign Darwin SLPA.

The ACF depends upon the extent to which the original time series is filtered. Table 1 summarizes the longest continuous intervals of positive or negative Darwin SLPA time filtered in different ways, the values of T_0 calculated from the ACF, and the range of T_0 at 95% significance (Appendix). T_0 ranges between 3–8, 6–10, and 9–13 mo for the unfiltered, 3-mo running mean filtered, and T84 filtered time series. Taking T_0 from the first zero crossing of the ACF instead gives 12, 12, and 13 mo, respectively. These latter, longer values greatly increase the expected frequency of occurrence of the recent period; we use the smaller values below.

Table 1. Effect of Different Time Filters

	Longest Intervals			Recent	T_0
Filter	# mo	Dates (mo:yr)	(±)	#pos/#total	(95%)
a) None	23	3:1940–1:1942	(+)	60/70	6
	18	4:1982–9:1983	(+)		(3–8)
	18	9:1986–2:1988	(+)		
	17	9:1878–1:1880	(–)		
	17	3:1930–7:1931	(+)		
	17	12:1949–4:1951	(–)		
b) 3 mo	35	10:1992–8:1995	(+)	67/70	8
	34	6:1915–3:1918	(–)		(6–10)
	32	9:1939–6:1942	(+)		
	28	11:1900–2:1903	(+)		
	28	11:1981–2:1984	(+)		
c) T84	73	9:1989–9:1995	(+)	73/73	11
	60	5:1906–4:1911	(–)		(9–13)
	50	5:1911–6:1915	(+)		
	41	5:1894–9:1897	(+)		
	40	5:1920–6:1923	(–)		

The time series is analyzed: a) unfiltered, b) filtered with a 3-month running mean and c) with the T84 11-term (or 13-mo triangle) filter. For each filter, we list the dates (and sign) of the five longest continuous positive or negative intervals. The recent period of predominately positive anomaly is listed by the number of months that are positive (#pos) out of the total (#tot). The nominal time between independent points (T_0) as calculated from the ACF (Equation (4)) is listed, as is the 95% confidence interval (Appendix).

Redoing the TH96 Student's-t test using the largest value of T_0 within our 95% confidence limits (8 mo), we find the difference between the long-term and Dec 1989–May 1995 means to be significant at the 98% level (TH96 found 99.5%) which yields a frequency of occurrence of every ~275 yrs.

We noted earlier that alternative seasonal binning led to either 20 or 21 positive seasons in the 22-season period between Dec 1989–May 1995. We have re-run TH96's 1882–1981 ARMA(3,1) model fit to test for the likelihood of these, and find 20 out of 22 seasons of one sign would be expected to occur by chance every 275 yrs rather than their 8850 yrs for 22 seasons. There are various other plausible ARMA fits to the Darwin time series, as discussed by TH96. The fit to 1882–1986 produced an estimate of 6500 yrs. Adjusting our 275-yr result by this ratio would lead us to expect the recent period behavior about every 200 yrs. In order to actually compute the 95% confidence limits on these ARMA results, it would be necessary to refit the ARMA to the 95% upper and lower bounds of the ACF.

We prefer a Bootstrap/Monte Carlo test that allows us to explore explicitly the sensitivity of our results to T_0, using the actual statistics of the Darwin SLPA time series without making a model fit. The 1876–1996 time series contains 121 yrs/T_0 independent points. The probability of finding a period like 1990–1995 in the 1876–1996 time series is the same as the probability of flipping a weighted coin $X = 121$ yrs/T_0 times and finding an interval of length I containing P (or more) heads, where I and P are the total number of months (#tot) and number of positive months (#pos) in the recent period divided by T_0 (Table 1). We generate $B = 10^6$ such series and count the number of such intervals. The weighting factor (w) is the proportion of positive values in the 1882–1981 period (the same period used in the TH96 ARMA fit). It is possible to apply this test to the unfiltered series or any of the filtered versions; we have explored the effect of both different values of T_0 and different amounts of filtering (with appropriate adjustments of T_0 and w).

We find that the most improbable situation is based on the 73 positive (out of 73) months found in the T84 filtered record, with this situation expected to occur once every ~350 yrs (T_0 = 11 mo), with a 95% range of 150 (T_0 = 13 mo)–1200 (T_0 = 9 mo) yrs. Other calculations had the expected frequency of occurrence less than every 100 yrs.

Summary

Testing for climate change (departure from previous conditions) typically requires the estimation of various parameters. Our results illustrate that it is important to include the uncertainty in the number of degrees of freedom, ν (or the time between independent data, T_0) when carrying out evaluations of statistical significance. It is straightforward to evaluate the uncertainty in the estimated ACF and to infer from this the uncertainty in ν (or T_0). We have used the Darwin SLPA record as an example, and show that it is plausible, within 95% confidence limits, that the unusual behavior in the early 1990s is the result of natural variability.

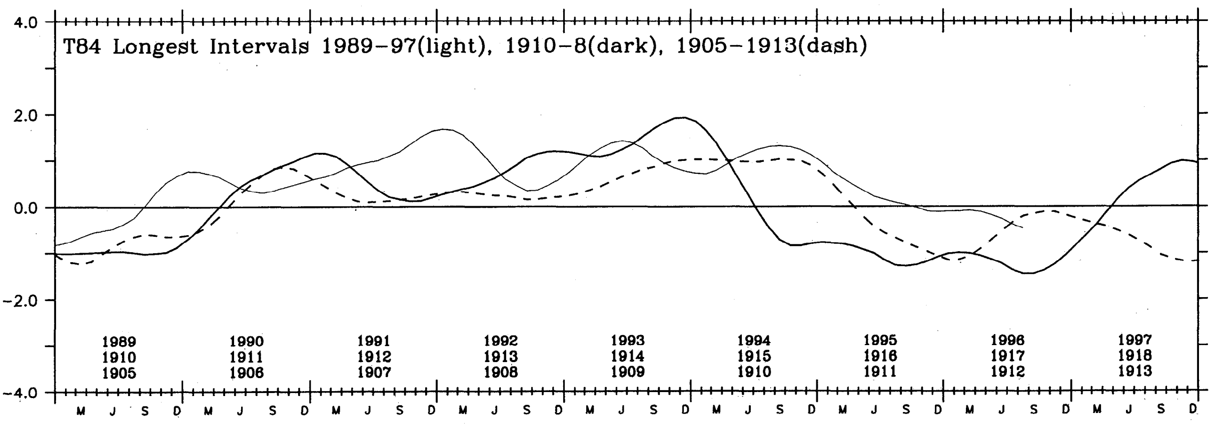

Figure 2. Darwin SLP anomaly in mb. Overlay of the three longest intervals of positive or negative values under the *Trenberth* [1984] filter. 1989–1997 [light line], 1910–1918 [dark line], and 1905–1914 [dash]. The 1905–1914 anomaly is multiplied by –1.

Appendix: Calculating the Number of Degrees of Freedom in a Time Series (With Confidence Limits)

It is necessary to estimate the number of degrees of freedom (ν) in any record in order to make estimates of statistical significance. Consider a time varying signal *a(t)*, sampled at regular intervals ΔT at points a_i, $i = (1,...,N_T)$, with zero mean and variance σ^2. In general N_T is not an appropriate estimate of ν due to serial coherence within the time series. We estimate the time between independent observations (T_0) in order to estimate ν (= $N_T \Delta T/T_0$).

We first estimate the auto-correlation function (ACF), $r(\tau)$, by r_l where

$$r(\tau) = \frac{\int a(t)a(t+\tau)dt}{\int a(t)^2 dt} \quad , \quad r_l = \frac{\sum_i a_i a_{i+l}}{\sum_i a_i^2} \quad (1)$$

Uncertainty arises because of errors in the a_i and through use of r_l to estimate the true ACF, $r(\tau)$ [e.g., *Priestley*, 1987]. The effect of errors in the a_i cannot be addressed in general; Monte Carlo techniques using the time series of interest provide one way to address this error source. We focus on the uncertainty associated with using a finite time series to estimate $r(\tau)$, which is not normally distributed. This error can be estimated by transforming $r \Rightarrow Z$ at each lag using the Fisher Z transformation, yielding the approximately normal distribution with standard deviation σ_Z

$$Z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right), \qquad \sigma_Z = \frac{1}{\sqrt{\nu-3}} \quad (2)$$

The confidence interval for this can be estimated conventionally in Z units, and then inverted to give the interval in terms of the correlation coefficient, *r*. However, we still need ν to estimate σ_Z; thus we must solve a system of simultaneous equations. This system can be solved for any particular time series using, e.g., relaxation techniques. For many purposes, it is sufficient to approximate ν in (2) by an estimate based on the nominal r_l.

There are two common techniques for estimating T_0 (and therefore ν) from r_l. The first is to use the first zero crossing of r_l. This is a generally safe, conservative technique which will tend to overestimate T_0. The second method (used here) is that of *Leith* [1973], and is based on the fact that a time series a_i with a variance σ^2, when filtered by a running mean of length *N* points, is expected to have a variance $\sigma_N{}^2 = \sigma^2/\nu$, where ν is now the effective number of independent points averaged together (= $N\Delta T/T_0$). This reduction in variance can also be estimated from the ACF as [*Leith*, 1973, T84]

$$\sigma_N^2(\bar{a}) = \frac{\sigma^2}{N}\left[1 + 2\sum_{l=1}^{N}\left(1 - \frac{l}{N}\right)r_l\right] = \frac{\sigma^2}{\nu} \quad (3)$$

Thus the time between independent points is [T84]

$$T_0 = \frac{N}{\nu} = 1 + 2\sum_{l=1}^{N}\left(1 - \frac{l}{N}\right)r_l \quad (4)$$

which is a function of *N*, but which (generally) asymptotes for large *N*. The 95% confidence interval can then be placed on T_0 by using the 95% interval limits on r_l (from (2)) in (4). This in turn yields the confidence interval on ν.

Acknowledgments. The Thermal Modeling and Analysis Project (TMAP) receives support from NOAA PMEL and ERL HQ, and the Office of Global Programs. Andrew Bennett, Ryan Whitney, and the TMAP staff provided valuable assistance. Grant Beard provided the Darwin data. This is PMEL contribution #1638 and Hayes Center/JISAO contribution #437. Ferret (http://www.ferret.noaa.gov) was used for analysis.

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(Received April 18, 1997; accepted May 31, 1997)