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The Sun is the climate pacemaker I. Equatorial Pacific Ocean temperatures

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A R T I C L E I N F O

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A B S T R A C T

Equatorial Pacific Ocean temperature time series data contain segments showing both a phase-locked annual signal and a phase-locked signal of period two years or three years, both locked to the annual solar cycle. Three such segments are observed between 1990 and 2014. It is asserted that these are caused by a solar forcing at a frequency of 1.0 cycle/yr. These periodic features are also found in global climate data (following paper). The analysis makes use of a twelve-month filter that cleanly separates seasonal effects from data. This is found to be significant for understanding the El Niño/La Niña phenomenon.

1. Introduction

In a detailed study of the equatorial Pacific sea surface temperature (SST) index *SST3.4*, Douglass [1] found two signals, one that was predominantly 1.0 cycle/yr, and one of low frequency (<1.0 cycle/yr) exhibiting the familiar El Niño/La Niña phenomenon. These were called N_H and N_L, respectively. N_L was found to contain time segments showing periodicities of multiples of one year. Ten such numbered segments were identified in the period 1870–2008 (see Table 3 of Ref. [1]). Either the beginning or end date, or both, of those segments had a near one-to-one correspondence with previously reported abrupt climate changes or climate shifts (CS). The two most recent of these segments studied were: 1991–1999, showing periodicity of three years, and 2001–2008, showing periodicity of two years. These, and the 1 cycle/yr component, were phase locked to the annual solar cycle. "Phase-locked" in what follows always refers to the solar cycle as reference. By phase locking we mean that a signal of frequency f_1 has a fixed phase with respect to that of a second signal of frequency $f_2 = (n/m) f_1$, where n and m are integers. The relationship is usually a result of a non-linear mechanism. For application to geophysical time series, see [1,2] and Section 5.

To explain the various phenomena it was concluded that this climate system is driven by a forcing F_S of solar origin at a frequency of 1.0 cycle/yr that causes the principal component of the direct response N_H. In addition, F_S may have caused the subharmonic response in N_L via some nonlinear mechanism.

Four additional atmospheric and surface climate indices exhibit the same periodic behavior [3] in the same segments: atmospheric pressure variation in the western Pacific; temperature anomalies in the tropical troposphere; *PDO*, a dimensionless index based upon temperature measurements north of 20°N; and tropical wind.

It is of course not surprising that an annual signal is found in all the ocean–atmospheric climate indices. This, along with qualitative recognition of the superimposed subharmonics signaled by the El Niño/La Niña phenomenon, has been recognized for over 100 years. A chronology of observations of phase locking was presented in Ref. [1]. The present study revisits the Pacific sea surface temperature index *SST3.4* starting from 1990, extends it through 2013, and presents a formal critique of the "climatology" method of removing seasonal (annual) components from data.

Section 2 describes the data sets, methods, and background material. The results are analyzed and discussed in Section 3. Section 4 considers related issues and Section 5 contains a summary of the conclusions.

2. Data and methods

2.1. Data

This study considers only data from the period January 1990 through December 2013.

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SST3.4: Region 3.4 of SST is the equatorial Pacific (latitude 5°S to 5°N and longitude 120°W to 170°W), which is commonly used to study the El Niño Southern Oscillation (ENSO) phenomenon. The geographical average SST of Region 3.4 is named *SST3.4* and ranges between 24 °C and 30 °C. A widely used anomaly index is *Nino3.4*, which is *SST3.4* with the seasonal effect supposedly removed. The Climate Prediction Center of NOAA posts monthly values of both *SST3.4* and *Nino3.4* that begin in 1982 [4].

2.2. Methods: precise separation of high- and low-frequency effects

Studies of many geophysical phenomena start with a parent signal G_0, such as a temperature or wind speed record, containing a component of interest mixed in with a seasonal component at frequencies of 1.0 cycle/yr and its harmonics. The component of interest might show ENSO effects with multi-year periodicity. An important task is to separate the seasonal component from G_0 to obtain the one of interest. A moving average is one of the methods used to make this separation. Such a filter of length one year, which we denote by an operator $\boldsymbol{F}$, is the most precise for seasonal components, as Douglass [5] has shown in a study of *SST3.4* (the parent signal). He showed in some detail that the remaining seasonal signal should be considered an essential component of the ENSO phenomena and be retained for study.

In the present analysis only anomalies are treated. Thus we replace a parent series G_0 by $G = G_0 - \langle G_0 \rangle$, where $\langle G_0 \rangle$ is the average of the parent series over the period January 1990 to December 2013.

The filter $\boldsymbol{F}$ is applied to the series G to create a "season-free" anomaly aG defined as

$$aG = \boldsymbol{F}(G). \tag{1}$$

This low frequency signal may contain the familiar ENSO phenomena. A "high frequency" index is also defined,

$$hG = G - \boldsymbol{F}(G), \tag{2}$$

which contains a coherent signal at 1.0 cycles/yr and its harmonics, along with noise.

2.3. Comparison with the climatology method

The low frequency index given by Eq. (1) poses a direct challenge to the commonly used climatology method of removing the seasonal effect. The climatology method for the case of monthly data consists of (1) creating a climatology function $\boldsymbol{C}$ which, for any given month, consists of the average over the values for each such month in the range of G; by definition the resulting time series $\boldsymbol{C}(G)$ has periodicity one year, and (2) defining the low-frequency residual index aG_C as

$$aG = G - \boldsymbol{C}(G). \tag{3}$$

Mathematically, the series $\boldsymbol{C}(G)$ consists of a periodic function of period 1.0 year with zero mean plus a constant that is the average of G. In the case of *SST3.4* the climatology scheme fails to remove all of the seasonal effect, as we show below. The $\boldsymbol{F}$-filter method does remove it [5] because, in addition to its obvious similarity to a low pass filter that allows frequencies lower than 1.0 cycle/yr to pass with only slight attenuation, it has another property that is not generally recognized. The Fourier transform of $\boldsymbol{F}(G)$ contains a factor $H_{12}(f) = \sin(12\pi f)/\sin(\pi f)$, which has zeros at multiples of the frequency $f = (1/12)$ month^{-1} [6]. Thus, components of $\boldsymbol{F}(G)$ whose frequencies are exactly $f = (1/12)$ month^{-1} and its harmonics are completely removed. This second property is highly desirable in reducing the seasonal signal that contains an annual component and its harmonics. One frequently sees the use of k-month filters where k has values 3, 5, 7, 9, 11, 12, 13 in attempts to reduce the seasonal signal; the $k = 12$ filter is obviously best for removal of such a signal. The data considered in this paper are either monthly (12 values/yr) or quarterly (4 values/yr). For the case of quarterly data the appropriate digital filter is a moving 4-point average.

Applying $\boldsymbol{F}$ to both sides of Eq. (3), one obtains

$$\boldsymbol{F}(aG_C) = \boldsymbol{F}\big[G - \boldsymbol{F}(G)\big]. \tag{4}$$

Since $\boldsymbol{F}$ eliminates $\boldsymbol{C}(G)$ because of its pure periodicity, Eq. (4) becomes

$$\boldsymbol{F}(aG_C) = aG. \tag{5}$$

This relation "repairs the damage" done by the climatology method and therefore proves useful when one has only an index generated by that method and no parent data.

In Appendix A an example of the filtering procedures is given, including a comparison of the 12-month filter and climatology methods. Application to El Niño data will be given in Section 4.

2.4. Identifying phase-locked time segments

Consider geophysical indices aG in which annual effects have been removed, and in which there exist time segments with components having periods that are exactly multiples of one year. One way of identifying these segments is to examine the autocorrelation function *versus* delay time τ of a candidate segment. If the segment is sinusoidal, the autocorrelation function is a cosine-like function with a minimum at $\tau/2$ and a maximum at τ. The location and extent of such a segment in time are determined by adding or subtracting beginning- and end-date data points from a candidate segment until a cosine pattern appears.

The several subharmonic segments observed in the extended study of *SST3.4* had maxima only during April–May–June (AMJ) or November–December–January (NDJ). When there are time segments in aG showing a periodicity of a multiple of one year, a complete classification is given by three discrete indices: subharmonic number, parity, and sub-state index [1]. See Appendix B for a review of these defined quantities.

3. Analysis and discussion

3.1. Temperature data from Pacific Region 3.4

While Region 3.4 is not global, there are two reasons for analyzing it here. Indices derived from it are widely used as a proxy for the study of the El Niño/La Niña phenomenon, and this region is one of the few climate systems where parent data, from which all other properties are derived, is available. In particular, the importance of the annual component will be demonstrated, and characteristics of the seasonally-repaired time series of global data sets will be shown to be virtually the same as those of this region.

It is useful to consider the amplitude of the high-frequency data series hG, defined as

$$\boldsymbol{A}(hG) = \left(2\,\text{average}\left(hG^2\right)\right)^{1/2}. \tag{6}$$

where the average is over one year, symmetric about the point in question, and hG^2 is the set of squares of the individual numbers in hG.

Fig. 1 shows the parent data *SST3.4*. Fig. 2a shows the high frequency signal *hSST3.4* (thin) and its amplitude $\boldsymbol{A}$(*hSST3.4*) (thick). Fig. 2b contains the autocorrelation of *hSST3.4*, which displays a