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Cool water brought by upwelling in the Sanya Bay benefits corals in the background of global warming

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Abstract

It has been reported that global warming has negative effects on coral ecosystems in the past 50 years and the effects vary in different ocean environment. In order to make clear the coral reef status in the background of global warming along the south coast of Hainan Island of China, satellite and *in situ* data are used to retrieve the information of the coral reef status and surrounding environmental factors. The results show that cool water induced by upwelling along the south coast of Hainan Island is found in the area every summer month, especially in the relatively strong El Niño years (2002–2003 and 2005). From the NOAA satellite data, degree heating week (DHW) index does not exceed 3 in Sanya Bay even in the relatively strong El Niño years. By comparison of a coral reef growth rate in the Sanya Bay with respect to El Niño events from 1957 to 2000, coral's growth rate is relatively greater during 1972, 1991–1994 and 1998 El Niño event. By analyzing the environmental factors, it is found that the cool water induced by upwelling may be the main reason for protecting corals from global warming effects.

Key words: cool water, upwelling, corals, degree heating week, Sanya Bay

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1 Introduction

An ocean temperature increase, overfishing and land-sources of sediment pollution were the main reasons for a coral reef ecosystem deterioration. Among these reasons, effects of the ocean temperature increase on coral bleaching were worldwide and far reaching. The El Niño events in 1982–1983, 1987, 1991, 1994, 1996, 1998, 2002–2003, 2005, 2008 and 2010 resulted in the summer ocean temperature being abnormally high in many regions, which damaged coral health (Glynn, 1984; Hoegh-Guldberg, 1999; Berkelmans et al., 2004; Wilkinson, 2008). Especially in the 1997–1998 strong El Niño event, over 80% of the coral reef coverage in the world was bleaching because a sea surface temperature (SST) increased more than 2°C (NOAA, 2010), and the corals in the Caribbean Sea, Great Barrier Reef, and Malaysia were all reported bleaching (Wilkinson, 1998).

In the early 20th century, some Chinese scientists began to notice the effects of an ocean temperature increase on a reef-building coral growth (Ma, 1937). In one of their papers, Ma (1937) regarded that a composition model of growth belt on coral reef bone can be used to deduce the position of ancient equator. In order to find the effects of the temperature on the coral growth, the relationship between the SST and coral *Porites* growth rate in the South China Sea (SCS) was retrieved and found that the relationship can be described as linear, that the correlation can be up to 0.92, and that the absolute error was 0.13°C (Nie et al., 1997). In recent years, the growth rate, density and calcification rate of the reef coral bone were used as basic factors for studying the global climate change.

The direct effects of the ocean temperature increase on coral reef were mainly that (1) decreased oxygen solubility; (2) changed organism metabolism rate, such as calcification, etc, which changed the concentration of different ions in the coral skeleton and ratios of Sr/Ca, Mg/Ca, U/Ca and δ^{18}O that can be used as geochemical indexes to retrieve ocean temperature (Houck et al., 1977; De Villiers et al., 1995; Mitsuguchi et al., 1996; Yu et al., 1999); (3) the increased ocean temperature can damage photosynthesis system II, which resulted in the mortality of both symbiotic and non-symbiotic reef organisms and finally killed zooxanthella, which resulted in coral reef bleaching (Yakovleva and Hidaka, 2004). Examples of such impacts ranged from prolonged reef-flat exposures (Yamaguchi, 1975) to reduced food supplies for suspension feeding populations due to nutricline depression (Robinson, 1985; Glynn, 1990; Gates et al., 1992).

The ocean temperature increase also had indirect effects on the coral reef growth, especially the physical and biological environmental factors, such as (1) the ocean temperature increase can produce calm doldrum-like sea-surface condition, which reduced circulation in reef lagoons (Glynn, 1984), prevented heat diffusing to the surrounding water and correspondingly increased the local water temperature; (2) the increased SST can induce more revolving tropical cyclone formation, which increased the chance of physical storm damage (Robinson, 1985;

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Harmelin-Vivien and Laboute, 1986), for increased turbulence associated with waves and currents generated by cyclones and hurricanes can result in direct physical damages; and (3) intense upwelling following ENSO activity, which brought cool water as well as plentiful nutrients to the upper water body, induced massive dinoflagellate blooms and decreased water transparency (Guzmán et al., 1990), which resulted in coral bleaching and mortality in the eastern Pacific, Panama and Costa Rica (Glynn and D'Croz, 1990). Though a heat stress has direct and indirect effects on the coral living status, however, some studies regarded that heat stress can improve the coral adaptability to adapt the global warming (Carilli et al., 2012).

Cool water, brought to the upper layer by upwelling, internal waves and typhoons, can neutralize high temperature surface water. In recent years, some researches show that cool water induced by upwelling associated with hurricane can have sizeable effects on a coral bleaching recovery. Manzello et al. (2007) provided evidence that hurricane-induced cooling was responsible for the documented differences in the extent and recovery time of coral bleaching between the Florida Reef Tract and the U.S.. Virgin Islands during the Caribbean-wide 2005 bleaching event. Some researchers regard that upwelling can provide refuge for coral survive from high water temperature (Riegl and Piller, 2003). However, other researchers regard that the effects of cool water due to the upwelling do not guarantee refuge for coral reefs in a warming ocean (Chollett et al., 2010), especially in the Caribbean, the upwelling tends to occur from January to March, which does not coincide with the summer period of major thermal stress. Some researches further regard that cold induced acute stress were ultimately more deleterious for the reef-building coral Acropora (Roth et al., 2012).

Along the coast of Hainan Island, the Qiongdong upwelling is typical hydrodynamics in the area, which generally starts in mid summer and lasts for months. It has been shown that Ekman pumping driven by the summer monsoon is the main reason for the Qiongdong upwelling formation, and a wind direction is the key factor for upwelling variation (Guan and Chen, 1964; Jing et al., 2009). However, some researchers regard that cool whirling is the main cause for the Qiongdong upwelling and wind is only the secondary factor (Yu, 1987). Some researchers also show that a topography is an important factor for the upwelling (Su and Pohlmann, 2009). These reasons for the formation of upwelling, whether the wind or topography, can give us some link to forecast the emergence of the upwelling in the area.

These researches are very valuable for us to further study effects of cool water on coral's living status in the Sanya Bay. Along the south and east coasts of Hainan Island of China, cool water induced by the upwelling appears almost in every summer month. However, few studies can be found about the effects of cool-water intrusion on the growth, distribution and living status of coral reef in the area. In this paper, we mainly present the temporal cool-water intrusion induced by the upwelling, the variation of coral species, and growth speed and climate change factors along the east coast of the Hainan Island using satellite remote sensing and *in situ* data. Our first aim is to testify whether cool water induced by the upwelling can protect corals from global warming effect in the area, especially in the Sanya Bay. And the second is to provide the information of coral reef distribution, living status and variation tendency, for researchers to modeling and forecast coral reef variation tendency in the background of the global warming in the area.

2 Data resources and methods

2.1 *Description of the study area*

The Sanya Bay, located in the south of Hainan Island (Fig. 1), was one of the most important bays along the south coast of Hainan Island and was used as study sites in the paper. A large area of fringe reef was found distributed along the coasts of Sanya and about 110 coral species have been found there. Among them, *Porite*, *Favosites favites*, *Acropora*, *Pavona*, *Turbinaria* and *Pocillopora* corals were the dominant species.

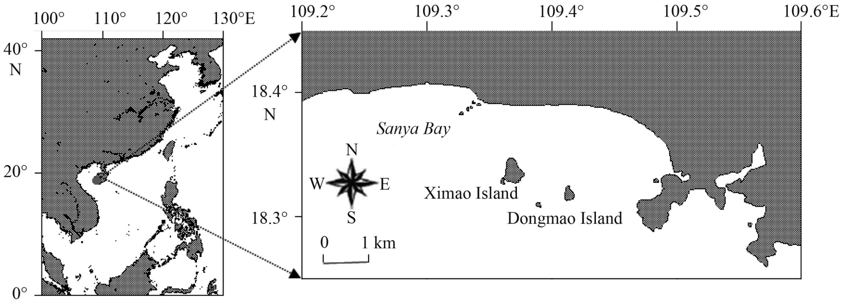

Fig. 1. The Sanya Bay, positions along the south coast of Hainan Province, China.

Along the coast of Hainan Island, the ocean temperatures are different in winter and summer. In winter, due to the influence of the northeast monsoon, the SST is generally 24–26°C, increases progressively from the coast to the outer sea. In summer, due to the influence of the southwest monsoon, the SST is generally 28–29°C (http://mds.coi.gov.cn/).

2.2 *Historical coral species and temperature data collection*

In situ temperature data (0.5 m underwater) was provided by the Tropical Marine Biological Research Station in Sanya of Hainan, Chinese Academy of Sciences and the South China Sea Ocean database. Coral species were mainly from *in situ* observations in 1962–1963, 1975, 1992–1993, 2005 and 2010, based on the historical data of the South China Sea Institute of Oceanology, Chinese Academy of Sciences (Zou, 1975; Yu and Zou, 1996; Zhang et al., 2006; Lian et al., 2010; Zhao et al., 2010; Li et al., 2011). Coral distribution and coverage data are mainly from these *in situ* observation data.

2.3 *Coral growth speed data*

A coral growth speed was measured with X-radiographs. The *Porites* coral skeleton sampled from Xidao Island (XD) and Luhuitou Peninsula (LHT) were sliced and detected with X-radiographs, and the growth speed can be calculated with a growth stripe (Shi et al., 2003). All measurements were controlled and evaluated and the ranges of data were adopted.

2.4 *Satellite SST data*

The SST data are from the MODIS (http://modis.gsfc.nasa.gov/) and NOAA (http://www.noaa.gov/) websites. The NOAA coral reef watch monitors thermal conditions at reef locations around the world using satellite data. These products are produced in near real time at 0.5° (50 km×50 km) resolution, twice each week, and are based on night-time SST values. The 0.5° SSTs are used to make the degree heating week (DHW) index, which combines the magnitude and duration of summertime thermal stress experienced by ocean ecosystems.

SST abnormality and DHWs (Strong et al., 2006) were used as indexes for evaluating coral health (the DHW refers to accumulated thermal stress that coral reefs experience. The DHW being 1 means temperature surpassed monthly-mean maximum 1°C for 1 week. The DHW being 2 means temperature surpassed monthly-mean maximum 2°C for 1 week or temperature surpassed monthly-mean maximum 1°C for 2 weeks.). According to the NOAA's results, the DHW greater than 4 was regarded as coral bleaching alert.

3 Results and discussion

3.1 *Cool-water intrusion in the Sanya Bay based on satellite remote sensing*

The cool-water intrusion brought by the upwelling can be detected with satellite remote sensing data. The SSTs from 2001 to 2010 in the Sanya Bay were obatined from the satellite data and shown in Fig. 2. During the 150th and 270th days of the year, the sea surface temperature is relatively higher and sometimes greater than 30°C, which is about 2–3°C higher than the upper limit of coral-appropriate temperature. However, the higher sea surface temperature only lasted for a short period and then decreased greatly, especially in 2000, 2001, 2006, 2007, 2008, 2009 and 2010. The temperature drop in the area in the summer and autumn season indicates the cool-water intrusion brought by the upwelling. Several days later, the seawater temperature increased again, and maintained for more than one week.

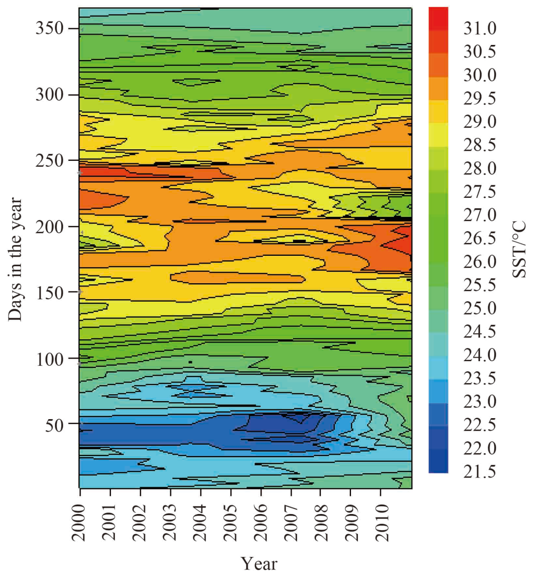

Fig. 2. The SSTs detected by satellite remote sensing from the year of 2000 to 2010 in the Sanya Bay, which shows cool water brought up by the upwelling during summer to autumn.

The pattern of high temperature water and upwelling emergence differed greatly in different years. During the year of 2000–2002, there were two-three times of the upwelling occurrence and the highest temperature sea water emerged in September. During the year of 2003–2007, relatively cooler seawater and high temperature sea water emerged alternately. During the year of 2008–2010, the highest temperature sea water emerged first at the end of June and early of July and then cool water emerged at the end of July and the early of August. These cool waters, though only emerged for a short time (about 10 days), greatly attenuated the negative effects of high seawater temperature on corals.

In order to verify the satellite retrieved results, in situ observations of the seawater temperature are used. Monthly-mean SST data in the Sanya Bay from the year of 2000 to 2003 were obtained based on in situ observation and shown in Fig. 3. The SST in the Sanya Bay was between 23–30°C annually. Water column was mixed and temperatures at bottom and surface were almost the same from each October to the following April. However, a thermocline formed from May to September each year (Fig. 3). In June 2001, the bottom water temperature was 3°C lower than that in May and July, which is the characteristic of cool-water intrusion in the area. Surface water in June 2001 was not affected by cool water. In July 2001, both surface and bottom water temperatures were detected to be lower than those in June, which shows the effects of cool-water intrusion. In July 2002, the cool-water intrusion was also detected and bottom temperature recorded the lowest in the year (23.23°C). In the years of 2000 and 2003, cool-water intrusion was only detected in the bottom water, mainly because upwelling was relatively weaker.

Though the intensity of cool-water intrusion was different in these years, cool water was detected in Sanya Bay every year; in contrast, cool-water intrusion was not always detected in the surface water. These results prove the existence of upwelling in the summer season in the area, though it may not be observed from the SST data.

The SST data from 2002 to 2010 show that the upwelling is mainly distributed along the east and south coasts of Hainan Island and can be validated by Yang et al.'s results (2011). The cool-water intrusion in the Sanya Bay brought by the upwelling occurred almost in every summer month, especially at the end of July and the beginning of August, as shown by *in situ* observations and satellite remote sensing data. This cool water was mainly formed by the upwelling and can neutralize high temperature water in the area. These results indicat that cool water brought by the upwelling in the area in summer months benefit coral health and the corals distributed in the area can be protected from high temperature water induced by El Niño effects.

3.2 *Degree heating week in the Sanya Bay*

The NOAA satellite-derived degree heating week (DHW) is an operational product designed to indicate the accumulated thermal stress that coral reefs experience. In the paper, the DHW in the Sanya Bay from 2001 to 2010 was retrieved. The high DHW was mainly from June to September each year. In 2007 and 2008, the DHW was 0 even in summer month.

The DHW data from 2001 to 2010 are used here to illustrate the global warming effects on the coral reef health. The DHW was less than 3 in the Sanya Bay, even in relatively strong El Niño year (2002, 2005) (Fig. 4). Some researches show that there is no coral bleaching when the DHW is less than 4, a certain proportion of

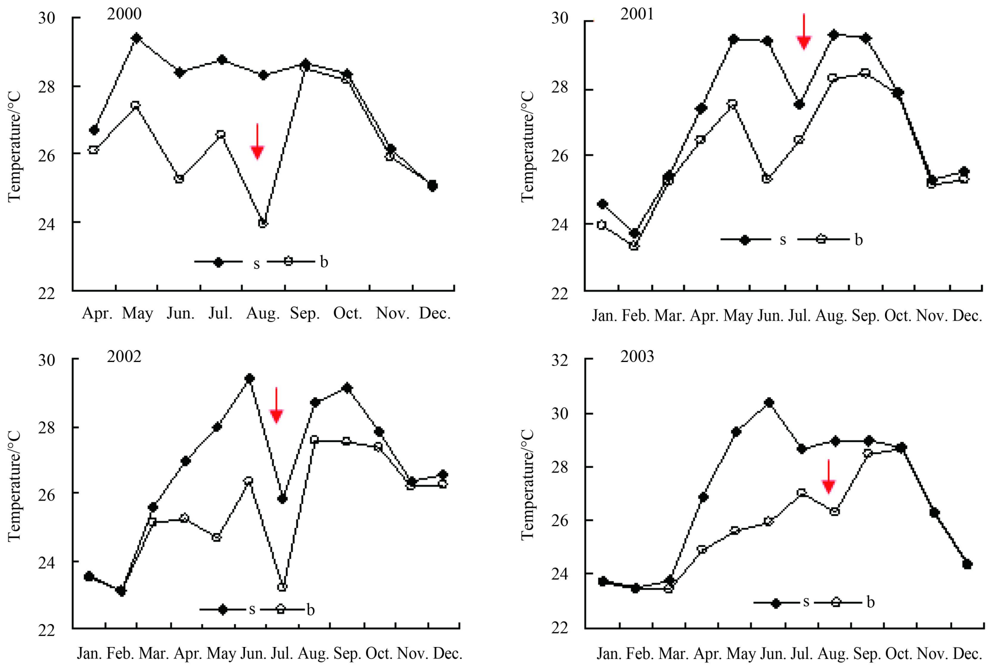

Fig. 3. The monthly-mean sea water temperatures from 2000 to 2003 for validating satellite remote sensing data, showing strong cool water intrusions in 2001 and 2002 in the Sanya Bay. s represents the surface water and b the bottom water.

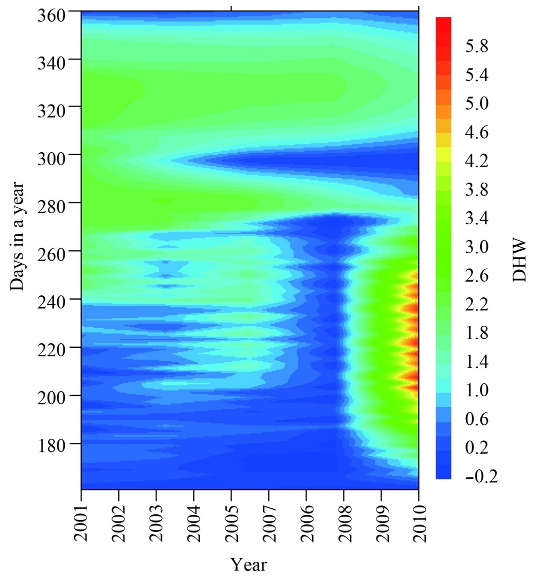

Fig. 4. DHW in the Sanya Bay from 2001 to 2010, showing that the DHW was less than 3 from 2001 to 2009 even in relatively strong El Niño year (2002–2003 and 2005–2006); during 2009–2010, the DHW was relatively higher.

coral began bleaching when the DHW is greater than 4 and majority of coral species began bleaching and died when the DHW is greater than 8 (Strong et al., 2006). From the results of the DHW in the Sanya Bay, the DHW was less than 3 from 2001 to 2009 (Fig. 4), even in relatively strong El Niño year (2002 and 2005), which means the DHW is not up to coral bleaching alert during these years. The DHW being smaller than 3 suggests that global warming has little effect on corals in the area around the Hainan Island.

3.3 *Comparison of coral coverage and growth rate with SST abnormality in the Sanya Bay and JMA SST*

An SST abnormality in the Sanya Bay was retrieved with satellite remote sensing from 2001 to 2011. Compared with the Japan Meteorological Agency (JMA) SST abnormally, the SST abnormally in the Sanya Bay was inconsistence with JMA SST abnormally, especially during strong El Niño events in 2002–2003, 2005 and 2010. SST abnormally in Sanya Bay sometimes show conversely variation tendency with JMA SST abnormally (Fig. 5), especially in 2002–2003. Cool water brought by upwelling may be the main reasons for this inconsistence.

Coral coverage in Sanya Bay was shown in Fig. 5(a). By comparison with the SST abnormality in Sanya Bay and the JMA SST, the coral coverage in Sanya Bay was in the tendency of reduction. No direct relationship can be found between the tendency of coral coverage reduction and the JMA SST, effects of El Niño events on the coral coverage were not evident.

The shortcoming of the comparison was that the times of a coral coverage survey is relatively less. However, from the results of the paper, the tendency of coral coverage variation had no direct relationship with the El Niño events can still be observed.

A coral growth rate was also used in the paper to compare with the JMA SST and found that the strong El Niño events sometimes can facilitate corals' growth in Sanya Bay. *Porites* coral growth rate and the El Niño events was compared for finding the relationship between them. *Porites* coral growth rate was not negatively related to the strong El Niño events (Table 1). In 1972, 1991–1994 and 1997–1998, especially in 1998, the strong El Niño events almost resulted in 80% coral bleaching in the world, however, coral growth rate in the Sanya Bay was almost the fastest (Table 1); which indicats that the strong El Niño events in 1972, 1991–1994 and 1997–1998 El Niño events can facilitate the corals' growth in the Sanya Bay (Shi et al., 2003).

In some El Niño events year, low coral's growth rate can also be observed (Table 1). In the 1982–1983 and 1986–1987 El Niño

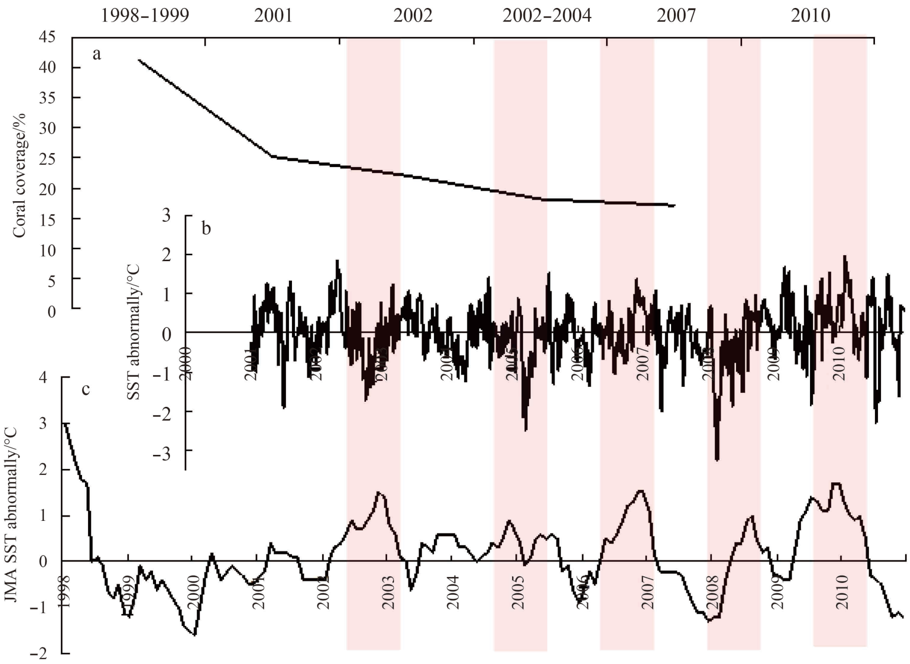

Fig. 5. The comparison of the SST abnormally in the Sanya Bay (b) and that of the JMA SST (c) with coral coverage (a), showing that during strong El Niño events (in 2002–2003, 2005 and 2010), the SST in the Sanya Bay does not increase evidently, i.e., coral coverage also does not correlated with the JMA SST.

Table 1. Statistics of El Niño events effects on *Porites* coral growth in the Sanya Bay

El Niño events year	El Niño events intensity	Coral growth/cm		Coral growth rate
		XD	LHT	
1972	relatively strong	0.65–0.70	–	increased greatly
1982–1983	very strong	0.30-0.40	–	decreased a little, only a little less than the perennial average
1986–1987	relatively strong	0.50–0.60	–	increased, greater than the perennial average
1991–1994	relatively strong	0.53–0.57	0.45–0.50	increased
1997–1998	very strong	0.50–0.70	0.50–0.70	increased greatly

Note: XD is the forth sample gathered at the Xidao Island; LHT the samples gathered at the Luhuitou Peninsula, and – no data.

events year, the coral growth in the Sanya Bay was observed a little less than the perennial average (Table 1).

4 Conclusions

Cool water brought by the upwelling in summer months can be detected evidently with satellite remote sensing and *in situ* observations data. Though the area of the Sanya Bay is frequently affected by anthropogenic activities, some direct and indirect results can be proved that cool water benefits coral reefs in the area. (1) The corals growth rate is positively correlated with the El Niño events especially in the 1998 El Niño year and negative effects of El Niño events on the coral growth can only be found a little lower than perennial average in the 1983–1984 and 1986–1987 El Niño events year. (2) The DHW is smaller than 3 in the area in most years in the Sanya Bay, which suggests that the El Niño effects had little effect on the coral living status in the area. (3) The SST data from 2000 to 2010 show that upwelling mainly occur in summer season along the east coast of Hainan Island, when the sea water temperature of the South China Sea is the highest in the year, which may be the main reason for coral reefs being protected from global warming effects. In a word, cool water brought by upwelling may benefit corals from global-warming-induced bleaching in the Sanya Bay.

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