SENSITIVITY OF THE OCEANIC TURBULENT BOUNDARY LAYER TO CYCLIC INSOLATION CHANGE WITH RESPONSE PERIODS OF 23 TO 2.5 KY: AN EQUATORIAL ATLANTIC RECORD FOR THE LAST 200KA.

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ABSTRACT

Time series of sea-surface temperature in cores sited beneath the region of maximum divergence centered on 10°W are characterized by two sets of periodic signals. The dominant signal is centered on a period of 23 Ky and is coherent with and lags, ~2.5 Ky, the precessional component of orbitally controlled insolation. The subdominant periods occur between 4.0 and 2.5 Ky. Both sets of signals record variation in the seasonal intensity of oceanic divergence modulated by variation in tropical easterly intensity. The longer periods are a response to precessional forcing. The forcing responsible for the shorter periods is unknown.

INTRODUCTION

Direct response of climate to insolation forcing is well documented for the annual cycle (1). Evidence from the geologic record indicates that orbital variations of insolation control climate at the primary periods of eccentricity, obliquity, and precession (2). Between the annual cycle and orbital cycles there is an interval where evidence and hypotheses for solar control are uncommon yet tantalizing. Historical evidence, the Maunder and Sporer minimums in sun-spot number, indicates the inconstancy of the solar constant (3) but is too short a record to establish cyclicity. The geologic record contains cycles that fall within the interval, e.g. oscillations in alpine glacier extent (4) and ice accumulation on Greenland (5) both with estimated periods around 2.5 Ky. To date, there is neither acceptable cause nor mechanism to explain the signals in these short continental records. Signals from long continuous records in ocean sediments have supplied the best proofs of orbital control of climate (6,7,8). In these long records cycles with periods lower than the orbitals have been discerned (9). This paper describes the signals generated by a known oceanographic response to climatic forcing over an interval of 200 Ka.

DATA BASE

When ignorant, one must work with the best known and most responsive system available. The climate/ocean system response to annual insolation forcing for the turbulent boundary layer of the Equatorial Atlantic is well documented. Asymmetry of continent and ocean configures the tropospheric structure such that the southern hemisphere tropical easterly winds extend into the northern hemisphere for much of the year (10). Sea surface temperature, SST, is cool due to upwelling/divergence at and south of the equator. This diminishes cloud cover and enhances radiative heat gain in the south Equatorial Current, SEC, (11). The strong seasonal variation in the forcing winds, the tropical easterlies, produces a fluctuating equatorial system (12,13,14). In boreal summer, June-September, strong southern tropical easterlies invade the northern hemisphere and the Inter Tropical Convergence Zone is furthest from the equator. Along the equator, divergence, SEC speed, and thermocline slope are all at their maximum, SST in the eastern equatorial Atlantic is at its minimum, and the sea surface slopes upward to the west (14,15,16). The water transiting the SEC warms (17,18) and forms the heat reservoir of the western Atlantic/Caribbean.

In boreal winter (December-March), the southern hemisphere tropical easterlies are weak and part of the equatorial surface water piled up in the west flows back as countercurrents (19).

Divergence, thermocline slope, and SEC speed are minimal, and SST is at its annual maximum. Thus the SEC and its attendant features have two quite different seasonal aspects. In terms of the TBL and attendant biota, the system is forced by changes in annual insolation which controls tropical easterly wind zonality and Ekman divergence. These, in turn, produce marked variations in the planktonic community whose remnants provide the proxy of climate/oceanographic change.

Statistical-dynamic models developed for and applied to equatorial oceanography (20,21,22,23,24,25,26,27,28) support observational data with respect to the seasonal response of the equatorial Atlantic. The westward-flowing SEC is tropical easterly forced and responds essentially in phase with tropical easterly variations. The maximum change in the TBL is centered on 10°W.

The annual response of the TBL to tropical easterly control is a model applicable to orbitally forced variations. The stronger the Hadley circulation, the more intense the zonal velocity of the tropical easterly winds. This leads to greater Eckman drift and increased equatorial divergence. For times of maximum Hadley development, there is a decrease in the meridional wind vector, with a concomitant increase in aridity in Africa (10). This scenario has been documented for the last glacial maximum by CLIMAP (29). Global climate models have been used to simulate the atmosphere of the last glacial maximum (30,31,32,33,34). All show tropical easterly wind zonality as strong or stronger than today, a time when perihelion is aligned with boreal winter. A corollary to this exists in the modeling of the youngest interval when perihelion was aligned with boreal summer. COHMAP Members (35) show in their simulation for 9 ka that the meridional component was stronger while the zonal component was weaker relative to both today and the last glacial maximum at 18 Ka. This circumstantial evidence supports tropical easterly modulation of divergence.

When perihelion is aligned with boreal summer, summer insolation is at a maximum over North Africa and the monsoon dominates. The result, at the equator, is a time of minimal divergence, productivity, and seasonality, with the warmest equatorial SST. This is depicted in cartoon form in Figure 1.

When perihelion is aligned with boreal winter, the southern hemisphere tropical easterlies dominate. The result, at the equator, is a time of maximum divergence, productivity, and seasonality, with the coolest SST (Fig. 1).

Three deep-sea cores, RC24-07 (1° 20.5'S, 11° 53.3'W) and RC24-16 (5° 2.3'S, 10° 11.5'W), sited beneath the zone of maximum variation centered on 10°W and V30-40 (0° 12.0'S, 23° 09.0'W) west of, but still within, the region of maximum divergence document the orbital control of equatorial oceanography (7,8). The signals of planktonic organisms that inhabit the TBL and presented here as estimated SST show marked cyclic character (Fig. 2). Spectra of these signals are dominated by the precessional band centered on 23 Ky which accounts for approximately 49% of the total variance (Fig. 2). The signal indicates that, with increasing zonality of the tropical easterly winds, divergence and thermocline shallowing intensify (lower SST) to reach maxima when perihelion is centered on boreal winter. When perihelion is centered on boreal summer tropical easterlies have minimum zonality and the opposite conditions occur. These signals are coherent and nearly in phase with both the precessional component of orbital variation and boreal summer insolation (6,7).

The presence and dominance of precessional periods is unequivocal; it can be both seen in and quantified from these time-series (Fig 2). In addition, there are variations of lower amplitude and shorter period (higher frequency) but these are overshadowed by the precessional signal. They are particularly evident in the time, 0-100 Ka, when eccentricity modulated precessional forcing is minimal. Are these periodic or aperiodic?

SHORT PERIOD RESPONSE

Eccentricity modulation of the precessional component of orbital forcing is at it lowest over the last 330 Ka between approximately 100 and 0Ka (36). This interval has been extracted from the two cores with the best chronologic control for analysis of short period response. Both V30-40 and RC24-16 contain well defined short period signals within this interval of time (Fig. 3). The time span between peaks was computed and is presented as a stem and leaf display (Fig. 3). The mean value for this computation is 3.0 Ky for V30-40 and 2.8 Ky for RC24-16. Both the signals and the periods are intriguing but are they real or merely an artifact of sample interval and/or data acquisition?

The sampling interval has a mean value of 0.8 Ky and a range of 1.6 to 0.4 Ky based upon the chronology applied to convert a depth series into a time series (see 7 for details of method). Added to this is the age error of +/-1.5Ky involved in the chronologic control (2). The combined error on any one point could produce extreme periods >9 Ky between two adjacent highs or lows. The fact that the periods have the form of a gaussian distribution and half the possible range indicates this is not a valid explanation for the signal (Fig. 3).

These cores were counted by one individual sequentially from youngest to oldest sample. Many of these highs are defined by single data points (7). Is the periodic response a result of counting error in the data? Two pieces of evidence deny this idea. First, many of these levels, chosen randomly, were recounted to determine if counting error alone could produce these short period signals. In all cases the recounted samples agreed within 2% of the original value and without systematic error in time. This is approximately a 5% error in SST estimation and is insufficient to alter signal shape. Second, signal regularity is high, e.g 88% of V30-40 and 80% of RC24-16 signal is regular in terms of high - low - high values within one standard deviation of the mean. Random error as a cause of these signals would have values grouped around 50%. The short period signals are considered real.

The Tukey method of spectral analysis (37), is used for oceanic records because it has proven reliable when applied to records of variable interval (6). However, its output is influenced by strong amplitude. Prewhitening cannot remove, only suppress, the longer periods whose amplitudes are high (like precession) in these cores. Nevertheless, prewhitening does show that there are higher frequencies common to signals intra and intercore. The most significant are found between 4.0 and 2.5 Ky. There is an alternative way to examine the shorter and lower amplitude periods. Computing the first derivative of the time series emphasizes the cyclics of change while minimizing biasing by amplitude. Spectral analysis of the times series of the first derivative give weight to the regularity of response rather than the amplitude, i.e. significance depends on the periodic dominance of a period (Fig. 4). Spectral analyses of the proxy times series and the derivative time series document the presence of these short periods in both data. The periods between 3.5 and 2.5 are significant.

CONCLUSIONS

There are at least 2 sets of significant periods recorded in these cores. Those correlated with the primary orbital period of precession dominate the signals and indicate that the equatorial Atlantic responds to insolation forcing by the precessional component of orbital variation. They can be explained by the intermediary mechanism of the tropical easterly control of TBL dynamics described here and in McIntyre *et al* (7). A second set of periods, subdominant in terms of time and amplitude, indicates that this sensitive region of the ocean oscillates at much shorter periods that fall between the primary orbital and the annual periods. The character of these short periods indicates they are a response to the same type of TBL dynamics as are the longer periods, i.e. tropical easterly modulation. The force that produces these short periods remains a mystery.

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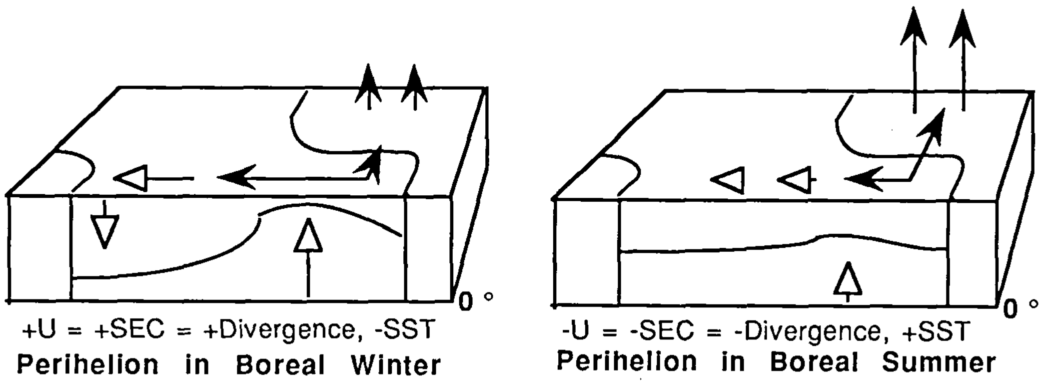
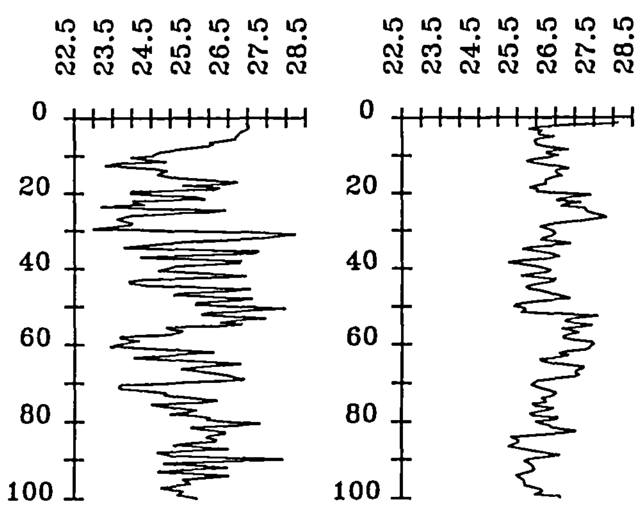


Figure 1. Cartoon of the response of the turbulent boundary layer, TBL, of the equatorial Atlantic to the annual extremes (boreal summer and boreal winter) of precessional forcing. The front of the cartoon represents a cross section of the TBL along the equator and the curved line indicates the position of the thermocline. Solid arrows are wind, open arrows are ocean motion. When perihelion is centered on boreal summer, the zonal, U, component of the southern hemisphere tropical easterly is decreased relative to the meridional. The result is a decrease in SEC velocity, seasonal divergence, and an increase in SST. Aphelion in boreal summer yields the opposite effect.



Ky	0.1 Ky	
1	.4 6 6 7 7 7 8	
2	.0 0 1 2 2 4 4 5 5 5 5 5 6 6	
3	.0 0 0 1 7 7 7	
4	.2 9	V30-40
1	.4 6 7 8	RC24-16
2	.1 2 4 4 4 5 6 6 7 7 7 9	
3	.5 6 6 6 6 7 8	
4	.0 7	

Figure 3. Time series for cores V30-40 and RC24-16 over the interval of time where eccentricity modulation of precession is minimal. In this time interval high-amplitude short-period response is not masked by the strong precessional signal. The time interval between prominent peaks has been measured and is displayed in the stem and leaf display below the time series. The mean values for cores V30-40 and RC24-16 is 3.0 and 2.8 Ky respectively.

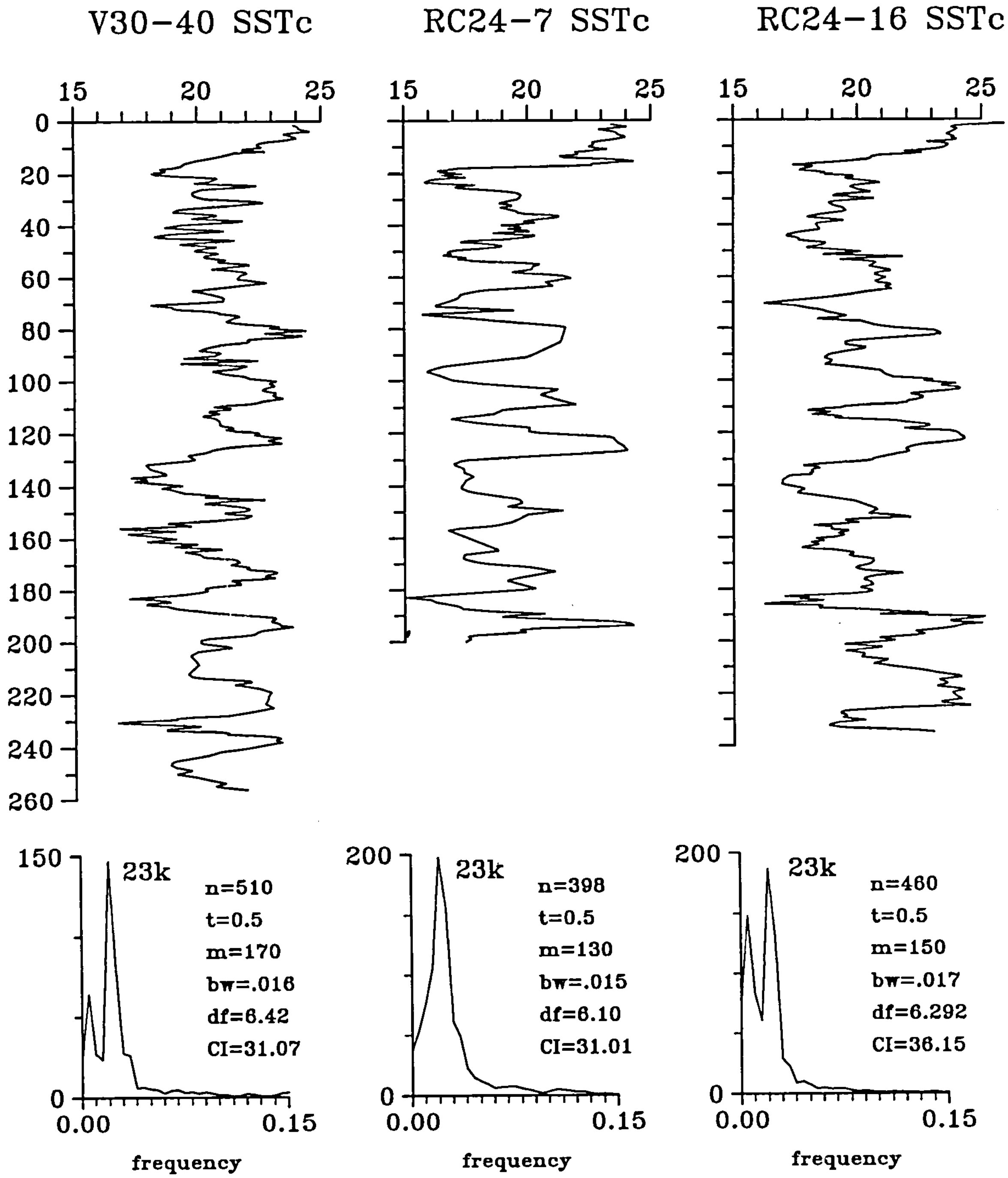


Figure 2. (a) Time series of estimated SST in three deep-sea cores from the maximum divergence region of the equatorial Atlantic (all data published in 7 and 8). The X axes are °Celcius and the y axes in Ka.(kiloyears before present). (b) variance spectra of SST. Dominant periods in Ky (kiloyears) are indicated. Abbreviations are: n, number of points; int., time interval between points; m, lag (the number of points lagged in the Fourier analysis); BW, bandwidth; df, degrees of freedom; CI, confidence interval for the lower limit. These abbreviation apply to figure 4 as well.

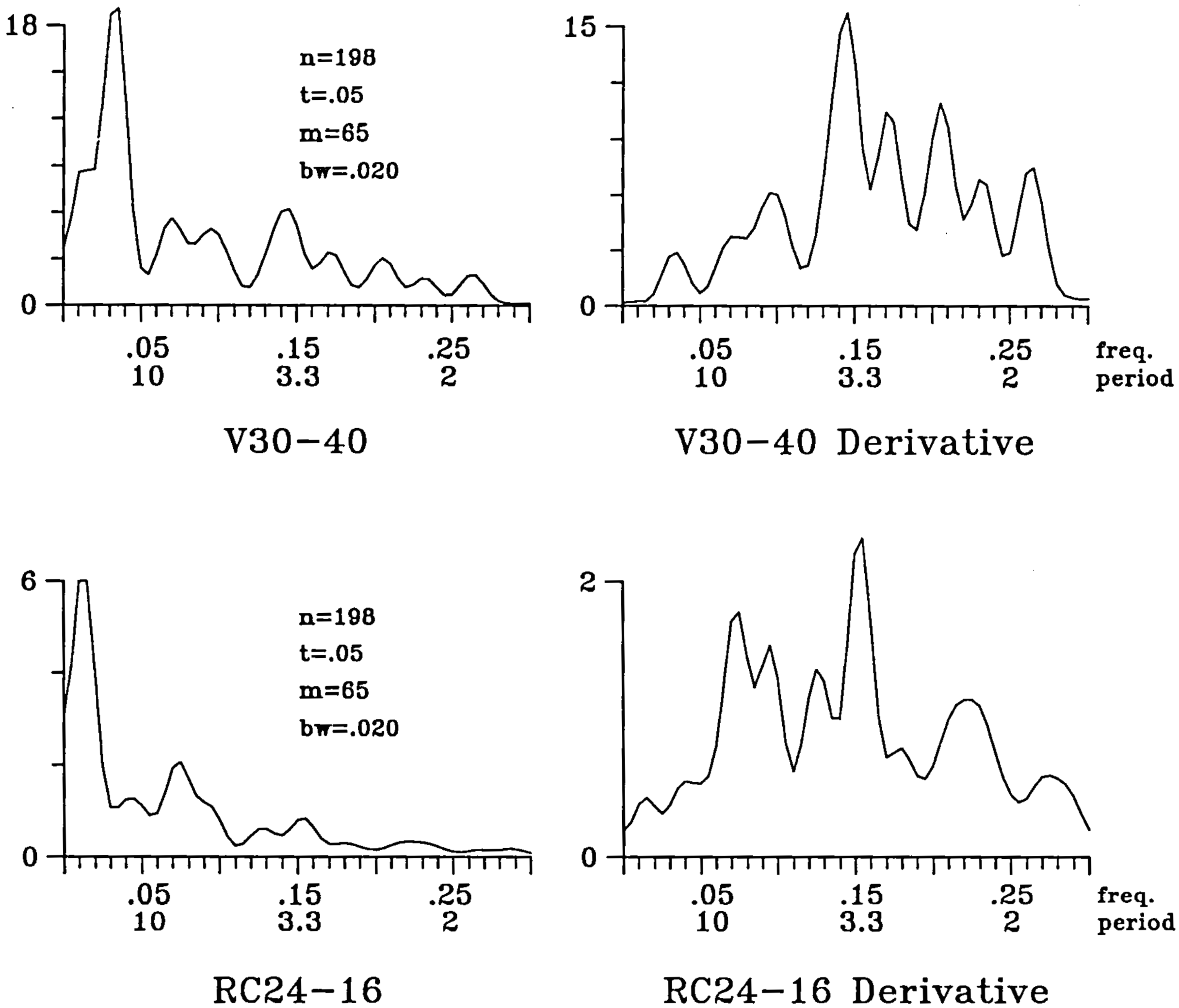


Figure 4. Variance spectra of estimated SST (left) and the first derivative of estimated SST (right) for the interval 0-100Ka from V30-40 and RC24-16. The first derivative enhances the shorter period spectrum by essentially prewhitening the entire series giving a better definition of these short period oscillations.