Acta Oceanologica Sinica 2005, Vol. 24, No. 5, p. 27~34
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Cloudiness regime shift during 1946~1992 recorded by coral in the South China Sea

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Received 26 April 2005; accepted 21 July 2005

Abstract

By extracting and comparing long-term trend components of coral gray value, sea surface temperature, cloudiness, and net heat flux for the period of 1946~1992, the relationships among them are addressed. There exists a prominent regime shift in the cloudiness associated with the corresponding variabilities of sea surface temperature and net heat flux occurred in the mid-1960s, which can be successfully recorded by coral gray value, a climatic proxy. Long-term cloudiness variations in the South China Sea are completely opposite to the equatorial western Pacific in the past five decades, whereas they share a similar trend to that over Asian monsoon prevailing waters. The fact that the coral gray value is highly correlated to cloudiness provides a unique perspective on utilizing this coral to study cloudiness variations in the pre-instrumental period.

Key words: coral gray value, cloudiness, regime shift, South China Sea

1 Introduction

Corals from the tropical oceans are the well-known paleoclimate proxies that offer both the high-resolution and multi-century record length needed for quantification of seasonal to centennial variations. Most corals build skeletons of aragonite ($CaCO_3$) and grow at rates of millimeters to centimeters per year (Sun et al., 2002). During growth, annual density bands are produced in the skeleton that shows time markers for the development of chronologies (see Fig.1). Coral skeletons may provide much useful information on environmental changes over the past several centuries in a region. Most of these records reveal surprisingly large variability at decade to century time scales (Cobb et al., 2001; Boiseau et al., 1999). Climate change has been the principal subject of extensive research because of the profound social and economic consequences. As instrumental climate records are too short to fully reflect the long-term climatic variability, in recent years, the coral-based climate reconstruction has become an increasingly important consideration with regards to our understanding of the climate variability, e.g., the El Niño–Southern Oscillation (ENSO) phenomenon (Charles et al., 1997; Zinke et al., 2004), the Asian monsoon (Klein et al., 1997; Charles et al., 2003), the North Atlantic oscillation (Felis et al., 2000), and the Pacific decadal oscillation (Gedalof and Mantua, 2002), and so on.

Studies on the coral *Porites* in the South China Sea (SCS) indicate that the coral growth rate is highly and linearly correlated to SST (Nie et al., 1999; Sun

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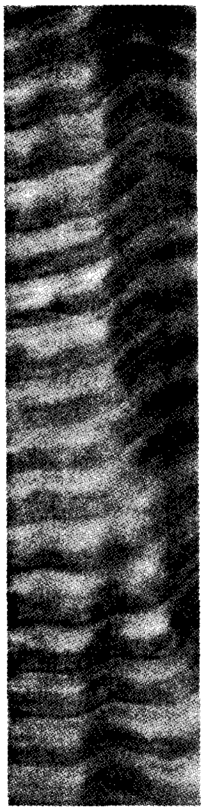

Fig. 1. X-radiograph of part coral core. This coral was collected at Yongxing Island, SCS, from a 2.5 m high specimen of *Porites lutea*. It reveals annual variations in coral skeletal density.

et al., 2002; Shi et al., 2004). It has been successfully applied to make the coral-based SST reconstruction demonstrate its variations in the pre-instrumental period (Nie et al., 1999). However, most previous studies concentrated on stable isotopes (e.g., $\delta^{18}O$, $\delta^{13}C$) and/or chemical indicators (e.g., Sr/Ca, Mg/Ca). However, the coral gray value, manifestations of the coral growth density (Knutson et al., 1972), has received less attention in the climatic research, which provides the motivation for this study. In this paper, we tentatively perform gray value analysis of a coral collected from Yongxing Island (16°50′N, 112°20′E), in the SCS. The SCS, located in the central area of the Asian-Australian monsoon system (see Fig. 2), to some extent, plays an important role in the regional and global weather and climate (Ose et al., 1997). It can be inferred from Fig. 2 that cloudiness variations at this site show high uniformities with those in the whole basin, implying that the chosen site is representative. The purpose of this study is to examine whether coral gray value variability can capture the local, long-term climate changes in the SCS, in particular about multidecadal variabilities of cloudiness, known as indicative variation of monsoon intensity. And if so, to what extent this effect extends spatially. Here we just focus on trend components during the period from 1946 to 1992.

2 Data and method

In June 1994 a 2.5 m long section of continuous coral core was retrieved from a colony of *Porites lutea* growing on the fringe reef areas on the northwest side of the Yongxing Island at a depth of 10 m. In the present study, we focus only on the specimens during the period from 1937 to 1992 to match the meteorogical parameters on record. The time series of coral gray value is generated by standard techniques (He et al., 2000; Sun et al., 2002), with 50 samples per year. Seasonal anomalies of coral gray value are obtained by removing the climatological annual cycle. For illustrating the long-term climatic variability in the SCS, and for determining its relationship to coral gray value variations, monthly mean sea surface temperature anomaly (SST), cloudiness anomaly (CLD), and net heat flux anomaly (NHF) from COADS (Silva et al., 1994) are analyzed. All COADS data extend from 1945 to 1993. The NHF from the atmosphere to the ocean is generally positive downward.

In order to get long-term trends of the above-mentioned variables, singular spectrum analysis (SSA) is employed as it allows us to get robust estimations of trends and quasi-periodic components (Ghil et al., 2002). The SSA has been applied extensively to the study of climate variability as well as to other fields (Charles et al., 1997; Boiseau et al., 1999). It is a fully non-parametric analysis technique based on the principal component analysis of delayed coordinates in a vector space for a time series. It uses lagged copies of a time series to calculate eigenvalues and eigenvectors of their covariance matrix, and the reconstructed components are then calculated to produce their different frequency components. In addition, correlation and regression analyses are used to explore the connections among the long-term variations.

3 Results

3.1 Long-term trend of coral gray value

The SSA was applied to the lagged-covariance matrix with a time window of 16 a. In Fig. 3a, there is a clear grouping of the first nine eigenvalues followed by the remaining eigenvalues, which form the mildly sloping and flattening out "tail" of the SSA spectrum. The leading nine eigenvalues are grouped into three pairs (λ_3 and λ_4, λ_6 and λ_7, and λ_8 and λ_9) according to the criteria suggested by North et al. (1982), and each pair of eigenvalues is approximately equal, representing oscillatory modes (Vatuard et al., 1992). Here we consider the first two significant and separate eigenvalues as the trend components accounting for about one-third of the total data variance. The empirical orthogonal functions (EOF) corresponding to the first two eigenvalues are calculated. Projecting the time series onto each EOF yields the corresponding principal components (PCs). Both PC1 and PC2 contain a long-term, highly nonlinear trend of the data (figure omitted). We can extract the trend component displayed in Fig.3b from the original time series based on reconstruction. The long-term variability of coral gray value is characterized by a decreased trend beginning in about 1950, while, since the mid-1970s, it becomes slightly increased. The non-uniform trend of coral gray value also appears to shift between high and low states occurring in the mid-1960s.

3.2 Relationships among the trend components

To describe the local long-term climate variability in the SCS, we also employed the SSA to SST, CLD, and NHF anomalous time series averaged in a 1° latitude by 1° longitude grid centered on Yongxing Island with a time window of 12 a. Figure 4 depicts the trend component of each variable. It is shown that the profile of the monthly SST, cloudiness and net heat surface anomalies also exhibit a non-uniform trend or a notable shift over the past 50 a. The trends of the SST, CLD and NHF capture 7.2%, 13.8%, and 53.3% of their total variances, respectively. From the observed trends of meteorological parameters, it can be obviously detected that the regime shift, defined as a transition from one climatic state to another, occurred in the mid-1960s, which corresponds to the shift of coral gray value record.

In association with the regime shift in the 1960s, cooling and warming were observed in the trend component of SST shown in Fig.4, which agrees well with the result reported by He et al. (2000). Cloudiness shift in the same region exhibits long-term changes corresponding to the shift of SST. Correspondence between cooler/warmer SST and less/more cloudiness is apparent. The local relationship between the SST and cloudiness has been argued in a variety of contexts for several decades (Graham and Barnett, 1987; Xie, 2004). In terms of the role SST acts in forcing atmospheric convection, it can be interpreted as a consequence of the reduced/enhanced convection induced by cooler/warmer SST (Graham and Barnett, 1987). The local relationship between the trend components of SST and net heat flux is reversed with negative/positive SST anomalies collocated with a downward/upward net heat flux. It is reasonable to assume that, with respect to the long-term variability, the net heat flux is not the driving force to SST variations, and there must be a net inflow/outflow of cold/warm water into the research area. That is, the SST long-term trend variability in the research region is probably regulated by ocean dynamics, which has been proved on interannual time scales (Wang et al., 2002). A detailed investigation of it is beyond the scope of this study. In compari-

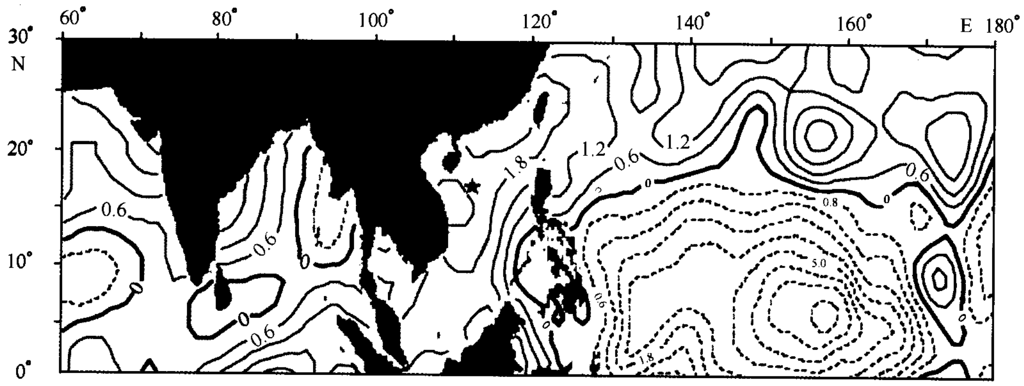

Fig. 2. Map of the SCS and surrounding Indian—Pacific Oceans with the location of the coral core within the lagoon off southwest Yongxing Island, marked by a green star. Contour lines show cloudiness difference for the period of 1966~1985 minus the period of 1946~1965, with dashed lines for negative values.

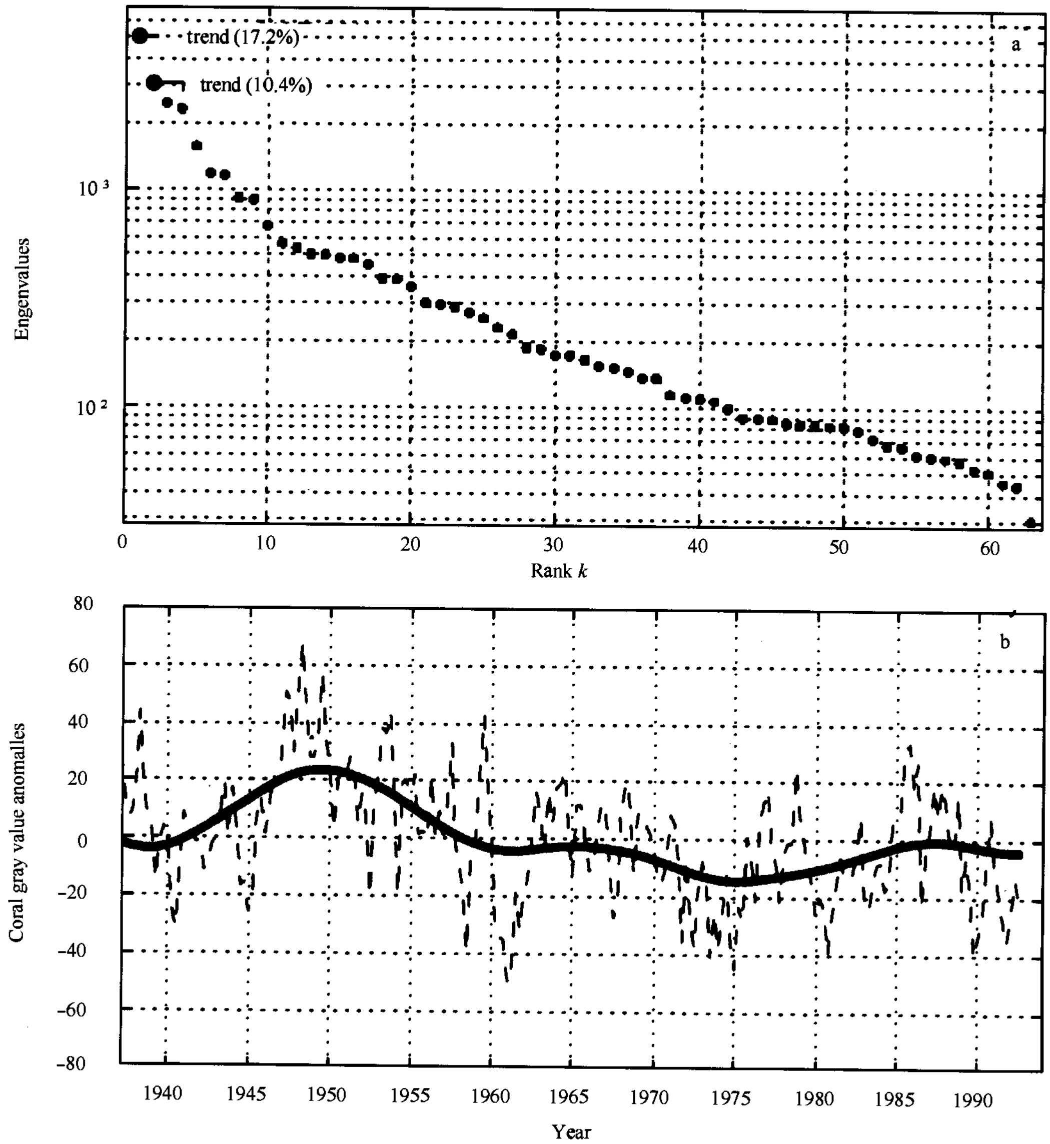

Fig. 3. Singular spectrum of the seasonal time series of coral gray value with the eigenvalues plotted in decreasing order (a), and the reconstructed trend component based on leading two modes, superimposed on the original seasonal anomalous time series (b).

son with the cloudiness variations, it is assumed that long-term net heat flux changes are dominated by the incoming solar radiation due to the associated cloud systems. The results discussed above present evidence to support the fact that the cloudiness regime shift, occurring in the mid-1960s similar to the coral record, is prominent in the SCS.

Further analysis indicates that there is a weak negative correlation between the coral gray value and SST (figure omitted). However, the coral gray value is more correlated to variations of cloudiness and net heat flux based on the correlation and regression be tween them. Figure 5 is a scatter diagram of annual mean cloudiness anomaly and net heat flux anomaly versus coral gray value anomaly, with the regression line plotted on, respectively. The coral gray value and local cloudiness correlate at about –0.4, and the local net heat flux correlate at about 0.5. The correlation coefficients are significant at the 99% level based on 45 freedom degree (±0.28), which means that the coral gray value is closely correlated to the sunlight influenced by cloudiness. To a large extent, it is confirmed that the long-term trend of coral gray value can record the cloudiness regime shift.

In order to get some ideas of to what extent spatially this coral reflects cloudiness variations, we construct a regression map of cloudiness anomalies relative to the trend component of coral gray value. The pattern obtained from the regression map is identical to that in Fig.2 except the opposite signs, which demonstrates a seesaw structure with the negative and positive centers located in the SCS and the equatorial western Pacific, respectively (see Fig.6). In the scenario of both Figs 2 and 6, compared cloudiness variability after and before the shift, it increases in the SCS as well as in the Bay of Bengal, while it decreases in the equatorial western Pacific, which agrees well with the conclusion reported by Wielicki et al. (2002). Therefore, this coral gray value record can be used as a reliable indicator to reflect the cloudiness regime shift in the whole SCS.

4 Concluding remarks and discussion

The objective of this study is to examine whether the coral gray value record at the selected location carries the local long-term climatic information. The primary issues addressed in this study involve determining: (1) the long-term trend of coral gray value; (2) the local long-term climatic variations; and (3) the possible relationships among them. The coral record from the Yongxing Island in the SCS shows a remarkable, non-uniform long-term trend based on the SSA exploited to the gray value record for the period of 1937~1992. Over the full record, the long-term trend presented in the seasonal coral gray value manifests itself as an apparent regime shift occurring in the mid-1960s. In general, the coral gray value before the 1960s is substantially high, but relatively low after the 1960s. Cloudiness associated with SST variations also shifts in the mid-1960s on the principle that enhanced/reduced cloudiness reflects a response to warmer/cooler SST through convection. The synchroneity of the shifts in both cloudiness and net heat flux implies that the long-term net heat flux changes here are primarily influenced by solar radiation variations induced by cloudiness. The fact that the shift contained in the seasonal coral gray value record appears to be mainly associated with the corresponding shift displayed in local cloudiness variations, demonstrates that this coral record successfully captures the long-term behavior of cloudiness, therefore suggesting a possible use of this coral to study cloudiness variations in the pre-instrumental period. Long-term cloudiness variations in the SCS and the nearby monsoon regions are obviously opposite to those in the equatorial western Pacific in the past five decades. The cloudiness regime shift in the SCS expresses itself at a slightly lower state before the mid-1960s and at a higher state after the mid-1960s.

Cloudiness in the SCS experiences a smoothly decreased tendency from the mid-1970s to the 1990s. Apparently it cannot be fully attributed to local SST

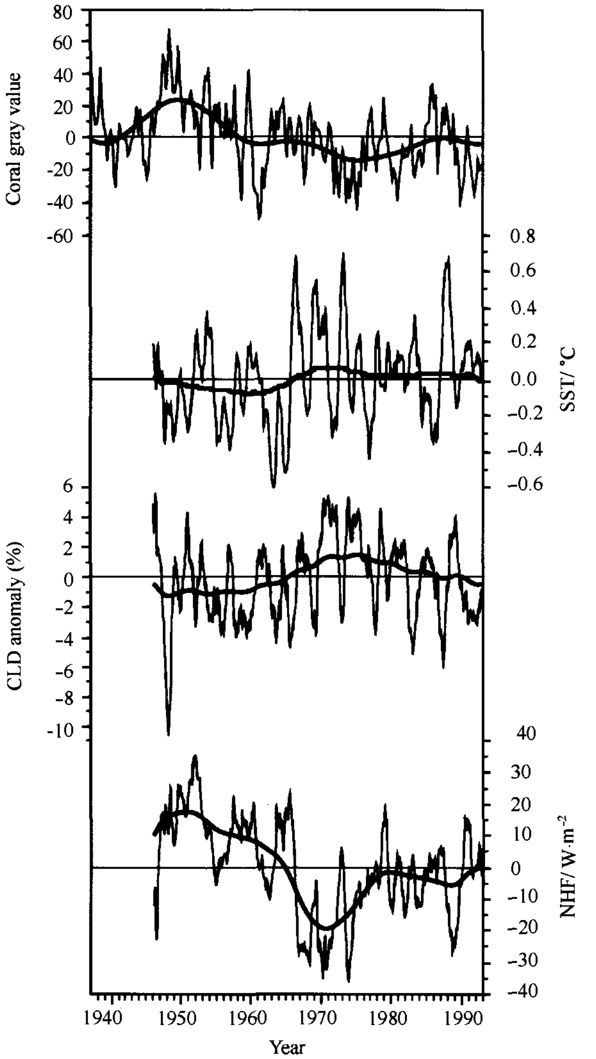

Fig. 4. Coral gray value, SST, CLD, NHF anomalous time series (black line) with respective long-term trends superimposed (red line). Prior to the SSA, the monthly SST, CLD and NHF anomalies were preliminary filtered by the 12-month running mean.

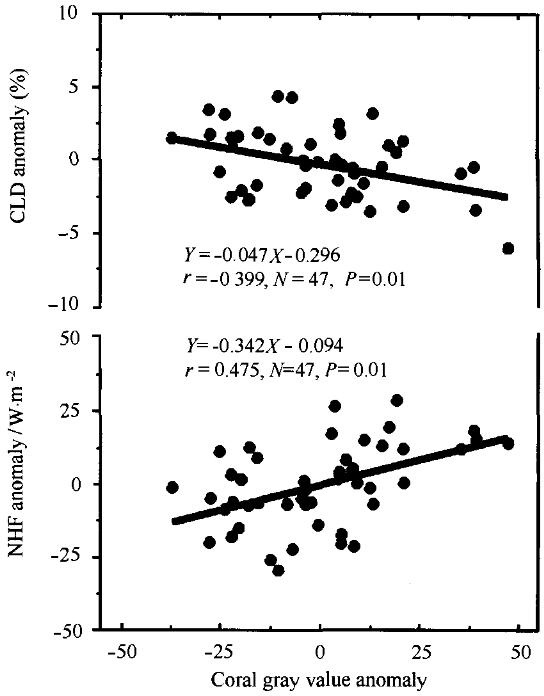

Fig. 5. The regression plot of the annual mean coral gray value anomaly and the observed annual mean cloudiness anomaly (upper) and net heat flux anomaly (lower) from 1946 to 1992. The equation represents the regression line and r is the correlation coefficient, respectively.

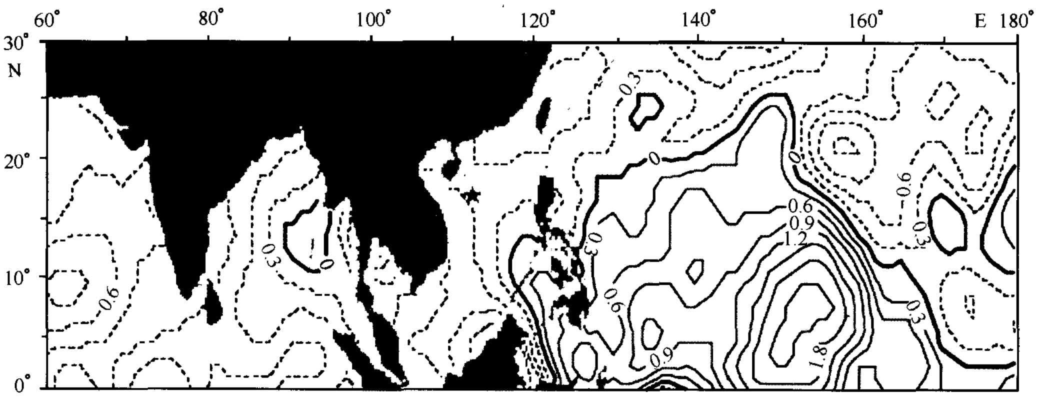

Fig. 6. Regression map of cloudiness and coral gray value trend time series for the period of 1946~1992. Values have been enlarged by 100.

variations (see Fig.4). One convective explanation is the impacts exerted by the weakened monsoon activities in recent years. On the one hand, it might be interpreted as the weakened summer monsoon activities from the mid-1970s (Wang, 2001). On the other hand, it might possibly link to the Arctic oscillation (AO) phenomenon, which displays an increasing tendency from the 1970s (Wang et al., 2005). It has been documented that there is a significant out-of-phase relationship between the East Asian winter monsoon and the AO through its influence on the Siberian high (Li, 2005). As illustrated by Chang and Lau (1980), weakened winter monsoon causes less convection associated with the cold surge. Of course, further studies are necessary to identify the specific physical mechanism responsible for the long-term variability of cloudiness in the SCS.

Acknowledgements

This research was supported by the National Natural Science Foundation of China under contract Nos 40136010 and 40305009 and the Guangdong Science Foundation under contract No. 04001308. The authors thank the anonymous reviewers for their comments and suggestions.

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