An Evaluation of Environmental Parameters Coincident with the Partial Bleaching Event in St. Croix, U.S. Virgin Islands 2003

Derek MANZELLO[1*], James C. HENDEE[1], Dave WARD[2] and Zandy HILLIS-STARR[3]

[1] National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratories, Miami, Florida 33149-1026
[2] Scuba Shack, P.O. Box 3221, Frederiksted, US Virgin Islands 00841-3221
[3] National Park Service, Christianhead, St. Croix, US Virgin Islands 00820-4611
[*] Corresponding author: Derek Manzello
Fax: +1-305-361-4447, email: Derek.Manzello@noaa.gov

Abstract A partial bleaching event was reported in September and October 2003 in St. Croix, yet no bleaching alert was produced by the expert system software dubbed the Coral Reef Early Warning System (CREWS). This presents an opportunity for refining the modeling and predictive success of the CREWS software specifically for the St. Croix site by examination of the pertinent environmental parameters (sea temperature, wind speeds, irradiance) associated with the 2003 bleaching event. Elevated sea temperatures were likely the primary catalyst of bleaching and were coincident with dampened wind speeds. The least attenuation (greatest penetration) of UVB occurred during October when bleaching was most severe, but was variable. A nearly parallel trend with wind speed and UVB penetration was found and supports the hypothesis that the attenuation of UVB into the water column is controlled by CDOM concentrations, which are elevated due to wind-driven mixing.

Keywords Coral Bleaching – Thermal Stress – Solar Radiation – Wind – CDOM

Introduction

The Coral Reef Early Warning System (CREWS)

The Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA) has set a course to complete installation of a network of meteorological and oceanographic monitoring stations at all major United States coral reef areas by 2010. The basic instrumentation array measures air temperature, wind speed and direction, barometric pressure, photosynthetically active radiation (PAR, above and below water), ultraviolet radiation (UVR, above and below), salinity, and sea temperature. The oceanographic instruments, including light sensors, are situated at a nominal depth of 1m. Additional instruments are added for site-specific research programs. A data acquisition system gathers and averages the data, then transmits the hourly averages via satellite to NOAA's National Environmental Satellite, Data and Information Service data-download facility at Wallups Island, Virginia, USA, and is acquired via automated procedures for processing at AOML. Once the data arrive at AOML they are processed with a suite of expert systems which determine if the data being received are reasonable values, and whether environmental conditions are conducive to coral bleaching. The entire data collection and processing system is termed the Coral Reef Early Warning Sytem (CREWS, Hendee et al. 1998) and has successfully alerted to events apparently conducive to coral bleaching in the Florida Keys (Hendee et al. 1998, 2001) and the Great Barrier Reef (Hendee and Berkelemans 2003; Berkelmans et al. 2002). The latest stations added to the CREWS network were installed at Lee Stocking Island, Exuma Cays, Bahamas in 2001 and Salt River Bay, St. Croix, US Virgin Islands in 2002.

Coral Bleaching

Coral bleaching can be described as the general whitening of coral colonies due to the loss of the symbiotic zooxanthellae from the coral tissues and/or a reduction in the densities of zooxanthellae and photosynthetic pigment concentrations within the zooxanthellae (Glynn 1993). Bleaching in corals is a generalized stress response to unfavorable environmental conditions such as high sea temperature (especially at large spatial scales; Glynn 1993; Brown 1997; Hoegh-Guldberg 1999), acute salinity disturbances (Goreau 1964), and bacteriological or viral infection (Kushmaro et al. 1997), as well as other conditions (Glynn 1993, 1996). The relationship between rising sea temperatures, attributed to the El Niño-Southern Oscillation event, and coral bleaching became especially apparent in 1998 when virtually all reef areas of the world were impacted (Wilkinson et al. 1999). This one ENSO event resulted in mass coral bleaching that was responsible for the destruction of 16% of the world's coral reefs (Wilkinson 2000). Other conditions associated with high temperatures and bleaching are low wind speeds and/or low tide (Glynn 1993; Causey 1988; Jaap 1979, 1988; Lang 1988; Lang et al. 1988). These conditions favor localized heating and increased penetration of solar radiation. Further, a calm sea surface reduces the dappling (wave and ripple-associated reflectance) of sunlight creating the doldrum conditions that have been hypothesized to increase water clarity and decrease the attenuation of UVR in the water column due to the decrease in vertical mixing (Lesser and Lewis 1996; Lesser 2000). Elevated levels of UVR have been shown to induce coral bleaching without temperature stress (Gleason and Wellington 1993).

Corals and Irradiance

It has been known for more than three decades that severe photoinhibition of isolated zooxanthellae occurs at wavelengths less than 300 nm (Halldall 1968). Coral reefs naturally occur in clear oceanic water that is notably transparent to UVR (Jerlov 1950; Smith and Baker 1979), thus offering little protection to shallow water reef communities (Falkowski et al. 1990). Photosynthetic organisms that rely on the sun for energy are out of necessity exposed to high levels of both PAR and UVR (Jokiel 1980; Jokiel and York 1982, 1984). PAR incorporates the visible light spectrum from 400-700 nm, whereas UVR is conventionally split into UVB (280-320 nm) and UVA (320-400 nm) (Klein and Klein 1970; Parrish et al. 1978). The harmful effects of UVR may involve damage to DNA, proteins, and membrane lipids (Shick et al. 1996; Lesser 2000). UVB is known to be the most biocidal, as the energy at wavelengths between 280 and 320 nm are known to damage nucleic acids (Smith 1969; Setlow 1974) and inhibit chloroplast function (Jones and Kok 1976). The effect of UVR on coral-algal symbioses may be exacerbated because tissues are hyperoxic during the day (>250% air saturation: Kuhl et al. 1995) and most photoautotrophic corals produce more oxygen than the symbioses consumes in respiration (Mangum and Johansen 1982; Chalker et al. 1985; Shick 1990). Thus, conditions are conducive to oxidative stress in the symbioses via the production of reactive oxygen species, such as hydrogen peroxide, and hydroxyl and superoxide radicals (Dykens and Shick 1982; DiGiulio et al. 1989; Tyrell 1991; Dykens et al. 1992; Shick 1993). Recent work has shown that thermal stress coupled with high irradiances damages both the photochemistry and carbon fixation in zooxanthellae, whereas DNA damage, apoptosis, or necrosis occurs in the host tissues of hermatypic corals (Lesser and Farrell 2004). Therefore, long-term exposure to UVR may significantly affect the metabolic cost in both the coral host and zooxanthellae through the maintenance of enzymes that protect against oxygen toxicity which may occur under elevated temperatures and solar radiation (Dykens and Shick 1982; Lesser and Shick 1989; Lesser et al. 1990).

Impetus for Study

The objectives of the present contribution are to assess the roles of environmental parameters measured coincident with an episode of bleaching, and to further refine the expert system software. A partial bleaching event was reported in September and October 2003 in St. Croix, yet no CREWS bleaching alert, based on general production rules successfully utilized at Sombrero Reef (Hendee et al. 2001), was produced. The nature of the event (mild to moderate) indicated that the environmental parameters eliciting the bleaching response were right at the critical threshold values. An opportunity was thus available for refining the modeling and predictive success of the CREWS software specifically for the St. Croix site. This study assesses sea temperature, wind speeds, and irradiance associated with the 2003 partial bleaching event in St. Croix, at a small spatial scale, to better understand how those parameters may interact *in situ* to produce a bleaching event.

Methods

Expert System Software

The methodology and rules used in the development of the CREWS expert system software for producing bleaching alerts have been described in detail elsewhere (Hendee 2000; Hendee et al. 2001).

Light Penetration

The daily maximum values of UVB (280-320 nm) were determined. The determination of the penetration of UVB into the water column was approximated using the Δ UVB parameter. Δ UVB = $UVB_{surface} - UVB_{1m}$ and acts as a proxy for the attenuation of UVB in the water column as the higher the value, the greater the UVB attenuated (less penetration into the water column). In other words, low Δ UVB values indicate low attenuation of UVB (greater penetration of UVB into the water column), or clearer water with less particulate and dissolved organic matter. The daily maximum values of PAR (400-700 nm) and the determination of the penetration of PAR into the water column was approximated using the Δ PAR parameter as was done for UVB described above.

Description of Bleaching Event

September 2003

On September 5, 2003, a few scattered colonies of *Agaricia* spp. and *Diploria labyrinthiformis* began to show signs of paling adjacent to the CREWS station at Salt River Bay, St. Croix, US Virgin Islands (Fig. 1). Later, on September 17, 2003 a few scattered colonies of *Diploria strigosa* were observed to be pale; these colonies were adjacent to healthy looking conspecifics. Most (> 75% of colonies observed) of the *D. strigosa* colonies and a few *Millepora* spp. were found to be bleached in shallow water

(< 5 m), whereas between 10 and 13 m about half of the *D. strigosa*, *Millepora* spp., and *Montastraea annularis* spp. complex were bleached on September 30, 2003. At a depth > 15 m only three coral colonies (1 *D. labyrinthiformis*, 1 *M. annularis*, 1 *Millepora* spp.) were bleached within a 20 m radius of the CREWS station.

October 2003

On October 23, another field reconnaissance survey was made on the Buck Island Reef located east of the Salt River Bay CREWS station (Fig. 1). At this site, bleaching was reported in *Millepora* spp., *Porites porites*, *M. annularis* spp. complex, *D. strigosa*, *Siderastrea siderea*, *Agaricia* spp., and *D. labyrinthiformis.* All coral that was bleached was within an estimated depth range of 1 to 4 m. Small *Acropora palmata* recruits were found to have scattered pale blotches, but it was impossible in this type of survey to discern if this was due to bleaching, disease or the actions of gastropods or fireworms. For *P. porites* it was noted that the tops of the colonies were completely bleached, whereas the sides were still pigmented.

Sea Temperature and Wind Speed

Table 1 details the ranges and averages of sea temperature and wind speeds during June, July, August, September and October, 2003. The general trend to note from Table 1 is a gradual increase in mean sea temperature over the course of the summer that reached a maximum value in October. The mean wind speeds showed the opposite trend, decreasing steadily from June through October with the lowest mean values being in October. The first signs of paling in corals (*Agaricia* spp. and *D. labryinthiformis*) were noted after sea temperatures reached an average of 29.6 ^{o}C over three days and wind speeds fell to an average of 7.6 knots over the same three days (Fig. 2). Sea temperatures averaged 28.9 ^{o}C for the 30 days preceding the first signs of coral bleaching, whereas during the two months of bleaching sea temperatures averaged 29.4 ^{o}C

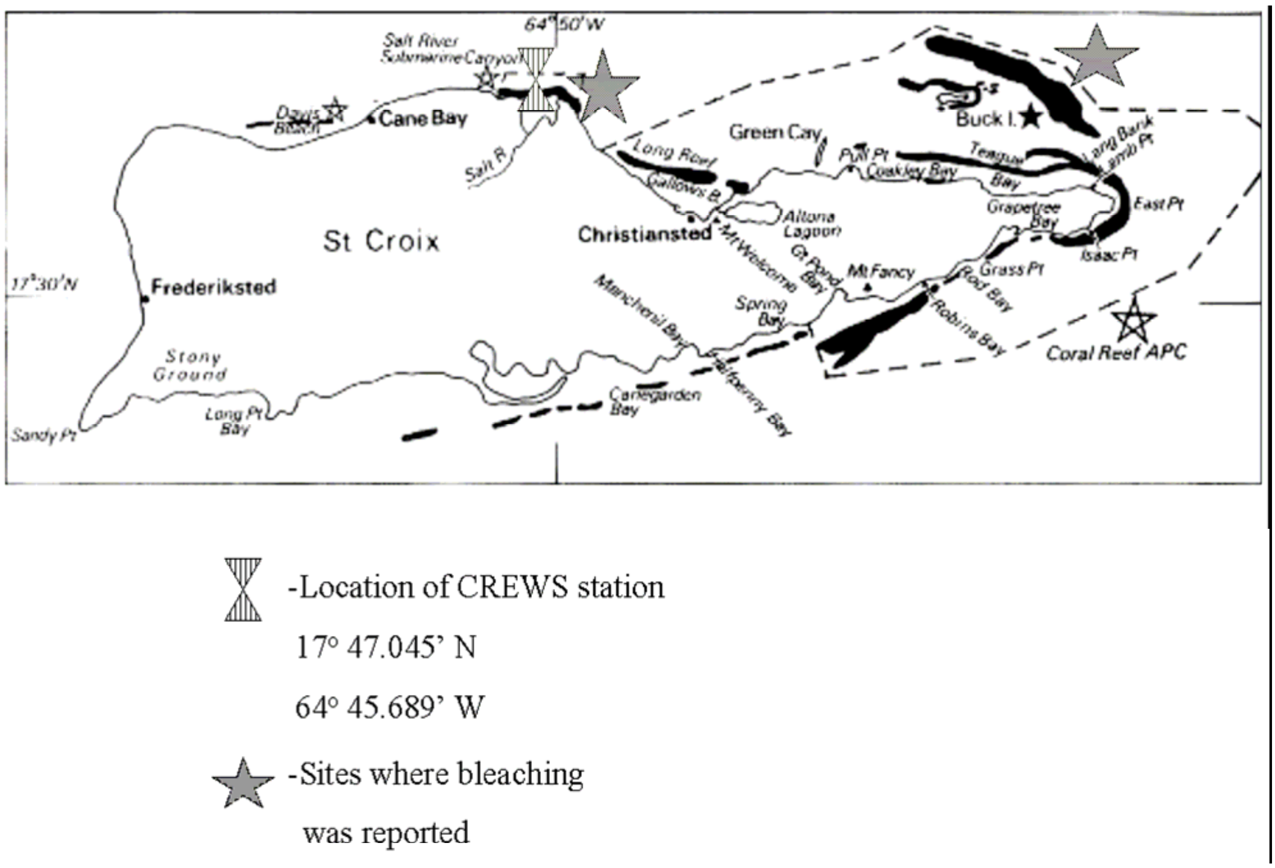

Fig. 1.Map of St. Croix, U.S. Virgin Islands depicting the location of the CREWS station and sites where bleaching was reported.

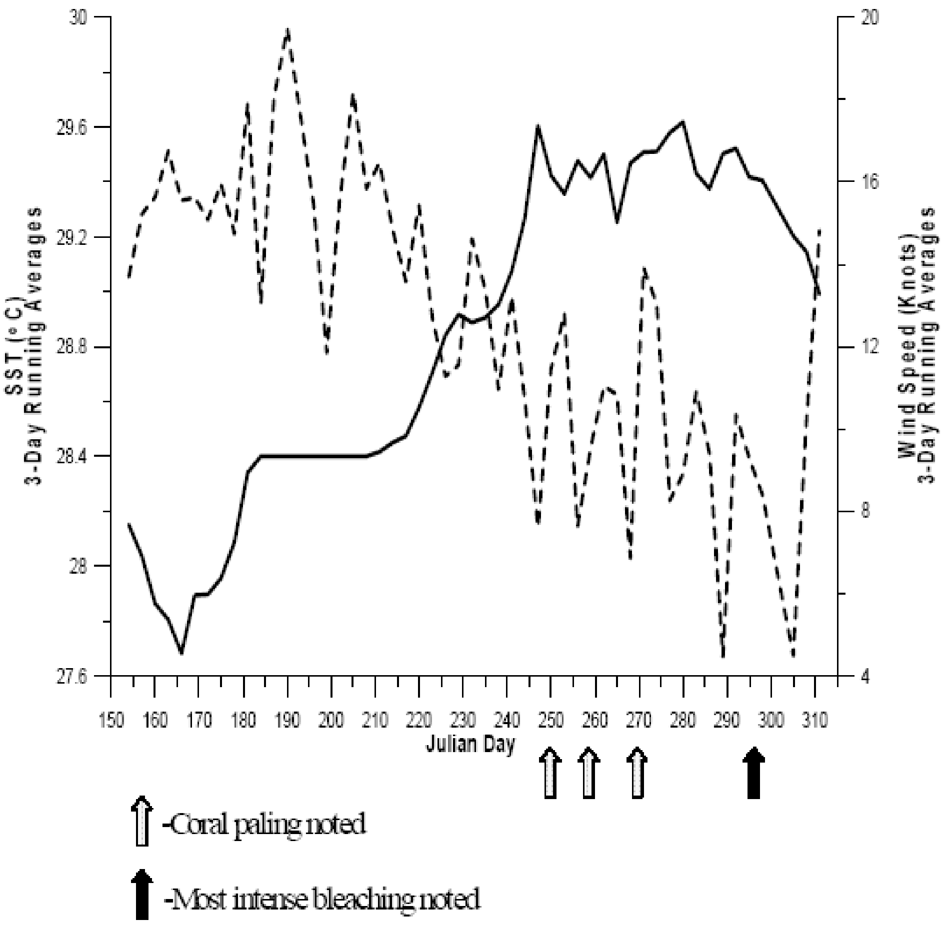

Fig. 2. Three-day running average sea temperatures (°C, solid line) and wind speeds (knots, dotted line) from day 152 (1 June 2003) through day 312 (6 November 2003) at Salt River Bay, St. Croix. Minor paling was noted in corals on days marked with dashed arrows. The most intense bleaching was noted on day 296 (23 October 2003) marked with the solid arrow.

Table 1. Sea temperatures (Celsius) and wind speeds (knots) at Salt River Bay during the summer and early fall of 2003.

Month	Sea Temp Range	Sea Temp
Mean	Wind Speed Range	Wind
Speed Mean		
June	27.5 – 28.6	28.0
	3.9 – 20.3	15.6
July	28.2 – 28.8	28.4
	3.6 – 23.3	16.1
August	28.1 – 29.8	28.8
	2.6 – 20.9	13.0
September	28.8 – 30.0	29.4
	0.3 – 18.9	10.4
October	29.0	29.5
	0.8 – 17.4	8.6

Results

The number of days per month that were categorized as hot, or exceeding the bleaching threshold (coral bleaching threshold sea surface temperature (SST) = maximum monthly mean SST + 1 °C; Strong and Liu, personal communication) of 29.3 °C set for the U.S. Virgin Islands are listed in Table 2. The entire month of September exceeded the bleaching threshold, whereas only 26 days of October exceeded this threshold value.

The potential Synergistic Role of Irradiance

UVR

Table 3 depicts the ranges and averages of Δ UVB for the months of June, July, August, September and October, 2003.

Table 2. Number of days sea temperatures were at or exceeded bleaching threshold of 29.3 ^{o}C (http://orbit-net.nesdis.noaa.gov/orad/sub/sst_series_virginpath.html)

Month	Number of Days
June	0
July	0
August	1
September	30
October	26

Table 3. Δ UVB (mW cm^{-2}) at Salt River Bay for Summer and early Fall 2003.

Month	Δ UVB Range	Δ UVB Mean
June	3 – 17	12
July	8 – 20	14
August	9 – 25	14
September	3 – 22	12
October	4 – 19	10

The lowest mean Δ UVB values occurred in the month of October and the highest values occurred during the months of July and August. It is interesting to note that the mean Δ UVB was the same in June as it was in September. Coral bleaching began in September and did not occur in June, thus UVB was clearly not the sole parameter responsible for this bleaching event. Figure 3 shows the relationship between the elevation in sea temperature and increase in the penetration of UVB into the water column during the bleaching event. It is important to note that UVB penetration did not stay elevated during the entire course of the bleaching event (Fig. 3), but on average was higher, although during some days light penetration was no different, or even lower (see Julian day 270 of Fig. 3) than that seen during the bleaching event. The fact that this bleaching event was mild to moderate in its extent may be due to the fact that Δ UVB did not stay low (decreased attenuation) even though the critical sea temperature threshold was exceeded for 57 days in a row (Table 2). In other words, a mass bleaching event, rather than the partial event reported here, may require a more constant elevated penetration of UVB into the water column and/or a more severe temperature anomaly (i.e., greater number of 'hot' days or more drastic temperature extremes).

PAR

Table 4 depicts the ranges and averages of Δ PAR for the months of June, July, August, September and October 2003. The penetration of PAR into the water column was greatest in June and decreased to a minimum in October. The greatest intensities of PAR reaching the corals at Salt River Bay were in the three months preceding bleaching (June, July, August) (Table 4).

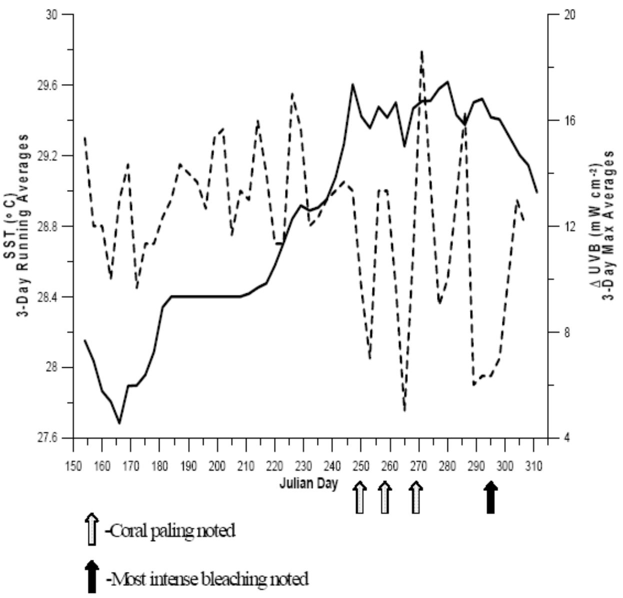

Fig. 3. Three-day running average sea temperature (^{o}C, solid line) and Δ UVB (mW cm^{-2}, dotted line) from day 152 (1 June 2003) through day 312 (6 November 2003) at Salt River Bay, St. Croix. Minor paling was noted in corals on days marked with dashed arrows. The most intense bleaching was noted on day 296 (23 October 2003) marked with the solid arrow.

Table 4. Δ PAR (μmol quanta m^{-2} s^{-1}) at Salt River Bay for Summer and early Fall 2003.

Month	Δ PAR Range	Δ PAR Mean
June	216 – 1107	811
July	385 – 1160	896
August	591 – 1363	999
September	527 – 1311	1003
October	589 – 1345	1008

Wind Speed and Δ UVB

Figure 4 depicts running 3-d averages in wind speed and Δ UVB. An elevated penetration of UVB into the water column (low Δ UVB) coincides with low wind speeds. As wind speeds slackened the penetration of UVB into the water column became greater, and vice versa.

Wind Speed and Δ PAR

Figure 5 depicts running 3-D averages of wind speed and Δ PAR. Converse to the trend seen in Δ UVB, Δ PAR was lowest (greatest penetration) when wind speeds were highest and greatest (least penetration) when wind speeds were lowest (Fig. 5).

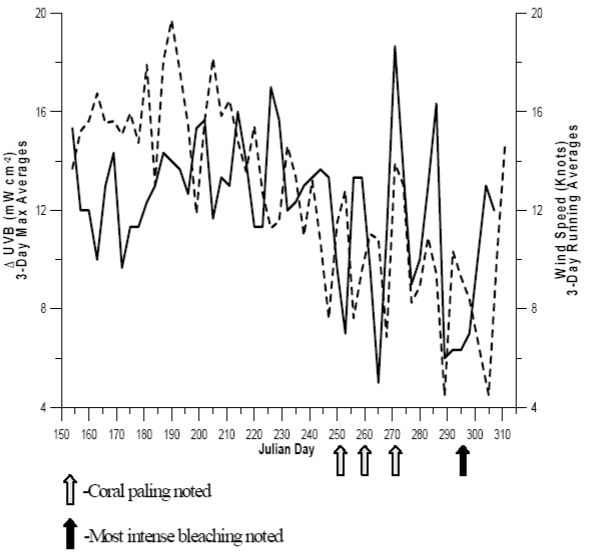

Fig. 4. Three-day running average Δ UVB (mW cm^{-2}, solid line) and wind speeds (knots, dotted line) from day 152 (1 June 2003) through day 312 (6 November 2003) at Salt River Bay, St. Croix. Minor paling was noted in corals on days marked with dashed arrows. The most intense bleaching was noted on day 296 (23 October 2003) marked with the solid arrow.

Discussion

Wind, CDOM and UVB penetration

CDOM is known to be the most important factor controlling the penetration of UVB into the water column (DeGrandpre et al. 1996; Vodacek et al. 1997; Blough and Del Vecchio 2002; Nelson and Siegel 2002; Zepp 2004). During summer months in the Florida Keys it was found that during periods of low winds a pronounced stratification occurs which indicates the development of a poorly-mixed thermocline that blocks transport of deeper, cooler waters to the surface layer (Zepp 2004). This stratification effect coincides with an increase in UVB penetration into surface waters due to photobleaching and microbial degradation of the CDOM (Vodacek et al. 1997; Moran et al. 2000; Nelson and Siegel 2002) coupled with a reduction in the influx of cooler, more opaque deep water (Zepp 2004). The net effect of this process is to increase the UVR penetration in surface waters above the thermocline. Surface waters are often laterally transported over reefs by current action, thus stratification enhances UVR exposure on reefs compared to well-mixed conditions when winds are stronger (Zepp 2004). This leads to the hypothesis that CDOM concentrations and UVR penetration in reefal waters are controlled by a complex interconnection between the stratification effect coupled with the transport and photobleaching of CDOM-laden nearshore waters as the primary source of CDOM is from seagrass and mangrove litter (Zepp 2004). The data reported here lends support that there was a minor stratification of warm, shallow waters that allowed a greater penetration of UVB (lower Δ UVB) at the onset and latter parts of the bleaching event (Fig. 3). It is highly pertinent to note that wind speeds increased during the months of bleaching and resulted a in greater attenuation of UVB (Fig. 4), likely due to enhanced vertical mixing and transport of more CDOM-rich waters from nearshore environments. This potential shading effect (greater attenuation of UVB) on the reefs may have played a role in making this bleaching event only moderate to mild, rather than severe, given that the bleaching threshold was met or exceeded for over 8 weeks. Further, the last bleaching report on 23 October 2003 noted that bleaching was most intense in the upper 4 m. Thus, the wind-driven mixing that can be seen as a greater attenuation of UVB in surface waters (Fig. 4) may have acted to shade deeper corals, whereas corals in shallow water were likely still light-stressed. The depth gradient seen in bleaching is highly suggestive of a light affect, but the slight paling of corals at depths > 15 m suggests temperature stress was a major factor as reefs near land masses typically have surface UVB levels penetrating to only ~6 m (Dunne and Brown 1996).

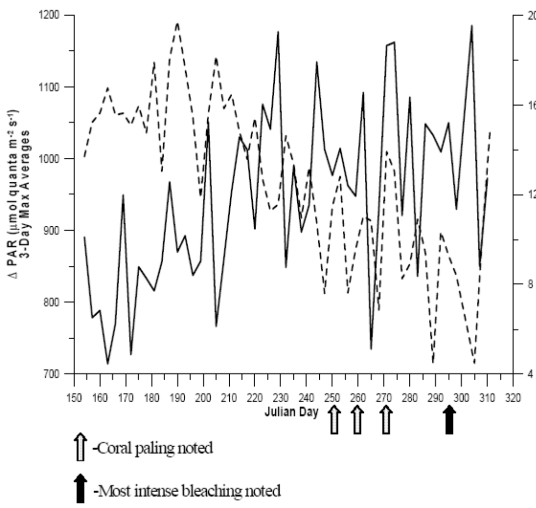

Fig. 5. Three-day running average Δ PAR (μmol quanta m^{-2} s^{-1}, solid line) and wind speeds (knots, dotted line) from day 152 (1 June 2003) through day 312 (6 November 2003) at Salt River Bay, St. Croix. Minor paling was noted in corals on days marked with dashed arrows. The most intense bleaching was noted on day 296 (23 October 2003) marked with the solid arrow.

In summary, sea temperature exceeded the bleaching threshold set for the U.S. Virgin Islands (http://orbit-net.nesdis.noaa.gov/orad/sub/sst_series_virginpath.html) for 57 days in a row (Table 2) likely making the primary catalyst of this bleaching event the temperature extremes. The increase in sea temperature was coincident with dampened wind speeds and, although variable, the least attenuation of UVB occurred during October (Table 3) when bleaching was most severe. The nearly parallel trend with wind speed and Δ UVB (Fig. 4) supports the hypothesis that the penetration of UVB into the water column is controlled by CDOM concentrations, which are elevated due to wind-driven mixing, as discussed earlier.

Two interesting questions can be addressed after assessing these data. 1) Will coral bleaching be more severe if UVB penetration stays elevated the entire time that the temperature threshold is met? 2) Will coral bleaching be less severe if temperature is at the threshold value, even if there is no observable change in the penetration of UVB into the water column? In other words, can moderate levels of CDOM help prevent thermally stressed corals from bleaching? Continued monitoring of these environmental parameters is needed to better understand the roles that each of these parameters is playing in the bleaching response. Specifically, a more detailed evaluation of the light parameters with quantification of attenuation coefficients (K_d) is needed to gain more reliable information on the potential stress the corals may be experiencing due to both PAR and UVR.

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