Mass coral bleaching in the Fiji Islands, 2000

R.L. Cumming [1], M.A. Toscano[2], E.R. Lovell[3], B.A. Carlson[4], N.K. Dulvy[5], A. Hughes[6], J.F. Koven[7], N.J. Quinn[8], H.R Sykes[9], O.J.S. Taylor[10], D. Vaughan[11]

Abstract The south-western Pacific island countries were largely unaffected by mass coral bleaching during the intense El Nino of 1998, but experienced mass bleaching in 2000 during the subsequent strong La Niña. Nineteen reef locations were surveyed in eight geographic regions within the Fiji archipelago between mid April and early July 2000, to assess the geographic extent and intensity of Fiji's first recorded mass bleaching event. 64% of all scleractinian coral colonies surveyed were bleached (partially or fully, or recently dead from bleaching), and mass bleaching occurred in all regions surveyed except in the far north (north of Vanua Levu).

Bleaching was most intense (>80% of colonies bleached) in southern and eastern sites (south and east from Viti Levu and Vanua Levu, Kadavu and Northern Lau), and lower in some western and one northern site(s). The geographic patterns in bleaching coincide with Fiji's position on the north-western edge of an area of high sea surface temperatures (SSTs), and support the prediction based on SSTs that bleaching should be most severe in the south and east. Seawater temperatures exceeded expected summertime maxima for 5 months and peaked at 30-30.5°C between early March and early April 2000. The bleaching threshold for Fiji appears to be in the range of 29.5-30°C. Our data estimate 10-40% of coral colonies had died from bleaching within four months of the onset of bleaching.

Keywords Coral bleaching, Fiji, Seawater temperature, HotSpot, Bleaching intensity, Bleaching mortality, Aerial survey, temperature logger, Degree Heating Weeks, Pathfinder

Introduction

Coral reefs of the south-western Pacific Islands largely escaped the global-scale El Niño-associated mass bleaching of 1998, but experienced mass bleaching in 2000 during the subsequent strong La Niña. In early 2000, satellite surveillance of sea surface temperatures (SSTs) showed a band of warming water initiating in Papua New Guinea (PNG) and extending down through the Solomon Islands (NOAA/NESDIS HotSpot website: http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/SST/climohot.html). By February 1 2000, HotSpot anomalies (HotSpots: SSTs 1°C or more above the climatological maximum monthly mean SSTs) extended across the south Pacific from PNG to Easter Island. Accumulated heat stress was greatest in a pool stretching south-east from Fiji, encompassing Tonga, Niue, southern Cook Islands and Tubuai (Fig. 1). Fiji was on the north-western edge of this pool and experienced within-country gradients in accumulated heat stress, with greatest heat stress in the south and east of the country.

Countries that experienced mass bleaching in 2000 include PNG and Cook Islands (WWF South Pacific Programme 2000a), Solomon Islands (WWF South Pacific Programme 2000b), Tonga (Lovell 2001), Easter Island (Wellington et al. 2001) and Fiji (Cumming et al. 2000; South and Skelton 2000; Lovell 2001). We are aware of only one previous report on mass bleaching in the south-west Pacific region, from Papua New Guinea in 1996 (Davies et al. 1997).

No coordinated country-wide monitoring program existed in Fiji at the time of the 2000 bleaching event. Instead, eight independent groups conducted surveys at 19 locations spread throughout Fiji (Fig. 2). These studies were not standardized and employed a wide variety of survey methods to estimate bleaching severity,

[1]R.L. Cumming (✉): Department of Biology, Marine Studies Programme, The University of the South Pacific, PO Box 1168, Suva, Fiji Islands. email: cumming_r@usp.ac.fj
[2]M.A. Toscano, NOAA/NESDIS/ORA/ORAD E/RA31, 1315 East-West Highway, SSMC3 Rm 3608, Silver Spring, MD 20910, USA
[3]E.R. Lovell, Biological Consultants, Fiji, PO Box 3129, Lami, Fiji Islands
[4]B.A. Carlson, Waikiki Aquarium, University of Hawaii, 2777 Kalakaua Avenue, Honolulu, Hawaii, 96815, USA
[5]N.K. Dulvy, Centre for Tropical Coastal Management, Department of Marine Sciences and Coastal Management, University of Newcastle, Newcastle upon Tyne, NE1 7RU, UK
[6]A. Hughes, Greenforce Environmental Expeditions, 11-15 Betterton Street, Covent Gardens, London, WC2H 9BP, UK
[7]J. F. Koven, Astrolabe, Inc., 601 Springloch Road, Silver Spring, MD 20904, USA
[8]N.J. Quinn, Discovery Bay Marine Lab, Discovery Bay, St. Ann, Jamaica
[9]H.R. Sykes, Resort Support, P.O. Box 2558, Govt. Building, Suva, Fiji Islands
[10]O.J.S. Taylor, Greenforce Environmental Expeditions, c/o National Trust for Fiji, PO Box 2089, Suva, Fiji Islands
[11]D. Vaughan, Department of Environment and Coastal Resources, South Base, Grand Turk, Turks and Caicos Islands, British West Indies

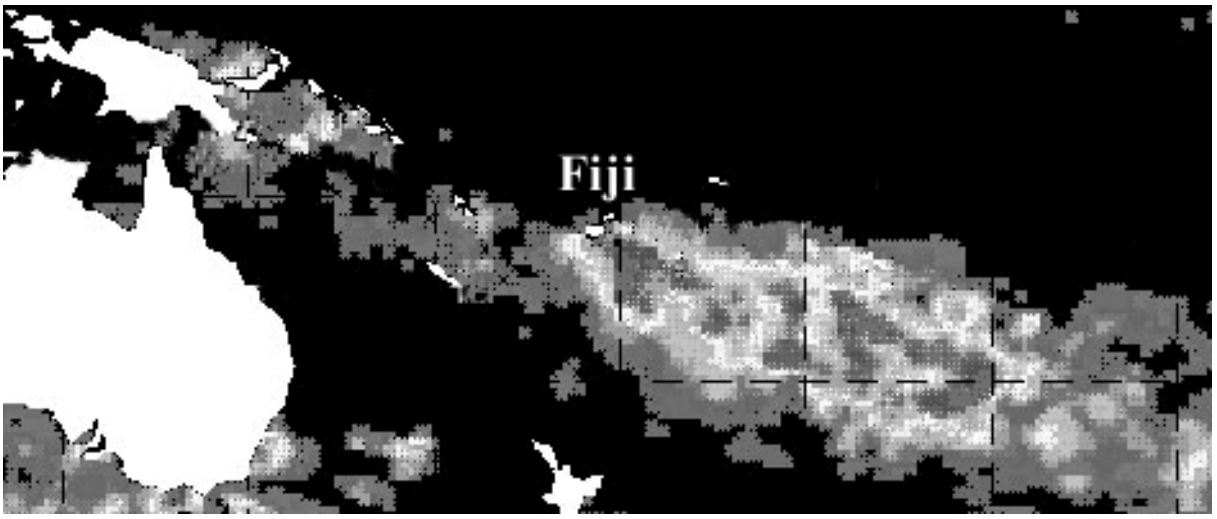

Fig. 1 NOAA/NESDIS Degree Heating Weeks (DHW) chart for the 90-day period up to 15 April 2000. DHWs accumulate Hot-Spot anomalies over a continuous 12-week period. One DHW is equivalent to one week of satellite-derived SSTs 1°C above the MMM (maximum monthly mean: 28.3°C for Fiji) SST; two DHWs are equivalent to two weeks of SSTs 1°C above the MMM SST or one week of SSTs 2°C above the MMM SST, and so on. Light shading indicates 8-10 DHWs, darker shading inside the light shading indicates 10-14 DHWs. This chart is available in colour on the NOAA DHW website: http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/SST/dhw_retro.html

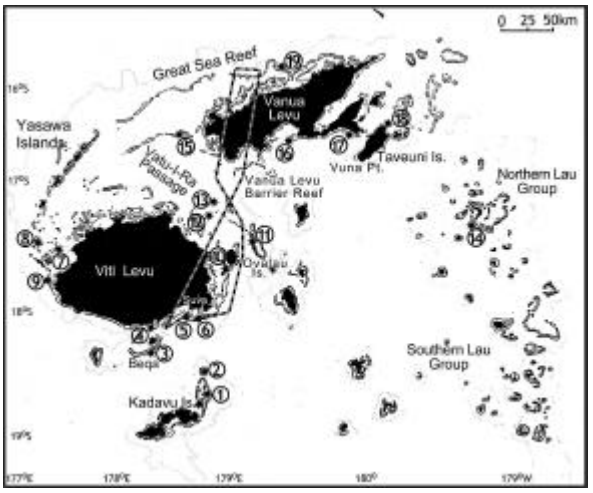

Fig. 2 Map of Fiji showing surveyed locations and the route of the aerial survey (dotted line) Adapted from UNEP/IUCN (1988). Site numbers, names and descriptions are given in Table 1.

including line intercept transects, belt transects, colony counts, point counts, video transects, video quadrats, coral tagging and aerial surveillance (see Table 1). We standardized these data to provide an overview of the geographic extent and severity of bleaching in Fiji. To investigate seawater temperature as a forcing factor, we accessed both *in situ* and satellite-derived data, and show a geographic pattern of bleaching that corresponds to seawater temperatures.

Materials and methods

Seawater temperatures

Seawater temperature has been recorded *in situ* since September 1996 at Suva Barrier Reef (site #5, Table 1), and since July 1997 at Vuna Point, Taveuni (see Fig. 2) by the Fiji Seawater Temperature Monitoring Project at the University of the South Pacific, Fiji (http://www.usp.ac.fj/marine/gcrmn/research/seatemp.htm). Hugrun Seamon s/f underwater temperature recorders (with an accuracy of ± 0.05°C) record hourly at approx. 10m depth.

Seawater temperatures for 1985-2000 are from new, high resolution satellite data (Toscano et al. this volume). The NOAA/NASA AVHRR Oceans Pathfinder Program (Vazquez et.al. 1998) introduced an improved archival SST dataset to dataset provide a long (currently 17 years), consistently calibrated time series of global SST fields for climate studies (Kilpatrick et al. 2001). All AVHRR data from 1985 to present have been reprocessed using a Pathfinder version of the current NOAA Non-Linear SST algorithm (Kilpatrick et al. 2001). Pathfinder algorithm coefficients are estimated by regressing the remotely-sensed brightness temperatures to *in situ* best available moored and drifting buoy SSTs (matchups) within 30 min and 0.1° latitude/longitude of each other. Algorithm performance is globally well within a 0.5° C range, with the tropics showing a slight negative bias of 0.1-0.2° C compared to buoys (Kilpatrick et al. 2001). Thus the Pathfinder

Table 1 Details of locations surveyed. Regions are ordered by latitude (refer to Fig. 2). Superscripts indicate surveyors, numbers match authors as listed on page 1. 'LIT' = line intercept transect.

Region	Date	Location	Site Description	Replicate samples
Kadavu	7 April	**1A. Great Astrolabe Reef** [5] Sites between: 18^0 45.24' S, 178^0 28.00' E, 18^0 43.31' S, 178^0 29.19' E.	Leeward (north-western) outer barrier. Dominated by *Acropora.*	3 sets of 0.25 m^2 video photos (n=42, 36, 39) at 7 m. Colonies surveyed per set: 129, 111, 121.
	7-10 June	**1B. Great Astrolabe Reef** [7] (1) 18^o 46.50' S, 178^o 31.56' E. (3) 18^o 46.05' S, 178^o 34.06' E. (4) 18^o 43.05' S, 178^o 34.06' E. (5) 18^o 43.68' S, 178^o 27.95' E.	Five sites: (1),(2) lagoonal sea mounts; (3) windward outer barrier; (4),(5) leeward outer barrier. All dominated by *Acropora* except (4) which was the most diverse site.	5 1 m belts, 33-69 m long, 1-27.5 m depth. Colonies surveyed per replicate: 150, 232, 249, 153, 113 respectively.
	8 June	**2. North Astrolabe Reef** [7] (1) 18^o 37.34' S, 178^o 33.30' E. (2) 18^o 37.20' S, 178^o 33.25' E.	Barrier reef on north-east corner. Dominated by *Acropora.*	2 1 m belts, 79 & 27 m long, 2-21.5 m. Colonies surveyed per replicate: 283, 68.
Southern Viti Levu	17 April	**3. Pacific Harbour** [4] 18^o 17.51' S, 178^o 4.84' E.	Two large, lagoonal patch reefs one mile apart. Dominated by *Acropora*.	2 30x1 m belts at 1.5-3.5 m. Colonies surveyed per replicate: 224, 155
	14 April	**4A. Beqa** [5]	Beqa Barrier Reef outer sides of channels. High coral cover, dominated by *Acropora* and *Pocillopora*.	10 60 m^2 areas at 4-9 m. Colonies surveyed per replicate: 23, 52, 28, 25, 33, 46, 62,89, 53, 67.
	18, 20 April	**4B. Beqa** [4] 18^o 27.57' S, 178^o 6.05' E. 18^o 24.12' S, 178^o 11.48' E. 18^o 28.97' S, 177^o 56.02' E.	Beqa Barrier Reef outer reef slope. High coral cover, dominated by *Acropora* and *Pocillopora*.	3 30x1 m belts at 3-10 m. Colonies surveyed per replicate: 181, 227, 135.
	19 April	**5. Suva Barrier Reef** [4,9] 18^o 09.55' S, 178^o 23.98' E.	Outer entrance to Suva Harbour. Submerged spur extending seaward from a barrier reef. High wave surge, often turbid. Dominated by *Acropora* and *Pocillopora*.	1 40 m LIT, 1 30x1 m belt, at 1.5-12 m. Colonies surveyed per replicate: 65, 24
	20 April	**6. Nukubuco Reef** [1]	Reef crest. High wave energy and strong currents, dominated by flattened *Acropora aspera*.	Two sites of tagged corals, at 0 m. Colonies surveyed per replicate: 21, 14.
	16 April	**7. Vunavadra Island** [4] 17^o 41.77' S, 177^o 18.73' E	Windward fringing reef (south-east facing) with moderate coral cover.	2 30x1 m belts at 1.5-5 m. Colonies surveyed per replicate: 79, 39.
Western Viti Levu	15 April	**8. Tavua Island** [4] (1) 17^o 33.90' S, 177^o 17.92' E. (2) 17^o 34.51' S, 177^o 20.76' E.	Two shallow patch reefs, 2 and 4 miles from Tavua Island: (1) south-east facing, 5 m, (2) top of reef, 2 m, with sparse corals.	(1) 1 10x1 m belt, (2) 1 30x1 m belt. Colonies surveyed per replicate: 21, 62.
	11 June	**9. Navula Reef** [9] (1) 17^0 55' S, 177^0 12' E. (2) 17^0 56' S, 177^0 12' E.	Two sites on the northern (1) and southern (2) sides of a barrier reef passage. Outer barrier reef slope, strong currents, rich in soft corals and *Millepora*, with predominantly small scleractinian colonies.	6 20 m LITs at 5-12 m (3 at each site). Colonies surveyed per replicate: 20, 25, 31, 18, 24, 35.

Table 1 cont'd

Region	Date	Location	Site Description	Replicate samples
Eastern Viti Levu	5-12 June	**10. Caqalai Island** [11] 6 sites between: 17° 47.25' S, 178° 43.65' E, 17° 47.60' S, 178° 44.28' E.	Shallow reef flats with low coral cover, dominated by *Pocillopora.*	6 sets of 1x1 m quadrats (n=34, 35, 36, 36, 40, 36) at 3 m, 81 point counts per quadrat, % cover data.
	1-8 June	**11. Wakaya Island** [9] 17° 35' S, 178° 58' E.	Outer corner of a barrier reef passage. Heavily impacted by crown-of-thorns predation in 1999/2000. Low coral cover, dominated by small colonies of *Pocillopora.*	2 40 m LITs at 10 m, colonies surveyed per replicate: 24, 22.
Vatu-I-Ra Passage	28 May - 2 June	**12. Pinnacle** [9] 17° 20' S, 178° 32' E.	Steep-sided pinnacle in the middle of a deep water passage. Dominated by large *Acropora* and *Porites.*	2 20 m LITs at 7-18 m, colonies surveyed per replicate: 32, 36.
	29 May - 5 June	**13. Vuya Reef** [9] Vanua Levu Barrier Reef 17° 15' S, 178° 34' E.	Sheltered shallow reef floor, almost flat, behind a barrier reef. High coral cover, dominated by large *Acropora.*	5 20 m LITs at 12 m, colonies surveyed per replicate: 40, 30, 34, 37, 26.
Northern Lau Group	16 April	**14. Vanua Balavu** [9] 17° 20' S, 179° 00' W.	Southern reef crest inside lagoon. Dominated by *Acropora.*	1 10 m LIT, 1 20 m LIT, at 1 m, colonies surveyed per replicate: 11, 26.
Southern Vanua Levu	27 April-1 May	**15. Yadua Tabu Island** [6,10]	Southern fringing reefs exposed to south-easterly trades. Data collected by volunteers.	3 sites of 1x1 m quadrats (n=6, 15, 6), at 0-15 m, colonies surveyed per replicate: 61, 186, 92.
	30 June-2 July	**16. Savusavu Bay** [2] Sites between: 16° 48.62' S, 179^0 14.35' E, 16^0 50.01' S, 179° 17.96' E.	Windward reef slope, approx. 60% coral cover, dominated by *Acropora* and *Pocillopora.*	6 20-75 m LITs at 3-6 m, colonies surveyed per replicate: 21, 19, 24, 21, 29, 58.
	3-4 June	**17. Rainbow Reef** [9] 16° 46' S, 179° 56' E. 16° 45' S, 179° 57' E.	Patch reef in a deep water passage with strong currents. Dominated by soft corals, scleractinian corals dominated by small *Pocillopora.*	3 20 m LITs at 9-15 m, colonies surveyed per replicate: 17, 15, 15.
	2 June	**18. Honeymoon Island** [9] 16° 40' S, 179° 51' E.	Shallow fringing reef off a small inshore island. No particular dominants.	2 20 m LITs at 1 m, colonies surveyed per replicate: 22, 12.
Northern Vanua Levu	5-6 July	**19. Great Sea Reef** [3] Sites between: 16° 19.75' S, 179° 18.14'E, 16° 14.43' S, 179° 02.10'E.	Shallow reef slopes on the outer and inner sides of a barrier reef. Approx. 60% coral cover, dominated by *Acropora hyacinthus*	3 20 m LITs at 2-3 m, colonies surveyed per replicate: 37, 34, 32.

NLSST algorithm is tuned to bulk SST measurements, closely (or slightly under-) estimating the bulk temperature felt by coral reef organisms.

Reef surveys

We standardized the reef survey data to colony counts for all locations except Caqalai (#10), and to four bleaching categories: (1) Not bleached (normal colouration), (2) Partially bleached (part of the colony white or pastel-coloured, often on the top only), (3) Fully bleached (whole colony white or pastel-coloured), (4) Bleached/dead (bleached colony with new algal turf on the skeleton). Categories (2), (3) and (4) were combined for the proportion of colonies affected by bleaching.

Aerial survey

Reefs between Suva and the Great Sea Reef north of Vanua Levu were surveyed by air on 21 April 2000 (Fig. 2). Reefs surveyed include barrier reefs around Suva and north to Ovalau Island, Vatu-I-Ra passage, Vanua Levu Barrier Reef, southern Vanua Levu, northern Vanua Levu and the Great Sea Reef.

We used photographs taken during the survey to categorize bleaching severity. Categories were: (1) <10%, (2) 10-30%, (3) 30-60%, (4) >60%, of substrate cover bleached. Two of the surveyed reefs (Suva {#5}and Nukubuco {#6}, both barrier reefs adjacent to Suva) were also assessed by SCUBA, allowing us to ground truth the aerial surveys for these sites.

Results

Seawater temperature and the onset of bleaching

Heat stress was most intense in southern and eastern Fiji. By mid April 2000, south-eastern Fiji (encompassing Beqa, Suva, Kadavu and the Southern Lau Group), had accumulated 12-16 DHWs and south-western Fiji had accumulated 8-12 DHWs. In the north-west, DHWs were ?4, suggesting a drastic difference in heat stress. The Northern Lau Group had 6-10 DHWs. North of Vanua Levu, 0 DHWs were recorded. These patterns can be seen in detail on the DHW website (Fig. 1).

The onset of mass bleaching was rapid, occurring over only a few days during the first week of March. Minor bleaching occurred up to two weeks earlier (Hendee 2000; Lovell 2001). By 1 February 2000, 2-3 DHWs had accumulated along the southern coast of Viti Levu, increasing to 5 DHWs by 29 February and 6 DHWs (1.5-2.0°C HotSpots) in the first week of March when mass bleaching occurred.

Neither HotSpots nor mass bleaching occurred in the far north (north of Vanua Levu), though this area did exhibit anomalies <1°C above climatological maximum monthly mean SSTs (and some minor bleaching).

Seawater temperature recorded *in situ* at Suva Barrier Reef exceeded the maximum monthly mean (MMM: 28.5° C) for five months, remained above 29°C for 3.5 months and peaked at 30-30.5°C between early March and early April (Fig. 3a). Similar patterns and peak temperatures occurred at Vuna Point, Taveuni, though the MMM is 0.3°C lower (Fig. 3b).

Seawater temperatures for 1985-2000 were constructed from both satellite-derived SSTs and *in situ* logger data, for Suva Barrier Reef and Vuna Point (Fig. 4). At Suva Barrier Reef, 2000 was the hottest year during this period, though 1989 was almost as hot. At Vuna Point, seawater temperature in 2000 was hotter than all other years except 1996.

Reef surveys

Eighteen of the 19 locations surveyed (Table 1) had bleached corals (Fig. 5). Bleaching was still widespread as late as July, four months after the onset of bleaching (Fig. 5). Sixty-four percent of all coral colonies surveyed were affected by bleaching, and were either partially or fully bleached, or recently dead from bleaching.

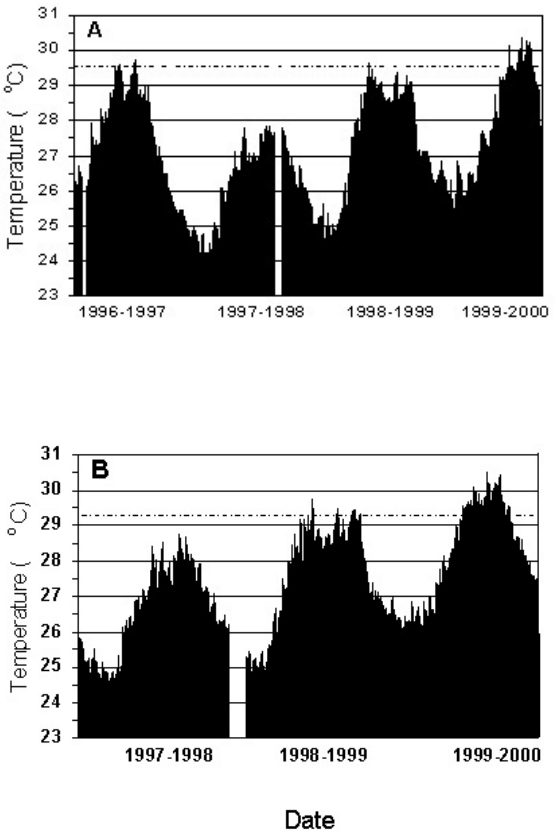

Fig. 3 Seawater temperature measured hourly by *in situ* temperature loggers at approx 10 m depth. **A** Suva Barrier Reef. **B** Vuna Point, Taveuni.

In the southern survey regions (southern Viti Levu and Kadavu; Table 1) 82% of colonies surveyed were affected by bleaching, with 13% already dead. Site means ranged between 67% and 100% of colonies bleached, and Beqa Barrier Reef outer reef slope (#4B) had the highest proportion of dead colonies (26%). Severe bleaching was not restricted to southern Fiji, however. Vanua Balavu (#14) in the Northern Lau Group had 94% of colonies affected by bleaching, mostly fully bleached, and the highest proportion of bleaching-related mortality of all sites surveyed in April (32%). Bleaching also occurred in the Southern Lau Group (ND pers obs).

The western sites surveyed in April, Vunavadra (#7), Tavua (#8) and Yadua Tabu (#15), had less severe bleaching. Vunavadra had significantly less colonies

affected than all other sites surveyed in April ($p<0.001$; one-way ANOVA, arcsin transform; SNK tests), with only 24% of colonies affected, no bleaching-related mortality and a relatively high proportion of partial bleaching (42% of colonies). Tavua and Yadua Tabu had significantly less bleaching than the most severely bleached sites: Beqa (#4), Vanua Balavu (#14) and Nukubuco (#6). Mass bleaching also occurred in the northern Yasawa Islands (T McLeod, Walt Smith International, pers comm).

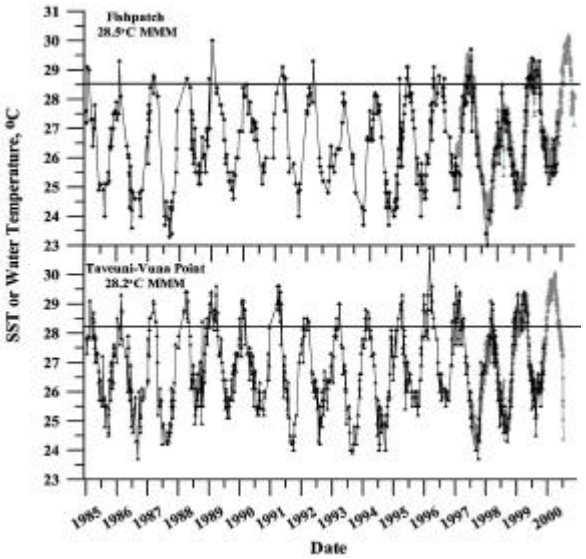

Fig. 4 Fifteen-year temperature records, combining 9km Pathfinder SST data, for 1985-1999 (black), and average daily *in situ* logger data for 1996/97-2000 (grey).

At sites surveyed in April, most bleached colonies were fully bleached, with relatively few partially bleached and dead colonies. This was reverse in June-July, with most bleached colonies only partially bleached. Less colonies were affected in the June surveys than the April surveys (53% vs. 74%), reflecting probable recovery of some colonies. Nevertheless, >70% of colonies were still bleached in June at the two sites in Vatu-I-Ra Passage. Site means for all other sites surveyed in June ranged between 39% and 57%, except for Honeymoon (#18; 17%) which had significantly less bleaching-affected colonies than all other sites surveyed in June ($p<0.001$; one-way ANOVA, arcsin transform; SNK tests), and had no bleaching-related mortality. The two most northerly sites, Honeymoon and Great Sea Reef (#19), had the lowest incidence of bleaching of all sites. Great Sea Reef had no bleaching in early July, though minor bleaching was seen during the aerial survey in April.

Mortality from bleaching was low (<15%) at most sites in the April surveys and was higher in the later surveys (Fig. 5). The highest mortality was recorded at Savusavu (#16) and Vuya (#13), where more than 40% of the scleractinian corals had died from bleaching by June/July.

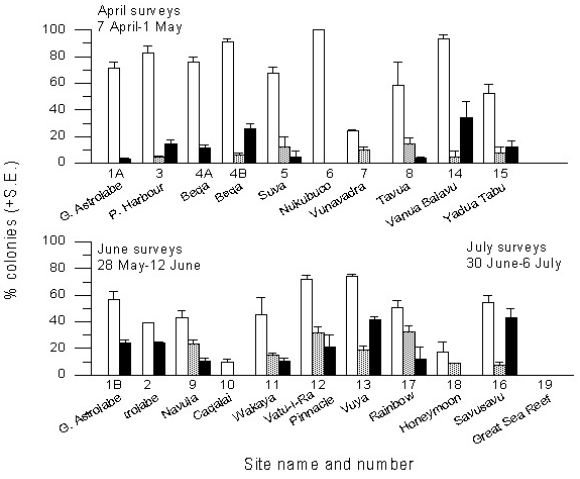

Fig. 5 Percentage of scleractinian colonies affected by bleaching (partially and fully bleached and recently dead from bleaching; white), partially bleached (grey) and recently dead from bleaching (black). The percentage not bleached is the inverse of the white bar. Site descriptions are given in Table 1. Partial bleaching was not recorded at sites 1A, 1B, 2, 4A and 10. Recent mortality was not recorded at sites 6 and 10. Data from site 10 are % cover.

Aerial survey

Extensive bleaching (>30% substrate cover bleached) occurred on all reef slopes surveyed south of Vanua Levu. We recorded 30-60% cover bleached through the Vatu-I-Ra Passage and 10-30% on a southern Vanua Levu fringing reef. Reef flats and crests were variable and often lower than 30%, but this may reflect low coral cover rather than low intensity of bleaching. Minor or no bleaching (<10% substrate cover bleached) was observed on all reefs north of Vanua Levu, including the Great Sea Reef.

Suva (#5) and Nukubuco (#6) outer reef slopes were the only reefs for which we recorded >60% cover bleached. Our estimate was lower for the adjacent reef crests (30-60%). The difference reflects the lower coral cover of the reef crests (RC, EL, unpubl data); Nukubuco crest had severe bleaching, with 100% colonies bleached in the two sites surveyed (Fig. 5).

Discussion

Geographic patterns of bleaching

Our data demonstrate that mass bleaching was widespread in Fiji south of Vanua Levu, and bleaching was only minor north of Vanua Levu. This geographic pattern coincides with Fiji's position on the north-western edge of an area of high heat stress (idenitfied by satellite-derived SST data), with accumulated heat stress greatest in the south and east of the country. More than 40% of scleractinian coral colonies were affected by bleaching at 16 of the 19 sites surveyed, including all seven geographic regions surveyed south of Vanua Levu.

The most severe bleaching (>80% of colonies affected) was recorded in April 2000 in the southern Viti Levu and Kadavu regions, and at a single reef crest site in the Northern Lau Group. The western sites surveyed in April (Vunavadra, Tavua and Yadua Tabu) had significantly less bleaching than the most severely bleached sites (Beqa, Vanua Balavu and Nukubuco), and the second most northerly site (Honeymoon) had significantly less bleaching than all other sites surveyed in June. These trends coincide with the accumulation of heat stress in the south and east. Several sites had low replication and/or small numbers of colonies per replicate, however, and these trends could also be explained by the smaller-scale, within-reef spatial variation in bleaching intensity which is known to occur (Spencer et al. 2000; Marshall and Baird 2000).

The two most severely bleached sites surveyed were both barrier reef crests (Nukubuco and Vanua Balavu). The adjacent reef flat of Nukubuco Reef was much less severely bleached, due at least in part to the predominance of massive and branching *Porites* spp. which were partially bleached or not bleached (RC unpubl data). The third reef crest site (Honeymoon) had much less severe bleaching (than other sites surveyed in June), however, suggesting variable responses on reef crests, though Honeymoon may have been less affected by bleaching because of its northern location.

Links with seawater temperature

Though no previous mass bleaching event is on record for Fiji, minor bleaching (involving a small proportion of colonies and/or a high proportion of partial bleaching) occurred in 1998 and 1999. In 1999, DHWs around south-eastern Viti Levu reached 7-8 (February–April 1999), and prominent bleaching of *Acropora* and *Platygyra* colonies occurred in Suva Harbour. Widespread bleaching occurred again in 2001, and was minor at most sites.

Since minor bleaching occurred in both 1998 and 1999 and major bleaching occurred in 2000, we can use Fig. 4 to estimate that the bleaching threshold lies in the range of 29.5-30^{o}C at both Suva Barrier Reef and Vuna Point, Taveuni. This range largely agrees with the bleaching thresholds used for HotSpot mapping of 1^{o}C above MMM. For both sites, 2000 is one of the two hottest years since 1985. The other hot year was 1996 at Taveuni and 1989 at Suva, suggesting the north and south of the country are influenced by different hot water masses. In 1996, bleaching occurred in PNG (Davies et al. 1997) and Williams and Bunkley-Williams (1990) provide an anecdotal report of bleaching in southern Fiji in 1989.

Mass bleaching occurred in western and northern areas that experienced thermal anomalies of <1^{o}C (Fig. 1). Our data therefore add to accumulating evidence that elevated seawater temperatures <1^{o} C above MMM can also lead to mass bleaching (e.g. Toscano et al. this volume; Goreau et al. 2000).

Mortality from the 2000 bleaching event

Bleaching mortality, estimated as the proportion of bleached colonies that were dead at the time of surveying, was low (<15%) at most sites in the April surveys and reached >40% (Savusavu {#16} and Vuya {#13}) in the later surveys. Mortality recorded in the later surveys may represent a reasonable estimate of ultimate mortality from bleaching because few colonies remained fully bleached (Fig. 5) and recovery of the remaining partially bleached colonies could have been high. On the other hand, the proportion of colonies affected by bleaching was probably underestimated in our later surveys because some bleached colonies recover their colour within four months (Lang et al. 1992; McField 1999; RC unpubl data).

Several of our sites are being monitored regularly as part of the incipient Global Coral Reef Monitoring Network in Fiji (http://www.usp.ac.fj/marine/gcrmn/). Preliminary estimates of impact from post-bleaching surveys and qualitative observations provide the following. By December 2000, <10% of coral cover was lost at both coral-depauperate Wakaya (#11) and coral-rich, *Acropora*-dominated Vatu-I-Ra Pinnacle (#12) (HS). Approximately 40% of coral cover was lost at Vuya (#13), which was also *Acropora*-dominated (HS). Possibly, the steep sides of the pinnacle reduced direct sunlight on the corals, compared with the flat Vuya site.

Beqa Barrier Reef outer reef slope and Pacific Harbour lagoonal patch reefs lost 99% and 80% of *Acropora* colonies respectively between April 2000 and April 2001 (BC). Much of this loss was probably due to the 2000 bleaching event, though this time period also includes a further bleaching event in 2001 and Cyclone

Paula in early March 2001, which damaged southern and south-western reefs.

Suva Barrier Reef outer reef slope (#5), which was *Acropora*-dominated and severely bleached, lost approximately 30% of coral cover and 45% of coral colonies by January 2001 (RC, EL). Nukubuco Reef crest (#6), which was also severely bleached, lost 65% of the dominant *Acropora aspera* colonies by August 2000 (RC).

In the west, no mortality of *Acropora* was detected at Vunavadra (#7), where bleaching was significantly less than at all other sites surveyed in April, and substantial mortality of *Acropora* colonies (47%) occurred at Tavua (#8) (BC).

The most severe bleaching recorded in Fiji (>80% of colonies affected) was of similar intensity to the worst-hit sites in the Indian Ocean in 1998. Mortality of 70-99% of coral cover was recorded at many of these sites (Goreau et al. 2000; Wilkinson 2000).

Acknowledgements The International Ocean Institute (IOI) Pacific Islands funded the aerial survey, the Nukubuco Reef study and map production. Jean-Michel Cousteau Resort, The Reef Check Foundation and the Fiji Division of Fisheries supported the reef surveys at southern and northern Vanua Levu. Nai'a Cruises supported the reef surveys at Vatu-I-Ra and Wakaya. The following people helped with data collection: R. Barrel, A. Champion, C. Hay, B.L. Kojis, J. Lee, R. Mitchell, R. Murphy, P.F. Newell, S. Tyne, S.R. Zetlan. We thank the following for information on bleaching events: S. Sauni, T. McLeod, R. Mitchell, T. Nahacky. *In situ* seawater temperature data are from the Fiji Seawater Temperature Monitoring Project at the University of the South Pacific, Suva (URC # 6299).

References

Cumming RL, Lovell ER, Hay C (2000) Geographic extent of the 2000 coral bleaching event in Fiji in relation to water temperature. Abstract, 9th Int Coral Reef Symp

Davies JM, Dunne RP, Brown BE (1997) Coral bleaching and elevated sea-water temperature in Milne Bay Province, Papua New Guinea, 1996. Mar Freshwat Res 48:513-516

Goreau TJ, McClanahan TR, Hayes RL, Strong AE (2000) Conservation of coral reefs after the 1998 global bleaching event. Cons Biol 14:5-15

Hendee J (2000) Coral-list listserver coral bleaching archives. ftp://www.coral.noaa.gov/pub/champ/bleach/ Part of the CHAMP (Coral Health and Monitoring Program) Network (http://coral.aoml.noaa.gov/index.html)

Kilpatrick KA, Podesta GP, Evans R (2001) Overview of the NOAA/NASA Pathfinder algorithm for sea surface temperature and associated matchup database. Journal of Geophysical Research, 106, C5, 9179-9197.

Lang JC (1988) Apparent differences in bleaching responses by zooxanthellate cnidarians on Colombian and Bahamian reefs. NOAA's Undersea Res Prog Res Rpt 88-2:30-32

Lovell ER (2001) Reef Check description of the 2000 mass coral bleaching event in Fiji with reference to the South Pacfic. Unpubl report to University of Rhode Island.

Marshall PA, Baird AH (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. Coral Reefs 19:155-163

McField MD (1999) Coral response during and after mass bleaching in Belize. Bull Mar Sci 64:155-172

South R, Skelton P (2000) Status of coral reefs in the south-west Pacific: Fiji, Nauru, New Caledonia, Samoa, Solomon Islands, Tuvalu and Vanuatu. In: Wilkinson C (ed.) Status of the Coral Reefs of the World: 2000. Australian Institute of Marine Science, Townsville, pp 159-180

Spencer T, Teleki KA, Bradshaw C, Spalding MD (2000) Coral bleaching in the southern Seychelles during the 1997-1998 Indian Ocean warm event. Mar Poll Bull 40:569-586

Toscano MA, Liu G, Casey KS, Guch IC, Strong AE, Meyer JE (in press) Improved prediction of coral bleaching using high-resolution hotspot anomaly mapping. Proc 9th Int Coral Reef Symp

UNEP/IUCN (1988) Coral reefs of the world. Vol. 3: Central and western Pacific. Wells SM, Jenkins MD (eds). IUCN and UNEP, 329 pp

Vazquez J, Perry K, Kilpatrick K (1998) NOAA/NASA AVHRR Oceans Pathfinder Sea Surface Temperature Data Set User's Reference Manual Version 4.0. JPL Publication D-14070 available online at http://podaac.jpl.nasa.gov/

Wellington, GM, Glynn PW, Strong AE, Navarrete SA, Wieters E, Hubbard D (2001) Crisis on coral reefs linked to climate change. EOS 82:1-7

Williams EH Jr, Bunkley-Williams L (1990) The world-wide coral reef bleaching cycle and related sources of coral mortality. Atoll Res Bull 335:1-71

Wilkinson C (2000) (ed) Status of coral reefs of the world: 2000. Australian Institute of Marine Science, Townsville.

WWF South Pacific Programme (2000a) Pacific reefs hit by coral bleaching. South Pacific Currents 10:1-4. (http://www.wwfpacific.org.fj/bulletin10.htm)

WWF South Pacific Programme (2000b) Coral bleaching hits reefs in Solomon Islands. South Pacific Currents 9: 3-4. (http://www.wwfpacific.org.fj/bulletin9.htm)