Aust. J. Mar. Freshwater Res., 1994, **45**, 1149–56

A Survey of Environmental Physico-chemical Parameters during a Minor Coral Mass Bleaching Event in Tahiti in 1993

Jacques H. Drollet[A], *Mizaël Faucon*[A], *Stéphane Maritorena*[B] *and Paul M. V. Martin*[A]

[A]Laboratoire de Biologie du stress en milieu marin, Institut Territorial de Recherches Médicales Louis Malardé, BP 30, Papeete, Tahiti, Polynésie Française.
[B]Laboratoire d'Ecologie Marine, Université Française du Pacifique, BP 6570, Faaa/Aéroport Tahiti, Polynésie Française.

Abstract
Hermatypic corals along two continuous 25-m-long line transects on the northern and eastern coasts of the island of Tahiti (Arue, outer reef slope, and Hitia'a, fringing reef, respectively) were monitored during a minor episode of coral bleaching in April and May 1993. From early February to the end of May, the physico-chemical parameters of the sea water (temperature, salinity, dissolved oxygen, pH and total solar irradiance) were noted once a week, and solar UV-B radiation was recorded from 1100 to 1400 hours every day.

The results are consistent with a synergistic interaction between temperature and UV-B radiation, possibly associated with total solar irradiance. The interval of four weeks between peaks in solar UV-B radiation and seawater temperature may explain why the 1993 bleaching in Tahiti was minor. Different patterns of bleaching occurred in different species, and all corals recovered within four to six weeks. Hermatypic corals appear to have multiform reactions in response to environmental stresses.

Introduction

Episodes of dysfunction of symbiotic cnidarians known as 'mass bleaching' have been observed by many scientists around the world since the early 1980s. Bleaching occurs during the highest irradiance and the warmest season of the year (Glynn 1983), and it is generally believed to be the result of increased seawater temperature and/or irradiance (Jokiel and Coles, 1977, 1990; Coles and Jokiel 1978). This mass bleaching has been defined as the complete loss of coloration of symbiotic cnidarians attributed to a reduction in the number of symbiotic dinoflagellates in the gastrodermis of the host, a rupture of the gastrodermis itself, or a loss of photosynthetic pigments (Hayes and Bush 1990). A severe mass bleaching phenomenon occurred in Tahiti (Society Islands) in 1991 (Salvat 1992) with lethal consequences for up to 25% of the Family Acroporidae. In the present paper, we report a minor bleaching episode (observed in Tahiti in April and May 1993) with complete recovery of the large majority of coral specimens.

The lack of measurement of changes in physico-chemical parameters accompanying bleaching events has hitherto made it difficult to identify parameter thresholds related to bleaching. In this study, physico-chemical parameters were recorded *in situ* before, during and after a minor bleaching event. At the same time, total solar irradiance (photosynthetically active radiation + ultraviolet, PAR + UV) and ultraviolet-B radiation (UV-B) were also recorded; once a week for PAR + UV and every day for UV-B. The bleaching event was qualitatively and quantitatively monitored on two 25-m-long continuous line transects (Loya 1978), one on the outer reef slope of Arue (northern coast of Tahiti) and another on the fringing reef of Hitia'a (eastern coast of Tahiti).

0067-1940/94/071149$05.00

Materials and Methods

Physico-chemical parameters of the Arue sea water (temperature, dissolved oxygen, salinity and pH) were recorded from February to May 1993 at 0900 hours every Monday at a depth of 4 m. Temperature and salinity were recorded with a WTW- LF196 microprocessor conductivity meter linked to a Tetracon 96A-4 WTW probe (Bioblock Scientific, 67403-Illkirch, France), and dissolved oxygen was measured with a YSI 58 dissolved oxygen meter, linked to a YSI 5739 probe and to a YSI 5795-A stirring rod (Bioblock Scientific). For the pH, sea water was taken in a 250-mL glass bottle to the laboratory, where the measure was recorded on a Metrohm pH meter (1/100) (Roucaire, 78143-Velizy Villacoublay, France) within 1 h after collection.

UV-B flux (in J cm^{-2}) was measured with a CX-312 sensor linked to a VLX-3W recorder (Bioblock Scientific) between 1100 and 1400 hours every day from Monday to Friday. Preliminary experiments showed that this period includes about 65% of the daily rate of the UV-B flux. PAR + UV was recorded once a week (in kJ cm^{-2}) from 0900 to 1700 hours with an LI-1800 UW underwater spectroradiometer (Eurosep Instruments, 95526-Cergy Pontoise, France). The spectroradiometer was programmed to scan from 300 to 700 nm in 2-nm increments once every hour.

In February and March, a weekly snorkling survey of the appearance of the coral community was done at the two sites. At the end of March and the beginning of April, large numbers of coral colonies in the Family Pocilloporidae (essentially *Pocillopora meandrina* Dana, 1846) started paling, gaining a characteristic grey-velvet colour. From the end of April to the end of May, qualitative and quantitative information on the condition of hermatypic corals was recorded once a week from a continuous 25-m-long line transect between two permanent poles at Arue (outer reef slope) during six weeks and at Hitia'a (fringing reef) during five weeks. The Arue transect was situated perpendicular to the shore on a shelf at 4 to 5 m depth, near the top of a submarine wall. It was permanently under the influence of a heavy swell. The Hitia'a transect was also situated perpendicular to the shore but sloped down gently from 2.3 to 4.5 m depth. It was protected by a lagoon and a discontinuous barrier reef and was more under the influence of light turbidity than of a swell. Healthy and bleached corals were recorded for each transect. As far as possible, hard corals were identified to species level, following the monograph series of the Australian Institute of Marine Science (Veron and Pichon 1976, 1980, 1982; Veron *et al.* 1977; Veron and Wallace 1984). According to the intensity and distribution of bleaching on each specimen, six different categories were noted: P, pale; pB, partially bleached; pBr, partially bleached on borders; pBt, partially bleached at tips; pBb, partially bleached at the base; and N, normal.

Results

Although local environment and ecology differ between Arue and Hitia'a, hard corals were the dominant taxa on both transects. Corals were mostly small (mean size 11.6 cm) at Arue and larger (18.9 cm ; $P < 0.05$, Student's t test) at Hitia'a. Living corals predominated over dead corals on each transect. Table 1 presents the abundance of coral species and the percentage bleached at both sites. The Arue site was dominated by Pocilloporidae (63.20%), whereas the Hitia'a site was dominated by Acroporidae (53.80%). Dead corals on the Arue transect were mainly *Pocillopora* spp., whereas at Hitia'a they were mainly tabular *Acropora* spp. Soft corals were not present in either transect.

Table 2 presents details on the chronology of the coral bleaching from April to May. Many specimens of each coral species did not bleach, and only those specimens involved in the bleaching event are mentioned. Bleaching was less common at Arue (14.9% bleached) than at Hitia'a (29.5%). No colonies were completely bleached at either transect, although completely bleached colonies of *Pocillopora damicornis* were noted in the lagoon adjacent to the Arue transect. All corals cited in Table 2 were bleached from the beginning of the study except for two at Arue (one paled and one started bleaching during the study on 12 May) and eight at Hitia'a (which were pale at the begining). Almost all of the specimens returned to normal in five or six weeks, and no mortality was noted on either transect. Some of the bleached *P. damicornis* next to Arue site died after two months of bleaching.

Table 3 shows the changes in four physico-chemical parameters for the Arue site sea water measured before, during and after the minor mass bleaching event. Salinity and pH were constant, but there was an inverse relationship between temperature and dissolved oxygen, as is to be expected. Corals became pale about the end of March, when the temperature was the highest and the dissolved oxygen the lowest.

Table 1. Abundance of coral species and percentage bleached (April–May) for one 25-m-long transect at each site

Taxon	Arue		Hitia'a	
	Number of colonies	% bleached (April–May)	Number of colonies	% bleached (April–May)
Anthozoa				
Thamnasteridae				
Psammocora profundacella	0	0	1	($n = 1$) 1.28
Total	0	0	1	($n = 1$) 1.28
Pocilloporidae				
Pocillopora meandrina	35	($n = 5$) 5.75	7	($n = 5$) 6.41
P. eydouxi	8	($n = 4$) 4.60	1	0
P. verrucosa	4	($n = 3$) 3.45	4	($n = 4$) 5.12
P. woodjonesi	3	0	0	0
Dead *Pocillopora* sp.	5	0	0	0
Total	55	($n = 12$) 13.80	12	($n = 9$) 11.53
Acroporidae				
Montastrea aequituberculata	5	0	10	($n = 2$) 2.56
Acropora hyacinthus	1	0	13	0
A. gemmifera	0	0	10	($n = 3$) 3.85
A. valida	1	0	4	($n = 3$) 3.85
A. cytherea	0	0	1	0
A. danai	1	($n = 1$) 1.15	0	0
A. robusta	0	0	1	0
Dead *Acropora* sp.	1	0	3	0
Total	9	($n = 1$) 1.15	42	($n = 8$) 10.26
Fungiidae				
Fungia fungites	0	0	7	($n = 2$) 2.56
F. paumotensis	0	0	2	0
Herpolitha limax	0	0	1	0
Total	0	0	10	($n = 2$) 2.56
Poritidae				
Porites solida	0	0	5	0
P. lobata	7	0	2	0
P. lutea	0	0	2	($n = 1$) 1.28
Total	7	0	9	($n = 1$) 1.28
Faviidae				
Montastrea curta	6	0	3	($n = 1$) 1.28
Leptastrea purpurea	4	0	0	0
Favia stelligera	0	0	1	($n = 1$) 1.28
Total	10	0	4	($n = 2$) 2.56
Merulinidae				
Hydnophora microconos	5	0	0	0
Total	5	0	0	0
Hydrozoa				
Milliporidae				
Millepora platyphylla	1	0	0	
Total	1	0	0	
Total	87	($n = 13$) 14.95	78	($n = 23$) 29.50

Table 2. Weekly bleaching patterns at the Arue and Hitia'a sites

Bleaching categories: P, pale; pB, partially bleached; pBr, partially bleached on borders; pBt, partially bleached at tips; pBb, partially bleached at the bases; N, normal

Arue site (14.95% of bleached corals)

Distance on transect (m)	Species	Bleaching category on the following dates (1993)					
		21 Apr.	30 Apr.	7 May	12 May	19 May	28May
1.0	*P. eydouxi*	pB	N	N	N	N	N
3.5	*P. meandrina*	pB	pB	N	N	N	N
5.0	*P. eydouxi*	pB	N	N	N	N	N
6.0	*A. danai*	pB	pBr	pBr	pBr	N	N
7.0	*P. verrucosa*	pB	P	P	P	P	N
8.5	*P. meandrina*	pB	P	P	P	P	N
10.0	*P. eydouxi*	pB	P	P	P	P	N
12.5	*P. verrucosa*	P	P	P	P	P	N
14.0	*P. meandrina*	pB	P	P	P	N	N
18.0	*P. meandrina*	pB	pB	pB	pB	P	N
20.0	*P. verrucosa*	pB	pB	pB	pB	P	N
22.0	*P. meandrina*	pB	P	P	P	N	N
23.5	*P. eydouxi*	N	N	N	pB	pB	pB

Hitia'a site (29.50% bleached corals)

Distance on transect (m)	Species	Bleaching category on the following dates (1993)				
		2 Apr.	28 Apr.	5 May	14 May	27 May
0.0	*M. aequituberculata*	pBr	pB	N	N	N
	Psammocora profundacella	pBr	pBr	pBr	pBr	N
0.5	*P. meandrina*	P	P	P	P	N
2.0	*A. valida*	pBt	pBt	pBt	pBt	N
2.2	*M. aequituberculata*	pB	pB	pB	pB	N
3.0	*F. fungites*	P	P	P	P	P
3.5	*M. curta*	pB	P	P	P	N
3.75	*F. stelligera*	pBr	pBr	pBr	pBr	N
	Porites lutea	P	P	P	P	N
8.2	*A. gemmifera*	pBr	N	pBb	pBb	N
	P. verrucosa	P	P	pBt	pBt	N
9.0	*F. fungites*	P	P	N	N	N
9.2	*A. valida*	P	N	N	N	N
11.2	*P. verrucosa*	pB	pB	pB	pB	P
	P. meandrina	pB	pB	pB	pB	P
13.2	*P. meandrina*	pB	pB	P	P	P
	P. verrucosa	P	P	P	P	P
13.5	*A. valida*	pBt	pBt	N	N	N
16.0	*A. gemmifera*	pBb	pBb	pBb	pBb	pBb
21.5	*A gemmifera*	P	P	P	P	N
22.0	*P. verrucosa*	pB	pB	P	P	P
23.0	*P. meandrina*	pB	pB	P	P	P
25.0	*P. meandrina*	pB	pB	P	P	P

Table 3. Changes in four physico-chemical parameters for the Arue site sea water

Temperature is expressed in °C, salinity in PSS units, dissolved oxygen (DO) in mgL^{-1}.(See Materials andMethods for details)

Parameter	1 Feb.	8 Feb.	15 Feb.	22 Feb.	1 Mar.	08 Mar.	15 Mar.	22 Mar.	29 Mar.	5 Apr.	12 Apr.	19 Apr.	26 Apr.	3 May	10 May	17 May	24 May	31 May
Temp.	28.4	28.3	28.4	28.4	28.8	28.8	28.8	29.3	29.3	29.2	29	28.8	29	28.6	28	28	28	28
Salinity	35.4	35.6	35.6	35.8	35.6	35.6	35.6	35.8	35.8	35.8	36.1	36.1	35.9	35.9	35.9	35.8	36	35.8
DO	6.8	6.82	6.69	6.6	6.43	6.21	6.34	5.94	5.79	5.95	6.12	6.03	5.82	6.13	5.94	6.01	5.74	5.84
pH	8.2	8.12	8.17	8.27	8.09	8.18	8.22	8.19	8.17	8.06	8.12	8.13	8.1	8.11	8.23	8.26	8.18	8.25

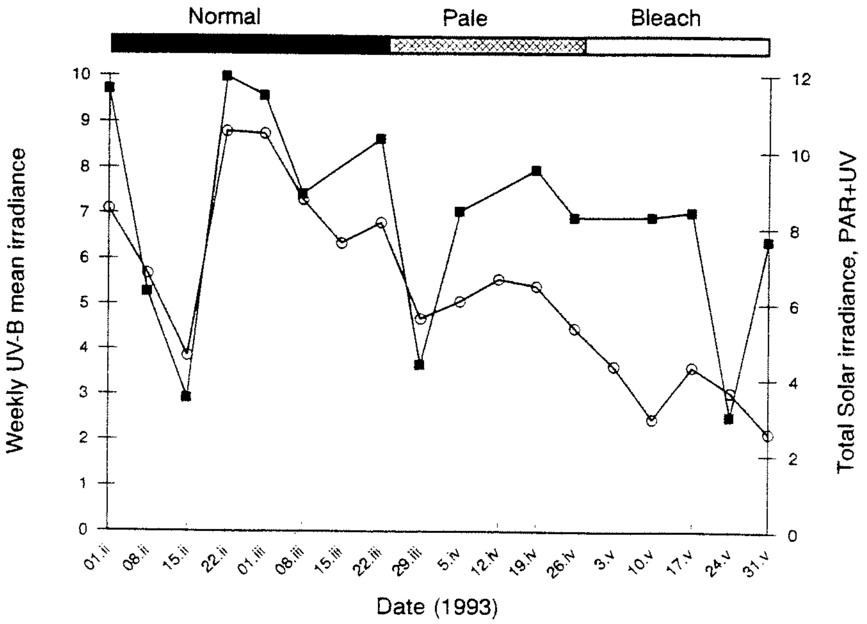

Fig. 1. Total solar irradiance (kJ cm^{-2}, ■) and weekly UV-B mean irradiance between 1100 and 1400 hours (J cm^{-2}, ○) at the Arue site from February to May 1993. The bar above the figure shows the timing of the bleaching phenomenon.

There was good correspondence between the total solar irradiance (PAR + UV) and UV-B radiation from February to the end of March (Fig. 1). Then, UV-B values continued decreasing but PAR+UV values stayed stable. UV-B peaked four weeks before (22 February, white arrow) the temperature reached its maximum (22 March, black arrow) (Fig. 2).

Discussion

This study is in agreement with the idea that corals bleach in response to several stresses. Among these stresses, increase in temperature seems to be the most important cause of bleaching, either as a brief increase (+3°C to +4°C) above the normal maximum for a short period of time or as a gradual increase (+1°C to +2°C) for a long period (Coles and Jokiel 1978). Besides temperature, Fisk and Done (1985) suggested that increased solar radiation caused the 1982 bleaching on the Great Barrier Reef (Australia) because it occurred without abnormal values of temperature. Harriott (1985) also suspected solar radiation because most bleaching occurred on the upper surfaces of coral colonies. At the same time, the possibility of a synergistic effect of light (PAR or UV alone or PAR + UV at the same time) must not be dismissed. Hoegh-Guldberg and Smith (1988) suggested that increased intensities of light induce bleaching of hosts by removing pigments, whereas increased temperatures do it by removing zooxanthellae. Recently, Gleason and Wellington (1993) reported results of a field experiment showing that coral bleaching induced by UV radiation alone results from reductions in zooxanthella densities rather than the combined effects of zooxanthellae expulsion and decreases in chlorophyll concentration per algal cell. The same authors also reported results showing that, irrespective of high water temperatures, short-term (three weeks) increases in ultraviolet radiation of a magnitude possible under calm, clear water column conditions can readily induce bleaching in reef-building corals.

In the present study, the seawater temperature was already elevated (28.4°C) in early February and rose to 29.3°C by the middle of March (average temperatures 1979–91 : 27.8°C

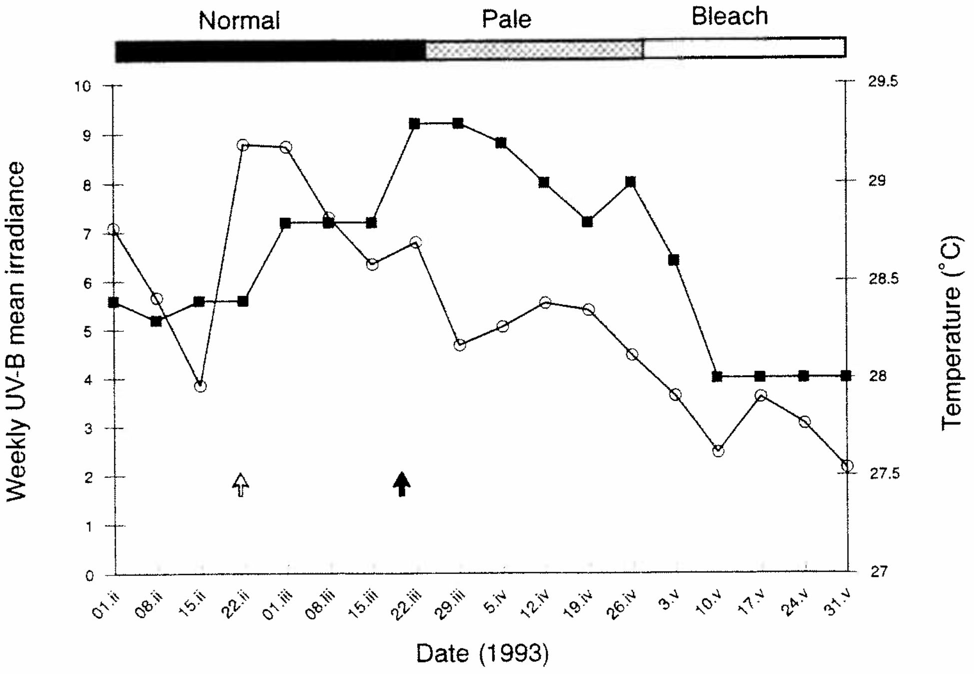

Fig. 2. Weekly UV-B mean irradiance between 1100 and 1400 hours (J cm^{-2}, ○) and seawater temperature (■) at the Arue site, from February to May 1993. The bar above the figure shows the timing of the bleaching phenomenon.

in February, 28.4°C in March; ORSTOM Papeete, personal communication). In contrast, UV-B radiation reached its peak at the end of February and decreased thereafter slowly and regularly. UV-B peaked four weeks before the temperature peak (22 February compared with 22 March), which is a longer interval than usual (one to two weeks, unpublished data).

The lack of synchrony among these parameters may explain why the bleaching event was minor and why it followed a long paling stage. The bleaching and death of *P. damicornis* in the vicinity of the Arue transect support the observation of others that the Pocilloporidae and some Acroporidae (Fisk and Done 1985; Salvat 1992) are among the most sensitive to bleaching.

Several patterns of bleaching occurred, although all corals recovered within four to six weeks. In the Pocilloporidae, *P. meandrina* was rather pale at first with a grey-velvet appearance then later it bleached, whereas *P. verrucosa* partially bleached at the tips on the top of the colony and *P. eydouxi* partially bleached on the verrucae and not on the coenosteum, giving a snow-covered aspect to the colony. In the Acroporidae, the bleaching was more variable: for example, *A. danai* (tabular ecomorph) bleached from the outside to the inside of the coral, *A. valida* bleached in patches on the top of the colony, and in *A. gemmifera* only the coenosteum and not the branches bleached.

To conclude, this study has shown that hermatypic corals have multiform reactions to stress. These likely depend on genetic variations within and among species. In general, severe coral bleaching episodes may occur when high total solar irradiance coincides with elevated seawater temperature for a few weeks (at least four weeks or more). In this study, the important interval between the maximum values of these two parameters may explain why the bleaching event was minor.

References

Coles, S. L., and Jokiel, P. L. (1978). Synergistic effects of temperature, salinity and light on the hermatypic coral *Montipora verrucosa*. *Marine Biology (Berlin)* **49**, 187–95.

Fisk, D. A., and Done, T. J. (1985). Taxonomic and bathymetric patterns of bleaching in corals, Myrmidon Reef (Queensland). *Proceedings of the 5th International Coral Reef Congress* **6**, 149–54.

Gleason, D. F., and Wellington, G. M. (1993). Ultraviolet radiation and coral bleaching. *Nature (London)* **365**, 836–8.

Glynn, P. W. (1983). Extensive bleaching and death of reef corals on the Pacific coast of Panama. Environmental Conservation **11**, 133–46.

Harriott, V. J. (1985). Mortality rates of scleractinian corals before and during a mass bleaching event. *Marine Ecology Progress Series* **21**, 81–8.

Hayes, R. L., and Bush, P. G. (1990). Microscopic observations of recovery in the reef-building scleractinian coral, *Montastrea annularis*, after bleaching on a Cayman reef. *Coral Reefs* **8**, 155–62.

Hoegh-Guldberg, O., and Smith, G. J. (1988). Physiological correlates of light and temperature stress in two pocilloporid corals. *Proceedings of the Associated Island Marine Laboratories of the Caribbean, Sarasota, Florida* **21**, 57.

Jokiel, P. L., and Coles, S. L. (1977). Effect of temperature on the mortality and growth of Hawaiian reef corals. *Marine Biology (Berlin)* **43**,201–8.

Jokiel, P. L., and Coles, S. L. (1990). Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. *Coral Reefs* **8**, 155–62.

Loya, Y. (1978). Plotless and transect methods. In 'Coral Reefs: Research Methods'. pp. 197–217. (UNESCO: Paris.)

Salvat, B. (1992). Blanchissement et mortalité des scléractiniaires sur les récifs de Moorea. (archipel de la Société) en 1991. *Comptes Rendus des Séances de l'Académie des Sciences* **314** (Série III), 105–11.

Veron, J. E. N., and Pichon, M. (1976). 'Scleractinia of Eastern Australia. Part I. Families: Thamnasteridae, Astrocoeniidae, Pocilloporidae.' (Australian Government Publishing Service: Canberra.)

Veron, J. E. N., and Pichon, M. (1980). 'Scleractina of Eastern Australia. Part III. Families: Agariciidae, Siderastreidae, Fungiidae, Oculinidae, Merulinidae, Mussidae, Pectinidae, Caryophylliidae, Dendrophyliidae.' (Australian Institute of Marine Science: Townsville, Queensland.)

Veron, J. E. N., and Pichon, M. (1982). 'Scleractinia of Eastern Australia. Part IV. Family: Poritidae.' (Australian Institute of Marine Science: Townsville, Queensland.)

Veron, J. E. N., and Wallace, C. C. (1984). 'Scleractinia of Eastern Australia. Part V. Family: Acroporidae.' (Australian Institute of Marine Science: Townsville, Queensland.)

Veron, J. E. N., Pichon, M., and Wijsman-Best, M. (1977). 'Scleractinia of Eastern Australia. Part II. Families: Faviidae, Trachyphylliidae.' (Australian Government Publishing Service: Canberra.)

Manuscript received 8 March 1994; revised and accepted 15 June 1994