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PHYSICAL PROCESSES RESPONSIBLE FOR ENSO EVENTS *

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ABSTRACT

We use the author's theory of sun-weather/climate links and climatic change to develop and explain the physical processes which give rise to El Nino and Southern Oscillation (ENSO) events. Our analysis apparently accounts well for all major characteristics of ENSO events already established from past observations. Finally we propose possible ways by which future ENSO events may be predicted.

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1. INTRODUCTION

El Nino and Southern Oscillation (ENSO) events are among the meteorological phenomena that have received extensive attention [1]-[8]. A comprehensive and up-to-date review of past studies on ENSO events has been given by Philander [9]. From the meteorological point of view, sufficient mastery of the processes which control ENSO events is of paramount importance because not only do these events significantly affect climate/weather in the tropics [10], but they also influence weather/climate processes even outside the tropics [7],[9]. The enormous research effort that has been channelled towards ENSO events has clearly led to improved understanding of the characteristics of these events, their meteorological consequences, as well as the extent of their geographical influence [9]. Besides, several models for these events have been developed [10]. Despite all these, there are still some basic questions about ENSO events which have not yet been answered [11]. For example, the physical processes which give rise to the events have not yet been fully understood [9],[11].

In this paper, we use the author's theory of climatic change and Sun-Weather/Climate links as well as some related work [12]-[24] as a starting point and then develop physical processes which are apparently responsible for the ENSO events. We justify our physical processes by showing that they actually account satisfactorily for the major characteristics of ENSO events already established through observations. After illustratively explaining the meteorological changes which inevitably precede an ENSO event, we finally propose possible ways by which ENSO events may be predicted.

2. ANALYSIS

As shown and explained in Refs. [12],[21],[22], the heat energy $F(t,\phi,\theta,T)$ available at a location in the earth-atmosphere system at latitude $\phi(\leq 65°\text{N or S})$, longitude θ and time t such that $0 \leq t \leq T$ and $T > 2$ days, is given as follows:

$$F(t,\phi,\theta,T) = \sum_{m=1}^{\infty} a_m \left\{ \left[1 + \frac{1}{\alpha} \sum_{k=1}^{N} f_k \left(t + \frac{\chi\theta}{2\pi}, \phi \right) \right] \alpha D_0 \left(t + \frac{\chi\theta}{2\pi}, \phi \right) \right\}^m \quad (1)$$

where

$$D_0(t,\phi) = \frac{2}{\pi} \left\{ \frac{1}{2} Ag + A \sum_{n=1}^{\infty} \frac{\sin(ng\pi)}{n\pi[1-(ng)^2]} \cos n\omega_{01} \left(t - \frac{B}{2} \right) \right\} Y(t,T) \quad (2)$$

where $B = 24$ hours, $\omega_{01} = 2\pi$ radians per 24-hour day, A is a latitude-dependent term, $g = \frac{1}{2} + \frac{A_s}{B} \sin \omega_s t$, A_s and ω_s are the amplitude and angular frequency, respectively, of the seasonal influence on the local sunrise-sunset duration, α is the constant component of incident (extraterrestrial) solar energy, f_k is the k^{th} variable component of incident (extrarrestrial) solar energy, N

is the total number of variable components in the incident (extraterrestrial) solar energy, a_m (for $m \geq 1$) is a location-dependent parameter, $\chi = (24)(60)(60)$ and $Y(t,T)$ is given as

$$Y(t,T) = \sin(\omega_{02}t) + \sin(2\omega_{02}t) + \frac{1}{3}\sin(3\omega_{02}t) + \frac{1}{5}\sin(5\omega_{02}t) + \ldots\ldots \quad (3)$$

where $\omega_{02} = \frac{\pi}{2T}$ radians per (24-hour) day. Derivation and other details regarding Eqs. (1) to (3) may be easily sought in Refs. [12]-[24].

The time-shift of $\frac{\chi\theta}{2\pi}$ in Eq.(1) gives rise to zonally aligned fluctuations in $F(t,\phi,\theta,T)$ whose phase change β is proportional to angular frequency ω and is given as

$$\beta = \frac{\chi\theta}{2\pi}\omega \quad (4)$$

All the fluctuations with periods greater than 2 days undergo phase shifts of less than 180° per each complete rotation of the earth. Consequently, weather fluctuations associated with the latter periodic zonal variations exist and exhibit a frequency-dependence eastward phase speed V given (in longitudinal degrees per day) as follows:

$$V = \frac{180\chi\omega}{\pi} \quad (5)$$

where ω is in radians per second.

Now if we trace and continuously take the earth's spinning motion into account, it is obvious that the zonal wavelength λ (in radians) of the waves governed by Eqs.(4) and (5) is given as

$$\lambda = \frac{(2\pi)^2}{\chi\omega} \quad (6)$$

Eq.(6) implies that for a wave at period H days, its zonal wavelength λ_H (in longitude degrees) is given as

$$\lambda_H = 360\,H \quad (7)$$

With respect to observations which do not continuously track and incorporate the effect of the Earth's spinning motion but are simply in form of daily (single-point or averaged) data, then the effective zonal wavelength (in longitude degrees) is denoted by λ_{HD} (instead of λ_H), and takes the form

$$\lambda_{HD} = H \quad (8)$$

since in this case the wavelength as given by Eq.(7) has actually been scaled down by a factor of 360. On the basis of observations that have been averaged over each $L(>1)$ days, the effective wavelength changes from λ_{HD} to λ_{HL} such that

$$\lambda_{HL} = \frac{H}{\frac{1}{2}L^2} \quad (9)$$

since in this case the wavelength that would otherwise be given by Eq.(8) is scaled down by a factor of L due to the averaging process and by a further factor of $\frac{1}{2}L$ due to the fact that the effective wavelength component in each block of L days in $\frac{2}{L}$ times the correct value in the absence of averaging. Calculations based upon Eqs.(5) to (9) agree quite well with actual observations [22]-[25].

The term $D_0\left(t+\frac{\chi\theta}{2\pi},\phi\right)$ in Eq.(1) is temporarily dominated by its component fluctuations at a period of 1 year after *either* a general increase in (monthly) temperature peaks for at least $\sim$1 year followed by a temperature drop for $\sim$1 year *or* a general increase in (monthly) temperature peaks for at least$\sim$ 1 year followed by a flattening of the temperature (peaks) for $\sim$ 1 year *or* a generally steady rise in (monthly) temperature peaks for at least $\sim$ 1.5 years. Each of these three conditions will hereinafter be referred to simply as a "trigger condition" or in short a TC. Usually D_0 has a component at a period of 1 year, but this particular component overshadows the others after a TC. We shall show later on that TC's are fairly frequent features of at least the tropical weather/climate system.

Now, the occurrence of a TC makes $D_0(t+\frac{\chi\theta}{2\pi},\phi)$ temporarily dominated and hence approximately equal to a 1-year period fluctuation which we shall represent here by $S(t+\frac{\chi\theta}{2\pi},\phi)$. But as soon as $D_0 \approx S$, the double-sideband amplitude-modulation plus carrier implied on the right-hand side of Eq.(1) is automatically changed to single-sideband amplitude-modulation plus carrier since the lower sideband is converted into constant (i.e. zero frequency) heat. Mathematically this means that

$$\begin{aligned} a_m&\left[1+\frac{1}{\alpha}\sum_{k=1}^{N} f_k\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right]\alpha D_0\left(t+\frac{\chi\theta}{2\pi},\phi\right)\\ &= a_m\left\{C_0+\alpha D_0\left(t+\frac{\chi\theta}{2\pi},\phi\right)+\left[\sum_{k=1}^{N} f_k\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right]D_0\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right.\\ &\qquad \left.-\left[\sum_{k=1}^{N} f_k'\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right]D_0'\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right.\\ &= a_m\left\{C_0+M\left(t+\frac{\chi\theta}{2\pi},\phi\right)\bar{D}_0\left(t+\frac{\chi\theta}{2\pi},\phi\right)\right\} \end{aligned} \quad (10)$$

where C_0 is a constant, the symbol *prime* denotes a phase change of $-90°$, the symbol *bar* denotes a phase change of Ω, and

$$M\left(t+\frac{\chi\theta}{2\pi},\phi\right)=\alpha\left\{1+\frac{2\sum_{k=1}^{N} f_k(t+\frac{\chi\theta}{2\pi},\phi)}{\alpha}+\frac{[\sum_{k=1}^{N} f_k(t+\frac{\chi\theta}{2\pi},\phi)]^2}{\alpha^2}+\frac{[\sum_{k=1}^{N} f_k'(t+\frac{\chi\theta}{2\pi},\phi)]^2}{\alpha^2}\right\}^{1/2} \quad (11)$$

Over the duration of our interest, $\sum_{k=1}^{N} f_k(t+\frac{\chi\theta}{2\pi},\phi)$ is significantly dominated by the seasonal cycle $X(t+\frac{\chi\theta}{2\pi},\phi)$ since the latter strongly dominates the former over time-lengths of up to some thousands of years. Thus if ψ is the mean phase angle of S, then it can be shown [26],[27] that

$$\Omega = \tan^{-1}\left\{\frac{\alpha \sin\psi + X \sin\psi + X' \cos\psi}{\alpha \cos\psi + X \cos\psi - X' \sin\psi}\right\} \tag{12}$$

In order to realize more clearly the physical changes involved, let us represent $X\left(t + \frac{X\theta}{2\pi}, \phi\right)$ and $\bar{S}\left(t + \frac{X\theta}{2\pi}, \phi\right)$ by $B_2 \cos(\Delta + \tau)$ and $B_1 \cos(\Delta + \Omega)$, respectively, where $\Delta = t + \frac{X\theta}{2\pi} + f(\phi)$, τ is a phase term, $f(\phi)$ is a latitude-dependent term [22],[23] and B_1 and B_2 are amplitude values. Then a combination of Eqs. (1) and (10) yields

$$F(t,\phi,\theta,T) = \sum_{m=1}^{\infty} a_m \left\{\frac{1}{2}B_1 B_2 + \left[\frac{1}{2}B_1 B_2 + \alpha B_1 \cos(\Delta + \Omega) + \frac{1}{2}B_1 B_2 \cos(2\Delta + \Omega + \tau)\right]\left[1 + \left(\frac{B_2 \sin(\Delta + \tau)}{1 + \frac{B_2}{\alpha}\cos(\Delta + \tau)}\right)^2\right]^{1/2}\right\}^m \tag{13}$$

In the tropics, $B_2 < B_1 \leq 0.2\,\alpha$ whenever $D_0 \approx S$.

During certain phases of the seasonal cycle $B_2 \cos(\Delta + \tau)$, notably between January and about March but also between March and June, July and September, as well as between September and January, $\sin(\Delta + \tau)$ is at or very close to zero so that Eq.(13) takes the form

$$F(t,\phi,\theta,T) \approx \sum_{m=1}^{\infty} a_m \left\{B_1 B_2 + \alpha B_1 \cos(\Delta + \Omega) + \frac{1}{2}B_1 B_2 \cos(2\Delta + \Omega + \tau)\right\}^m \tag{14}$$

Note that similar conclusion would be arrived at irrespective of the chosen sinusoidal form of $X(\Delta, \phi)$ simply because the annual temperature curve at or near the equator has two maxima following the two zenithal positions of the Sun and two minima at about the time of solstices.

It is clear from Eq.(14) as well as the preceding account that the following processes take place after the occurrence of any of the TC's which leads to the validity of Eq.(14).

(a) Sizable energy is squeezed out of the circulation (or kinetic) process and laid off as heat (in zero frequency mode).

(b) The 1-year period cycle in $D_0(\Delta, \phi)$ is amplified by an amplification factor of α. Since this cycle dominates $D_0(\Delta, \phi)$ it also dominates in influencing the corresponding zonal heat/temperature variations. According to Eq.(8), this 1-year period fluctuation, which we have denoted by S) has a zonal wavelength of $\sim 365°$ of longitude. Thus the (tropical) zonal circulation

is dominantly influenced by the wavenumber 1 mode of S whereby a warm and low pressure zone forms at the ebb phase and a relatively cooler and high pressure zone forms at the peak phase approximately 180° of longitude away. Partly due to some meridional wavy fluctuations discussed in references [22],[24], the straight line connecting the equatorial maximum of the high pressure zone to the north and south poles is littered with high pressure patches which influence weather condition even at regions away from the tropics. Similarly, the straight line joining the equatorial centre of the low pressure zone to the north and south poles is littered with low pressure patches which influence weather conditions in those regions involved even though some may be away from the tropics.

(c) The conditions represented by Eq.(14) are more favoured at certain specific phases of the seasonal cycle. Quite generally, any persistent 1–year period variation in $D_0(\Delta, \phi)$ is approximately phase-locked with reference to the seasonal cycle since it has zonal wavelength and speed of $\sim 365°$ longitude and $\sim 360°$ of longitude per year, respectively.

(d) The physical conditions represented by Eqs.(13) and/or (14) set in as soon as $D_0(\Delta, \phi)$ is dominated by $S(\Delta, \phi)$. These conditions persist until this dominance is removed.

(e) In approximate terms, the intensity of the physical processes represented by Eqs.(13) and (14) is inversely proportional to the amplitude of the seasonal temperature at the start of the preceding TC. This point will be ascertained through actual records later on.

(f) While under the influence of the conditions represented by Eq.(14), any two tropical locations separated by $\sim 180°$ longitude are characterized by a see-saw pattern of (relative) pressure variations, with one of the locations having high pressure for months at a time while the other has a low pressure.

(g) The frequency of occurrence of the conditions represented by Eq.(14) or (13) is equal or comparable to the frequency at which TC's take place. A look at the temperature conditions associated with TC's clearly shows that the latter can possibly be started by each up-and-down cycle of quasi-biennial temperature oscillations. In view of the significant quasi-biennial temperature/heat oscillations present in tropical climates, it is expected that occurrences of TC's would, on the average, follow a period close to 2 years. But generally this period could and should sometimes extend beyond ~ 2 years because TC's may be caused by other meteorological parameters such as harmonics of the sunspot cycles and beats of long-period temperature oscillations.

(h) Under the conditions represented by Eq.(14), the Walker circulation along the equator expectedly consists of either two large zonal cells or four relatively smaller cells. However, the number of these zonal cells may exceed 4 under the conditions represented by Eq.(13).

The features given by (a) to (h) above befit the basic characteristics of ENSO events so much [1]-[11] that the associated analysis (given above) explains the physical processes responsible for ENSO events. In fact our analysis clearly reflects the conclusion by Lamb [7] that there is little doubt that the striking changes in surface temperatures and the large-scale wind circulation which accompany ENSO events are responses to variations in the energy available to drive the winds and ocean currents or in the way this energy supply is fed into the system. Since sizeable parts of the Indian ocean and the Pacific ocean are apart by about 180° of longitude, a see-saw in barometric pressure is expected to exist between the two oceans whenever the conditions represented by Eq.(14) prevail. If in this case a high pressure zone sets up over the tropical Indian ocean, while a low pressure zone sets up over the tropical Pacific ocean,then an El Nino is said to be in progress. On the other hand, if a high pressure zone sets up over the tropical Pacific ocean, while a low pressure zone sets up over the tropical Indian ocean, then La Nina is said to be in progress. Both El Nino and La Nina are, therefore, two opposite phases of the Southern Oscillation [9].

Perhaps the easiest way of predicting ENSO events is to trace developments of TC's using daily or monthly temperature records from at least one of the regions involved. Once a TC is spotted at its infant stage, then its progress should be followed on the assumption that its maturity stage will be followed by an ENSO event. Available records clearly show that TC's are always followed by ENSO events as illustrated typically in Figs. 1 and 2. These figures display plots of monthly mean air temperature (solid lines) at two stations Zanzibar (6°13'S, 39° 13'E) and Tanga (5° 5'S, 39° 4'E) situated along the western edge of the Indian ocean from 1960 up to 1989 inclusive. Developments (to maturity) of TC's have been indicated on the two figures using discontinuous lines. According to data on past ENSO events from Ref.[9], each TC shown in Figs. 1 and 2 was followed by an ENSO event. This certainly shows the reliability of the proposed prediction method. After predicting an ENSO event using our proposed method, one would like also to predict whether it will be an El Nino or a La Nina. This prediction may be made from "temperature versus zonal location" plots which engulf enough zonal coverage to show the zonal progression of the 1-year period variation in temperature. As this variation has a zonal wavelength (as judged from daily records) of $\sim 365°$ longitude, the minimum zonal coverage of the plots would be about 90° of longitude.

We mentioned before that the intensity of an ENSO event is inversely proportional to the amplitude of the seasonal temperature cycle just before its associated TC. We may now test this assertion on Figs. 1 and 2. A look at the latter figures shows that the TC immediately preceded by the smallest-amplitude seasonal temperature cycle is that which triggered the 1982-83 ENSO event. Coincidentally it is the latter event which has been considered as the strongest among those on record [9,28].

According to Refs.[12],[22]-[24], the ozonosphere and the ionosphere are separately governed by heat/temperature equations of fairly similar mathematical layout as Eq. (1). It is suspected, therefore, that physical processes comparable to those analyzed in the text do occur in both the stratosphere-mesosphere and the ionosphere where they give rise to significant warmings. This suspicion is propped up by the following observations. Firstly, all the sudden stratospheric warming (SSW) events reported in Ref.[29] coincided in time with ENSO events. Secondly in both major and minor SSW events, the available stratospheric potential energy is mostly contained in zonal waves of wavenumber 1 while most of the stratospheric kinetic energy is contained in zonal waves of wavenumbers 1 and 2 [30]. Thirdly the mean frequency of major SSW events is equal to that of

ENSO events deduced in the text [31]. Fourthly the occurrence of an SSW event is accompanied by noticeable changes in the ionosphere [32].

3. CONCLUSION

We have described the physical processes which apparently initiate and drive ENSO events. Our description accounts well for the major characteristics of ENSO events that have been confirmed through observations. Finally we have suggested a simple method that can be used to predict occurrences of future ENSO events.

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Figure Captions

Fig.1 A plot of monthly mean air temperature at Zanzibar (6° 13'S, 39° 13'E) from 1960 up to 1989 (solid line). Occurrences of TC's are sketched on the plot using discontinuous lines. Locations of sunspot minima are indicated by arrow-headed lines.

Fig.2 A plot of monthly mean 15.00 local time air temperature at Tanga (5°5'S, 39°4'E)) from 1960 up to 1989 (solid line). Occurrences of TC's are sketched on the plot using discontinuous lines. Locations of sunspot minima are shown by arrow-headed lines.

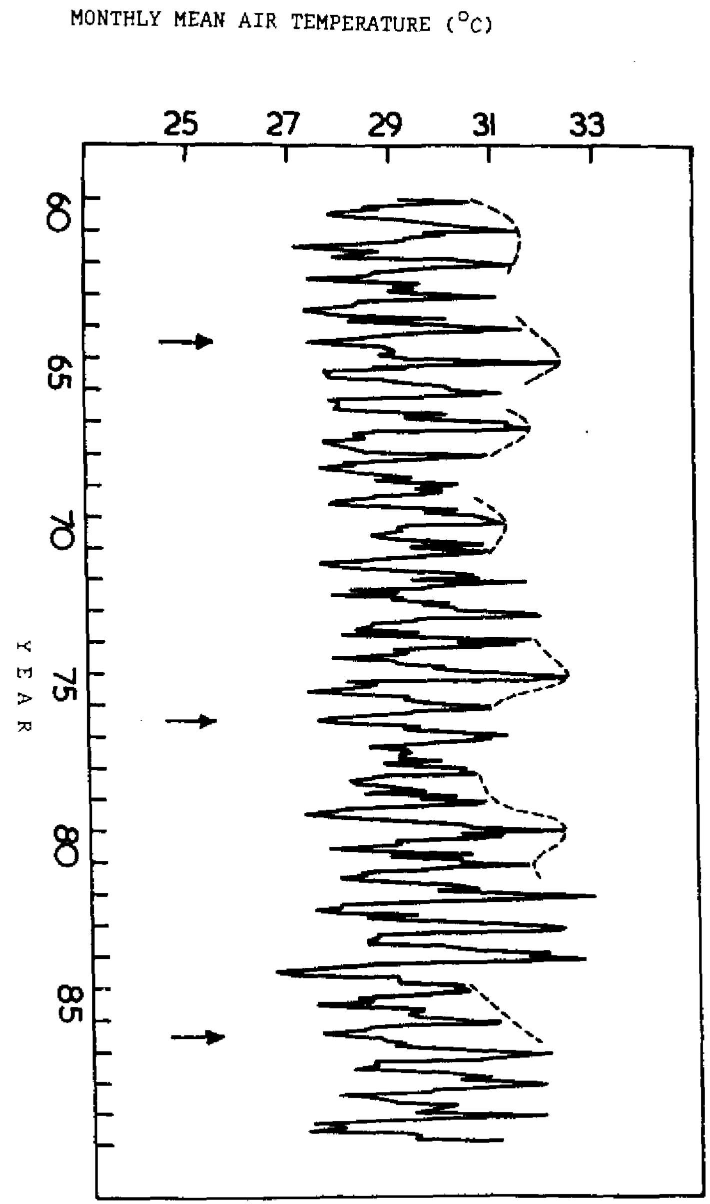

FIG. 1

MONTHLY MEAN 15.00 LT AIR TEMPERATURE (°C)

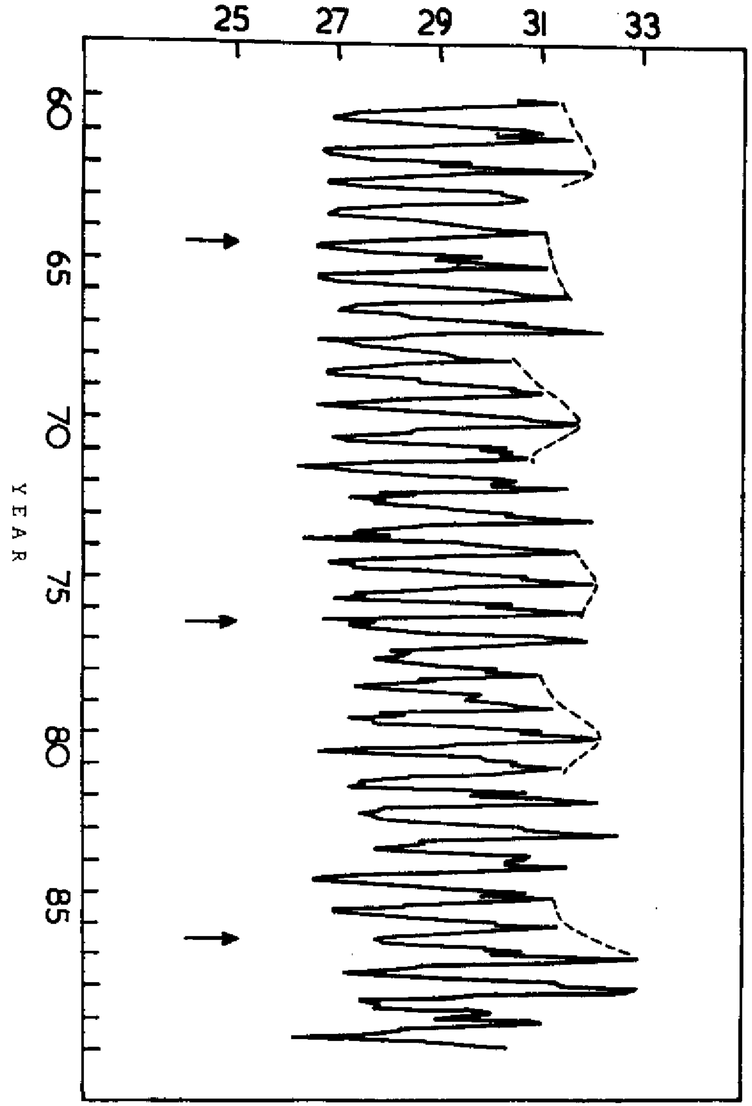

FIG: 2