Temperature Environments during Coral Bleaching Events in Sekisei Lagoon

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Coral reef ecosystems in Sekisei Lagoon, the largest coral reef complex in Japan, suffered from coral bleaching phenomena caused by elevated seawater temperature in 2001 and 2003. To investigate temperature environments during the bleaching events, seasonal changes in 3-m seawater temperature recorded at two fixed survey stations between 1998 and 2003 were analyzed with those in atmospheric temperature recorded at Ishigaki Island. The total number of days of which both daily average seawater temperature and daily average atmospheric temperature exceeded 30°C in 2001 and 2003 were larger than those in the other years. Accordingly the atmospheric temperature data in the past three decades were analyzed using an assumed bleaching subtracted temperature of 30°C and an index that was defined as a sum of the surplus value exceeding 30°C (the accumulated coral bleaching subtracted atmospheric temperature). The results indicated that coral bleaching can occur when a total number of days of which daily atmospheric temperature exceeded 30°C is larger than 30, and the accumulated coral bleaching subtracted temperature is larger than 10.

Key words: Coral bleaching, Sekisei Lagoon, accumulated coral bleaching atmospheric subtracted temperature, prediction of bleaching, thermal tolerance limit

Introduction

The coral reefs of the world have been rapidly declined due to overfishing, coastal development activities, and pollution runoff from terrestrial areas (Jackson *et al.*, 2001). From 1998 onward, coral bleaching phenomena caused by the global climate change became a major threat (Glynn, 1993; Huges, 1994). It is concerned that most coral communities in the world could suffer from periodical coral bleaching and extinct in the next few decades (Hoegh-Guldberg, 1999; Sheppard, 2003).

The mortality of corals by bleaching is due to the loss of symbiotic algae, zooxanthellae, and/or their photosynthetic pigments mainly due to elevated ambient temperature and subsequent chronic photoinhibition (Szmant and Gassman, 1990; Fitt *et al.*, 2001; Dove, 2004; Franklin *et al.*, 2004; Lesser and Farrel, 2004).

Japanese coral reefs were damaged by the mass coral bleaching event occurred in 1998 (Loya *et al.*, 2000; Environmental Agency, 2000). Almost all coral communities in Ryukyu Islands were affected by bleaching (Ministry of the Environment, 2004a). The Ryukyu Islands composed of Okinawa Island, Miyako archipelago including Miyako Island and Tarama Island, Ishigaki Island, Iriomote-Island and many small islands (Fig. 1). Coral mortality attained well over 90% in Okinawa Island (Yamazato, 1999). Remaining coral communities were damaged again by bleaching that had repeatedly occurred in 2001 and 2003 (Kimura, 2003; Ministry of the Environment, 2004a).

Sekisei Lagoon, the largest coral reef complex in Japan, is located between Iriomote Island and Ishigaki Island. The influence of the 1998 bleaching event in Sekisei Lagoon was not as severe as those in Okinawa Islands. Overall coral mortality in terms of coverage was approximately 8% (Environmental Agency, 2000). However, subsequent bleaching events in 2001 (Ministry of the Environment, 2002; Kimura, 2003; Okamoto, 2005a) and 2003 (Ministry of the Environment, 2004b) exacerbated damages on corals. Further deterioration of coral communities is concerned if bleaching occurs frequently in the near future. Also, phase shift of reef communities in Sekisei Lagoon from coral to algae would be realized (Huges, 1994; Hoegh-Guldberg, 1999; Jackson *et al.*, 2001; McClanahan *et al.*, 2001; McCock *et al.*, 2001).

Coral communities in Sekisei Lagoon and its surrounding islands group are thought to be an important seeding population for northern coral reefs that are downstream of Kuroshio current (Furushima and Okamoto, 2002). The significant decrease of live corals in Sekisei Lagoon is likely to affect the recovery of corals and coral reef ecosystems in other areas (Okamoto *et al.*, 2005b). Understanding the process and timing of coral bleaching is important to protect coral communities of wider areas in Japan by taking precautious actions, such as establishment of monitoring program and coral transplantation in Sekisei Lagoon.

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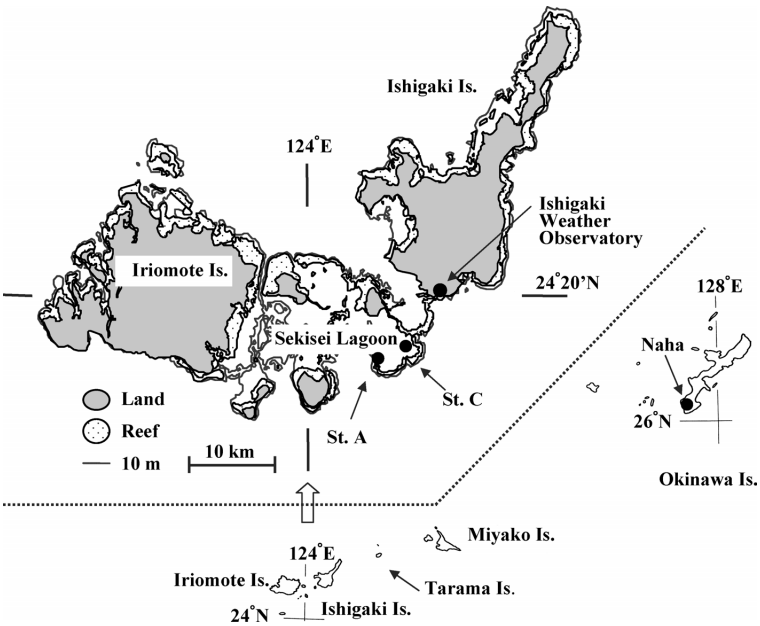

Figure 1. Map of Sekisei Lagoon and location of two survey stations (St. A and St. C) and Ishigaki Weather Observatory.

The authors recorded seawater temperature at two survey stations in Sekisei Lagoon between October 1998 and November 2003. These seawater temperature data were analyzed in combination with atmospheric temperature data in Ishigaki Island to describe their relationship with the recent coral bleaching events. Atmospheric temperature data over the past three decades were also analyzed to extract previous temperature anomalies in accordance with coral bleaching events. In this paper, methodology for prediction of coral bleaching is presented with the explanation of temperature conditions at which coral bleaching occurred in Sekisei Lagoon.

Materials and Methods

Study site

Sekisei Lagoon is a complex of barrier reefs, fringing reefs and small patch reefs that are located between Ishigaki Island and Iriomote Island of Yaeyama Islands in Okinawa, Japan (Fig. 1). The lagoon is ca. 25 km wide in the east-west direction and ca. 20 km long north-south. A large part of reef intersection is sandy bottom with the maximum depth of approximately 15 m. Outer slopes of the northern and southern barrier reefs are rocky down to the depth of 25 m, then sandy in deeper waters.

Data sources

Two temperature survey stations (St. A and St. C) were selected among 26 survey stations that were set up for other study within Sekisei Lagoon (Fig. 1). St. A (24°15.79′N, 124°05.78′E) was in an area of relatively exposed environment, whereas St. C (24°16.18′N, 124°07.26′E) was in

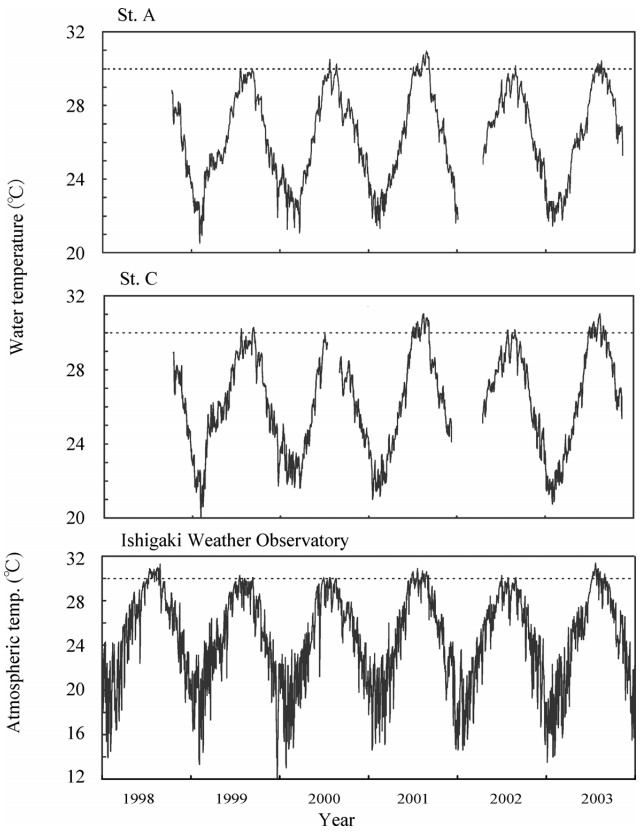

Figure 2. Seasonal changes in daily average seawater temperature recorded at two survey stations (St. A and St. C) and daily average atmospheric temperature recorded at Ishigaki Weather Observatory between 1998 and 2003.

sheltered back-reef area. At each station, automatic temperature loggers (MDS-T, ALEC Electronics Inc.) were fixed at the depth of 3 m below nearly lowest low water to record continuous seawater temperature (hereafter referred to as seawater temperature) at 10 min intervals in the period between October 1998 and November 2003.

A data set of daily atmospheric temperature between 1974 and 2003 recorded by Ishigaki Weather Observatory, was obtained from the Japan Meteorological Agency website. The observatory (24°19.09′N, 124°09.08′E, 5.7 m ALT) is located near the south west coast of Ishigaki Island (Fig. 1).

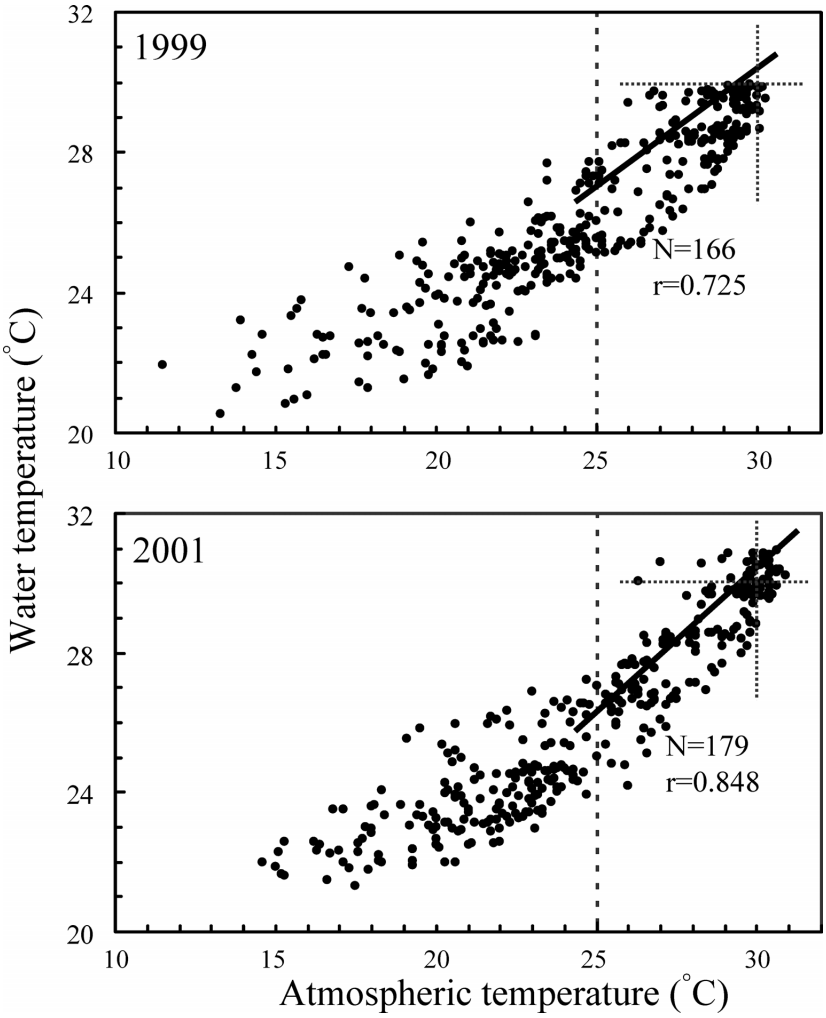

Figure 3. Relationships between daily average seawater temperature and daily average atmospheric temperature in 1999 (top) and 2001 (bottom). Regression lines were obtained from the temperature data of which extracted from the days of average atmospheric temperature higher than 25°C.

Table 1. Correlation coefficients between daily average atmospheric temperature (Atm.) and daily average seawater temperatures at two survey stations (St.A and St.C) from 1999 to 2003. Temperature data were extracted from the days of which average atmospheric temperature higher than 25°C.

	1999	2000	2001	2002	2003	1999–2003
St.A–Atm.	0.725*	0.801*	0.848**	0.752**	0.874**	0.810**
St.C–Atm.	0.751*	0.859*	0.848*	0.773*	0.845*	0.809**
St.A–St.C	0.977**	0.972**	0.940*	0.980**	0.898**	0.933**

*: $P<0.0001$, **: $P<0.001$

Results

Seasonal changes in seawater temperature and atmospheric temperature

Seasonal changes in daily average seawater temperature at St. A and St. C and atmospheric temperature in the period between October 1998 and November 2003 are shown in Fig. 2. Atmospheric temperature in Ishigaki Is. fluctuated widely in winter and early spring within the range between 16°C and 24°C, with the minimum of about 12°C in February. Atmospheric temperature started rising in March, exceeded 28°C in June and attained about 30°C in July, then relatively stabilized until early or mid September. In mid or late September, atmospheric temperature fell below 28°C and gradually decreased until late autumn with moderate fluctuation. Seasonal changes in daily average seawater temperature showed similar pattern to those of atmospheric temperature. Seawater temperature started rising in March from the minimum range between 20°C and 23°C, exceeded 26°C in May, 29°C in midor late June and attained the maximum of about 30°C or higher. Seawater temperature reached the maximum a few weeks later than did atmospheric temperature.

Daily average values of atmospheric temperature were plotted against those of seawater temperature at St. A using the data sets for 1999 (no bleaching) and 2001 (bleaching) (Fig. 3). It is clearly shown that the number of days of which both the atmospheric temperature and the seawater temperature higher than 30°C in 2001 was larger than those in 1999. There was a good correlation between the atmospheric temperature and the seawater temperature in the range where the atmospheric temperature is higher than 25°C. Correlation coefficients between the atmospheric temperature (>25°C) and the seawater temperature at St. A (0.725–0.874) and St. C (0.751–0.859) were all significant ($P<0.001$ or $P<0.0001$, Table 1). Correlation coefficient between the seawater temperature data sets at St. A and St. C was also significant ($P<0.001$).

Analysis of seawater temperature data using coral bleaching subtracted seawater temperature index

Changes in daily average seawater temperature at St. A and St. C in summer months (June–September) from 1999 to 2003 are shown with changes in daily average atmospheric temperature for the same years in Fig. 4. Although atmospheric temperature widely fluctuated with weather conditions such as heavy rain or typhoon, there is a tendency that atmospheric temperature was higher than seawater temperature in June and July and then this relationship was inversed from early August onward. Both atmospheric temperature and seawater temperature exceeded 30°C in 2001 and 2003 (bleaching) more frequently than other years (no bleaching). Coral bleaching is reported to occur in Okinawa Island

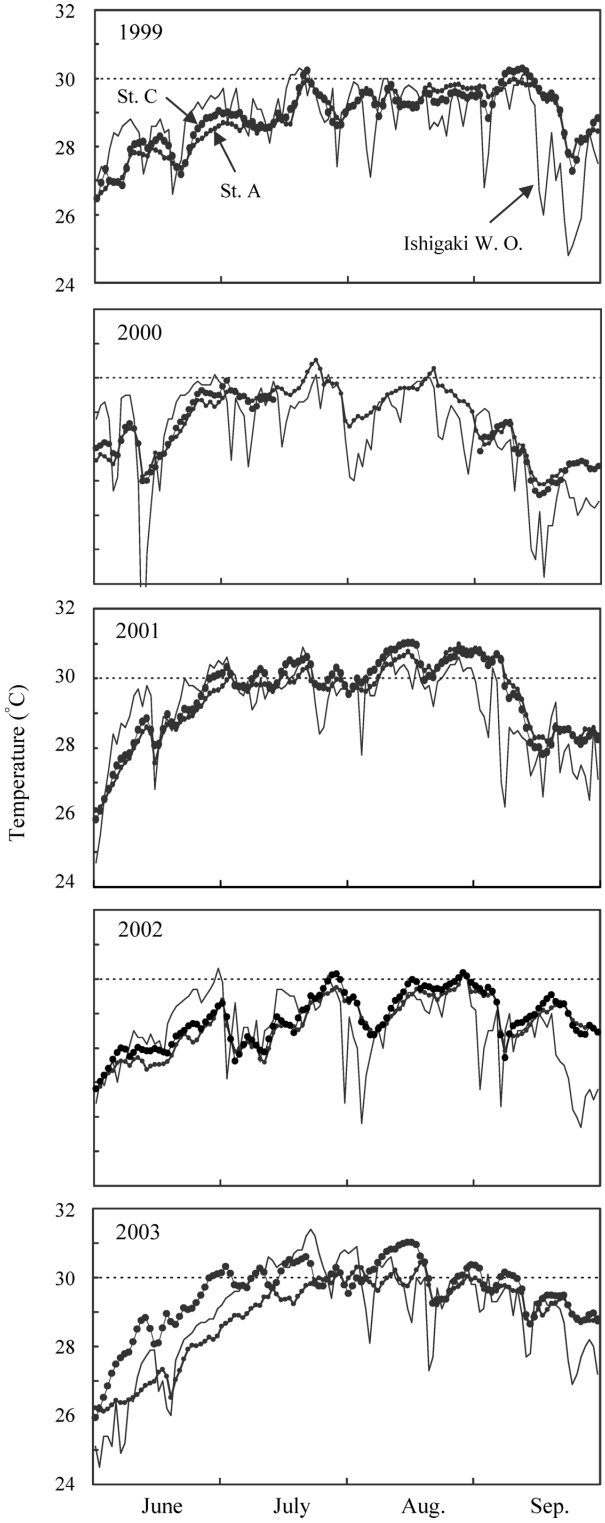

Figure 4. Changes in daily average seawater temperature recorded at two survey stations (St. A, line with small closed circle; St. C, line with large closed circle) and daily average atmospheric temperature recorded at Ishigaki Weather Observatory (solid line) in summer months between 1999 and 2003.

Table 2. Analysis results of seawater temperature recorded at two survey stations (St. A and St. C). MAWT: Monthly average seawater temperature, NDW30: Total numbers of days of which daily average seawater temperature >30°C, Acc. CBSWT: Accumulated coral bleaching subtracted water temperature, Dur. Over 30°C: Duration between the first and the last day on which daily average seawater temperature >30°C.

St. A

Year	MAWT (°C)				NDW30					Acc. CBSWT					Dur. over 30°C (Days)
	June	July	Aug.	Sep.	June	July	Aug.	Sep.	Total	June	July	Aug.	Sep.	Total	
1999	27.6	28.9	29.5	29.1	0	0	0	1	1	0	0	0	0	0	1
2000	28.2	29.7	29.4	27.7	0	4	4	0	8	0	1.4	0.4	0	1.8	31
2001	28.2	29.9	30.4	29	0	7	25	6	38	0	0.8	14.1	3.3	18.2	45
2002	27.6	28.7	29.3	28.8	0	0	2	0	2	0	0	0.3	0	0.3	2
2003	27.1	29.4	29.9	29.2	0	5	15	0	20	0	0.2	2	0	2.2	38

St. C

Year	MAWT (°C)				NDW30					Acc. CBSWT					Dur. over 30°C (Days)
	June	July	Aug.	Sep.	June	July	Aug.	Sep.	Total	June	July	Aug.	Sep.	Total	
1999	27.8	29	29.4	29.2	0	0	0	1	1	0	0	0	0	0	1
2000	28.3	—	—	—	0	—	—	—	—	0	—	—	—	—	—
2001	28.1	29	29.8	28.8	3	19	29	5	56	0.1	5	15.9	3.3	24.4	69
2002	28	28.9	29.5	28.9	0	3	4	0	7	0	0.2	0.3	0	0.5	33
2003	28.4	30.1	30.2	29.3	3	19	23	5	50	0.1	5	10.2	0.3	15.6	74

—: N.A.

when seawater temperatures exceed approximate threshold level of 29.9°C for a certain period (Hoegh-Guldberg, 1999). In this paper, we hypothesize that a tentative threshold in Sekisei Lagoon is 30°C and the number of days of which daily average seawater temperatures higher than the threshold could affect the occurrence of coral bleaching. As the tentative threshold temperature is used to obtain accumulative temperature in this paper, we defined it as subtracted temperature. Subsequent analysis was made using the data for days of which daily average seawater temperature higher than 30°C. An index for coral bleaching was then calculated by deducting 30 from each temperature value (hereafter referred to as coral bleaching subtracted seawater temperature, CBSWT).

Table 2 summarizes the analysis results of seawater temperature data recorded at St. A and St. C between June and September from 1999 to 2003. The number of days of which daily average seawater temperature higher than 30°C (hereafter referred to as NDW30) in 2001 and 2003 were 38 days and 20 days at St. A and 56 days and 50 days at St. C, while NDW30 values in 1999, 2000 and 2002 were 1 day, 8 days and 2 days at St. A and 1 day and 7 days at St. C (2000 data missing), respectively. The accumulated CBSWT values were the highest in 2001 at both St. A (18.2) and St. C (24.4). In 2003, the accumulated CBSWT value was high at St. C (15.6), but the value at St. A (2.2) was similar to that obtained in 2000 (1.8).

Seawater temperature data were not obtained in 1998 when mass bleaching was observed at Sekisei Lagoon, but it was very likely that the temperatures exceeded their normal seasonal maximum. As shown in Figure 4, seawater temperature is closely correlated with atmospheric temperature. The numbers of days of which daily average atmospheric temperature higher than 30°C (hereafter referred to as NDA30) in 2001 and 2003 were 34 days and 35 days, while those in 1999, 2000 and 2002 were less than 10 days (Table 3). In 1998, NDA30 was 45 days, suggesting that seawater temperature at St. A and St. C also exceeded 30°C for a long period.

Analysis of atmospheric temperature data using coral bleaching subtracted atmospheric temperature index

Atmospheric temperature data recoded at Ishigaki Weather Observatory in summer months (June–September) between 1974 and 2003 were analyzed to extract periods in which the temperature exceeded its seasonal maximum. Daily av-

Table 3. Analysis results of atmospheric temperature recorded at Ishigaki Weather Observatory. MAAT: Monthly average atmospheric temperature, NDA30: Total numbers of days of which daily average atmospheric temperature >30°C, Acc. CBSAT: Accumulated coral bleaching subtracted atmospheric temperature, Dur. over 30°C: Duration between the first and the last day on which daily average atmospheric temperature >30°C.

Year	MAWT (°C)				NDW30					Acc. CBSWT					Dur. over 30°C (Days)
	June	July	Aug.	Sep.	June	July	Aug.	Sep.	Total	June	July	Aug.	Sep.	Total	
1974	27.1	29.1	28.4	27.3	0	0	0	0	0	0	0	0	0	0	0
1975	27.8	29.2	28.2	28	0	2	0	0	2	0	0.5	0	0	0.5	2
1976	27.8	27.7	28.9	26.9	0	0	0	0	0	0	0	0	0	0	0
1977	28.3	29.4	28.6	28.3	0	10	2	0	12	0	1.6	0.3	0	1.9	34
1978	28.1	29.2	28.5	28	0	3	0	0	3	0	0.4	0	0	0.4	7
1979	27	29.6	28.2	27.8	0	7	0	0	7	0	1.4	0	0	1.4	8
1980	29	29.8	29.7	28	9	13	13	1	36	2.5	3	4.5	0.1	10.1	78
1981	26.8	28.4	29.3	27.7	0	0	7	0	7	0	0	2.9	0	2.9	12
1982	26.9	29.3	28.3	27.7	0	11	0	0	11	0	1.6	0	0	1.6	12
1983	28.3	30.2	29.4	29.2	1	20	7	2	30	0	7.3	3.7	0	11	75
1984	28	29.4	28.7	28.1	0	9	2	0	11	0	1.3	0	0	1.3	23
1985	27.3	28.6	28.2	27.6	0	0	1	0	1	0	0	0	0	0	1
1986	27.7	29.3	29.1	27.6	0	5	2	0	7	0	1	0.3	0	1.3	38
1987	27.3	29.2	29.4	27.3	0	2	4	0	6	0	0.4	0.3	0	0.7	50
1988	28.7	30.2	29.2	28	3	27	11	1	42	0.4	11.1	2	0	13.5	70
1989	28	29.7	29.2	28.2	0	14	4	0	18	0	6.1	0.9	0	7	43
1990	28	29.5	29.1	27.4	0	5	6	0	11	0	1.3	1	0	2.3	26
1991	29.3	30	28.9	28.1	2	21	8	0	29	0.3	3.7	2.9	0	6.9	60
1992	26.9	28.9	29.1	27.9	0	1	11	0	13	0	0.1	3.1	0	3.2	38
1993	28.3	30.1	29	27.7	0	18	9	0	26	0	6.1	1.6	0	7.7	50
1994	28	29.6	28.5	27	0	9	2	0	11	0	1	0.3	0	1.3	41
1995	27.8	28.8	28.9	28.1	0	1	1	0	2	0	0	0	0	0	33
1996	28.8	29.9	28.7	28.1	0	18	0	0	18	0	9.2	0	0	8.5	24
1997	27	28.8	28.7	27.1	0	0	0	0	0	0	0	0	0	0	0
1998	28.2	30.4	29.9	28.3	0	22	23	0	45	0	9.9	15.3	0	25.2	55
1999	28.2	29.2	29.2	28	0	5	2	2	9	0	0.7	0	0.2	0.9	57
2000	28.4	29.5	28.6	26.9	1	2	2	0	5	0.1	0.2	0	0	0.3	52
2001	28.8	29.6	30	28	4	11	18	1	34	1.2	3.7	5.6	0.3	10.8	74
2002	28.4	29	29	27.8	0	2	3	0	5	0	0.4	0.1	0	0.5	59
2003	27.1	30.3	29.6	28.6	0	23	11	1	35	0	12.6	3.9	0.1	16.6	41

—: N.A.

erage seawater temperature at St. A and St. C significantly correlated with daily average atmospheric temperature (Fig. 3, Table 1). It was indicated that both daily average seawater temperature and daily average atmospheric temperature exceeded 30°C more frequently in bleaching years than non-bleaching years (Tables 2 and 3). Therefore the data for days of which daily average atmospheric temperatures higher than 30°C were used for analysis. Indices of bleaching were calculated by deducting 30 from each temperature value. The index is referred to as coral bleaching subtracted atmospheric temperature (CBSAT).

Monthly average atmospheric temperature in summer months in Ishigaki Island between 1974 and 2003 shows several anomaly spikes (Table 3). The warmest year was 1998, in which the monthly average atmospheric temperature of July, August and September were the top three among all data. Both the NDA30 value (45 days) and the accumulated CBSAT value (25.2) were also the largest in 1998 (Fig. 5). The second largest NDA30 value was obtained from the data for 1988 (42 days), followed by 1980 (36 days), 2003 (35 days), 2001 (34 days) and 1983 (30 days). Large accumulated CBSAT values were obtained from the data for the same years, 2003 (16.6), 1988 (13.5), 1983 (11.0), 2001 (10.8) and 1980 (10.1). The duration between the first and the last day on which daily average atmospheric temperature exceeded 30°C in 1998 and 2003

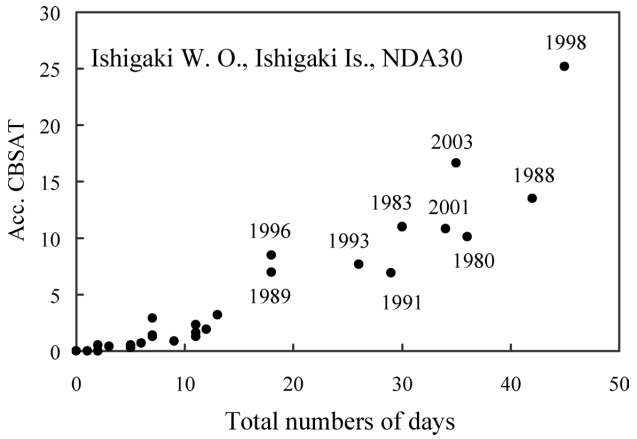

Figure 5. Scatter diagram of NDA30 values (total numbers of days of which daily average atmospheric temperature >30°C) and the accumulated CBSAT values (sum of the surplus values exceeding 30°C daily average atmospheric temperature) recorded at Isgigaki Weather Observatory.

(55 days and 41 days) were considerably shorter than those in 1980, 1983 and 2001 (78 days, 75 days and 74 days).

Discussion

Coral bleaching subtracted seawater temperature in Sekisei Lagoon

The onsets of the recent three bleaching events (years 1998, 2001 and 2003) were almost the same over the entire area of Sekisei lagoon. The accumulated CBSWT value as an index of bleaching was calculated on the assumption that a subtracted coral bleaching seawater temperature was 30°C (Table 2). The accumulated CBSWT values for St. A (18.2) and St. C (24.2) in 2001 were outstanding among all values. The value for St. C (16.5) in 2003 was also large, however, the value for St. A (2.2) in 2003 was similar to that calculated from the data of non-bleaching year 2000 (1.8). The NDW30 value for St. A in 2003 was 20, while the value in 2000 was 7.

The previous records of coral bleaching in Sekisei lagoon

Coral reefs of Sekisei Lagoon have been annually surveyed by the Environment Agency (the Ministry of the Environment) since 1980 in order to monitor the impacts of the crown-of-thorns starfish outbreaks. It was reported that most coral communities in Sekisei lagoon, except for the communities around Kayama Island and Komi Point off Iriomote Island, were devastated in 1984 and subsequent recovery was very slow until 1991 (Mori, 1995). Coral bleaching was recorded in a relatively large scale during the course of the survey in 1983 (Kamezaki and Ui, 1984), but not in 1980 and 1988.

According to the previous survey reports and the recent observation, coral bleaching occurred four times, 1983 (Kamezaki and Ui, 1984), 1998 (Environmental Agency, 2000), 2001 (Ministry of the Environment, 2002) and 2003 (Ministry of the Environment, 2004b) in Sekisei Lagoon. In 1980 and 1988, there were no records of bleaching despite the large accumulated CBSAT values (10.1 and 13.5, Table 3). In the case of 1988, coral bleaching might not be detected because of the sparseness of live corals after the outbreaks of crown-of-thorns starfish. There are only four records of bleaching in the past three decades, however, in the light of the frequency in recent years especially since 1998, it appears that coral bleaching occur when total NDA30 values become larger than 30 and the accumulated CBSAT values become higher than 10 regardless of length of high atmospheric temperatures periods as shown in Table 2 and Fig. 5.

Prediction of coral bleaching

Mechanism of coral bleaching is analyzed by oceanographic survey and biological examination of corals (Berkelmans and Oliver, 1999; Marshell and Baird, 2000; Dunne and Brown, 2001; Nadaoka *et al.*, 2001; Smith, 2001). Prediction of coral bleaching was attempted at several localities mainly by applying SST (Sea Surface Temperature), wind data and so on (Hendee *et al.*, 2001; Berkermans *et al.*, 2004; Wooldridge and Done, 2004).

Sekisei Lagoon is a geomorphologically diverse complex of coral reefs, including shallow moat on the north side of Kohama Island, relatively deep lagoon next to Kuroshima Island, solid barrier reefs off Ishigaki Island and Yonara Channel where strong tidal current passes. In such diverse areas, seawater temperatures are estimated to be varied depends on sites. As shown in the seawater temperatures at St. C, CBSWT value of 30°C seems a good indicator of coral bleaching (Table 2, Fig. 4). But corals at St. A which located 2.6 km WSW of St. C were bleached under the condition of which seawater temperatures slightly exceeded 30°C in 2003. The estimated differences of seawater temperature whole around the Sekisei Lagoon would make confusion to predict coral bleaching by using seawater temperature data. Probably, real-time monitoring of seawater temperature at many sites in the Lagoon is required.

However, a prediction method using atmospheric temperature data in Ishigaki Island enabled to distinguish the years of which the recent bleaching events occurred from the other years. The suggested indicators of coral bleaching are; the total number of days of which daily average atmospheric temperature > 30°C (NDA30), is larger than 30; and the accumulated Coral Bleaching Subtracted Atmospheric Temperature (CBSAT), which is a sum of the surplus value exceeding 30°C, exceeding 10. In the past three decades, daily average atmospheric temperature exceeded 30°C only once or twice in September. The maximum total NDA30

Table 4. Variation of the accumulated CBSAT values of 1998 at Ishigaki Island, Tarama Island, Miyako Island and Naha, Okinawa Island calculated from different coral bleaching threshold atmospheric temperature between 29.4–30.1°C. Data sets of daily atmospheric temperatures in summer months (June–September) of 1998 at Tarama Island (24°39.9′N, 124°41.8′E, 14 m ALT), Miyako Island (24°47.6′N, 125°16.6′E, 40 m ALT) and Naha, Okinawa Island (26°12.2′N, 127°41.3′E, 28 m ALT) were obtained from the Japan Meteorological Agency website.

Site	Threshold atmospheric temperature (°C)							
	29.4	29.5	29.6.	29.7	29.8	29.9	30.0	30.1
Ishigaki	58.7	51.8	45.5	39.5	34.4	29.7	25.2	20.9
Tarama	53.0	47.3	41.7	36.6	31.7	27.4	23.2	19.4
Miyako	28.2	23.0	17.8	13.5	9.8	6.9	4.4	2.4
Naha	33.0	27.8	23.2	19.3	15.5	12.1	9.1	6.9

value for August and September was 23. Therefore it is considered that coral bleaching is unlikely when a total NDA30 value by the end of July is not more than 10.

Coral bleaching was not observed at Sekisei Lagoon In 2004 in which total NDA30 value and accumulated CBSAT value were small (4 days, 0.5). In 2005, severe coral bleaching was concerned, as total NDA30 value and accumulated CBSAT attained 11 and 2.4 by July 15. After July 16, daily average atmospheric temperature exceeded 30°C only once on August 2 due to typhoon passing and subsequent northerly prevailing wind. The NDA30 value and accumulated CBSAT value were small (12 days, 2.4) in 2005. However, minor and localized bleaching was observed in several sites of Sekisei Lagoon in end of July (Nojima S, unpubl. data).

Another important suggestion was obtained from the data analysis by applying various coral threshold atmospheric temperatures at four islands (Fig. 1, Table 4). In 1998 when almost all coral communities in Ryukyu Islands were affected by bleaching, CBSAT value at 30°C of Tarama Island (23.2) was nearly the same as of Ishigaki (25.2). But, the values of Miyako Island (4.4) and Naha, Okinawa Island (9.1) were lower than at Ishigaki and Tarama Island. Threshold atmospheric temperature of 30°C used for the Sekisei Lagoon is thought difficult to apply for another sites of Ryukyu Island. One idea is to use another threshold atmospheric temperature for each Island; for example, 29.5°C for Miyako Island and 29.6°C for Naha, Okinawa Island to obtain nearly same CBSAT value as of Ishigaki. Anyway, information of coral bleaching at Ryukyu Islands is limited even in 1998 event. Systematic survey of coral bleaching phenomena for each coral species with continuous record of environmental condition would be needed to predict coral bleaching precisely. Also, analysis of past coral bleaching event at each sites would be needed to recognize the cause of bleaching.

Conclusion

There is no effective measure to physically prevent coral bleaching even if it is predicted. Prediction of bleaching is, however, a useful management tool for coral reef restoration. The authors are currently undertaking an experimental study on the transplantation of coral juvenile that are cultivated *in situ* using naturally-occurring larvae from a mass-spawning event in Sekisei Lagoon (Okamoto *et al.*, 2005b). As presented in this paper, coral bleaching can be predicted using atmospheric temperature data obtained by the end of July. This enables to relocate cultivated coral juveniles to an area of low seawater temperature for their survival. It is also possible to shift a time of transplantation work to avoid unwanted influence of seawater temperature anomalies. Prediction of coral bleaching using atmospheric temperature data is useful not only for coral reef restoration, but also for other research aiming coral reef management. The cause of three coral bleaching events at Sekisei Lagoon since 1998 is thought to be the elevated seawater temperatures in summer. However, other phenomena, such as terrestrial run-off and so on, has a possibility to accelerate the bleaching. It is important to understand the bleaching mechanisms of coral species in the Lagoon for further management to prevent extinction. The prediction of coral bleaching will enable scientists to make effective research from the early stage of bleaching. Also, the prediction may help to increase the interest for environmental conservation of Sekisei Lagoon especially among leisure divers, fishing diver and peoples who are living around the Lagoon.

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石西礁湖におけるサンゴ白化時の温度環境について

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日本最大のサンゴ礁「石西礁湖」の2定点の3m層水温と石垣島の気温を用い，2001年，2003年に礁湖全域でサンゴの白化が起きたときの状況を解析した．両年は，日平均水温と日平均気温が30℃以上の日が多かった．そこで気温30.0℃を白化差引気温とし，30℃を超えた値の合計を白化気温指数と定義し，過去30年の気温を解析した．その結果，気温30℃以上が30日以上で白化気温指数が10以上の年は，石西礁湖で広域の白化が起きる目安になると判断された．この手法は近隣の島々での白化予測にも利用できる可能性がある．

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