A DATA-DRIVEN EXPERT SYSTEM FOR PRODUCING CORAL BLEACHING ALERTS AT SOMBRERO REEF

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Abstract

A computer expert system shell was employed to provide interpretations of near real-time acquired combinations of meteorological and oceanographic parameters from a SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) station at Sombrero Reef. When environmental conditions were conducive to coral bleaching, according to different models, "alerts" were automatically posted to the World-Wide Web and emailed to researchers so they could verify and study bleaching events as they might happen The models were refined using feedback from field data on bleaching recorded after alerts from the expert system. The expert system was programmed to produce alerts when sea temperatures over 30°C occurred, or when temperatures of 30°C occurred concomitant with low winds. Alerts were produced in June 1998 when these conditions were met, but bleaching did not occur. Reconfiguration of the system, which included a point system for three models (high sea temperature only, high sea temperature plus low winds, high sea temperature plus low winds plus low tide), resulted in the transmittal of alerts which coincided with bleaching during early August, 1998. Bleaching occurred after sea temperature reached an average of 31.5°C over a period of three days, with excursions over 31.8°C occurring over 15 times during those three days. High sea temperatures, low wind speeds and a very low tide occurred coincident to the time of bleaching, but it was not possible to tell if these were factors acting synergistically.

Introduction

The SEAKEYS/C-MAN Network

The Coastal-Marine Automated (C-MAN) Network is a globally distributed collection of meteorological data acquisition stations, often at remote islands and lighthouses, maintained by the National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA). The data acquired from these sites are collected continuously then broadcast via satellite to a data archival site at Wallups Island, Virginia (USA). These stations are maintained by NDBC personnel, but because of their rugged construction require little maintenance. Within the Florida Keys National Marine Sanctuary (FKNMS) oceanographic instrumentation was added to all six C-MAN sites by the Florida Institute of Oceanography (FIO) in the early 1990s under the SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape; Ogden 1994) program so that long term data could eventually be compiled and used in helping to describe and understand environmental processes affecting coral reefs. The data from the oceanographic instruments are added to the standard meteorological data stream so that near real-time oceanographic data can accompany the meteorological data, and thus a more comprehensive picture might evolve. The oceanograhic instruments at the SEAKEYS/C-MAN stations are maintained by FIO personnel as part of an agreement between NOAA and FIO. The six sites of the SEAKEYS/C-MAN network are Fowey Rocks (within Biscayne National Park), Molasses Reef (east of Key Largo), southern Florida Bay (west of Long Key), Sombrero Reef (southeast of Marathon), Sand Key (south of Key West), and Dry Tortugas, at the terminus of the Florida Keys. The site of the present study is Sombrero Reef.

There are many physical, chemical and biological events of interest and concern to personnel of the FKNMS, marine biologists, oceanographers, fishermen and divers. Some of these events would be observable if it were possible to continuously be present at a remote site of interest, or if instrumentation could monitor the remote site and the observer could in turn routinely monitor the output of the instrumentation. Large volumes of data are generated by the SEAKEYS/C-MAN network, and no one has the time to look at every printout of data from every station, every day, seven days a week. The shear volume of data dictated the need for an automated system that could monitor the environmental data and produce specialized alerts of specific events, as indicated by prescribed or abnormal ranges or combinations of the measured parameters.

Expert Systems

The focus of the present study is an expert system (dubbed the Coral Reef Early Warning System, or CREWS) developed for the near real-time review of environmental conditions thought to be conducive to coral bleaching. Expert, or knowledge-based, systems are computer programs that are based on the use of artificial intelligence. Artificial intelligence involves the capability of a device such as a computer to perform tasks that would be considered intelligent if they were performed by a human (Mockler and Dologite 1992). Expert systems attempt to replicate the reasoning processes of experts and can make decisions and recommendations, or perform tasks, based on user input. Knowledge engineers construct expert systems in cooperation with problem domain experts so that the expert's knowledge is available at all times and in many places, as necessary. Automated processing of information, according to rules proscribed by experts, is the salient feature of expert systems. Expert systems derive their input for decision making from prompts at the user interface, or from data files stored on the computer. The knowledge base upon which the input is matched is generally represented by a series of IF/THEN statements, called production rules, which are written to approximate the expert's reasoning. If conditions are met for more than one production rule at the same time, the order of triggering for the rules is arranged according to the "salience" of the rule so that the rule with the highest salience is triggered (or "fired") first, then the rule with the next lowest salience, and so on. The degree of belief the expert has in the conclusion espoused in a production rule may be represented as a confidence factor (e.g., 0% to 100% confidence), or as a subjective term (e.g., "possibly," "probably," or "almost certainly") in the expert system. The expert system described herein provides automated coral bleaching "alerts" via email and the World-Wide Web ("the Web"), using subjective terms to describe probability of bleaching, and serves not only as a modeling tool for understanding the phenomenon of coral bleaching, but helps researchers to be present at a study site if conditions appear to be optimal for coral bleaching.

Coral Bleaching

Coral bleaching may be described as the general whitening of coral colonies due to the loss of symbiotic zooxanthellae from the coral tissues and/or reduction in photosynthetic pigment concentrations within the zooxanthellae (Glynn 1993). Bleaching may be a generalized stress response to harsh environmental conditions such as high sea temperature or abnormal salinity, bacteriological or viral infection, or for other unknown reasons (Glynn 1996; Kushmaro et al 1997). High sea temperatures are associated with most reported incidences of mass coral bleaching (Brown and Ogden 1993; Glynn 1996). Other conditions often associated with high temperatures and bleaching are low wind speed and/or low tide (Glynn 1993; Causey 1988; Jaap 1979, 1988; Lang 1988; Lang et al 1988). Such conditions favor localized heating and increased penetration of solar radiation. A very calm sea surface also reduces the "dappling" (wave and ripple-associated reflectance) of sunlight and this may contribute to photosystem damage in zooxanthellae.

Bleaching can be fatal to the coral if the duration and/or intensity of a stressor is suffficient (Glynn 1996). Bleaching events have been reported with increasing frequency during the past twenty years from a variety of locations. The bleaching reported in 1997 and, particularly in 1998 (Wilkinson et al 1999), was unprecedented with virtually all reef areas of the world affected, some severely with consequent mortality. This has been attributed to elevated sea surface temperatures associated with the most recent El Niño/Southern Oscillation (ENSO) event (Wilkinson et al 1999). Thus, there is an increasing interest in the early detection of bleaching events and the environmental conditions that cause such events and determine their intensity.

Methods

CLIPS (C Language Integrated Production System) was used for the expert system shell. Production rules which had a greater number of stressful environmental conditions for longer periods during the day had higher salience and scored higher than rules which had less matching conditions for shorter periods during the day. The number of points for each rule (representing a model of conditions) continued to be tallied for each week. Thus, if a 12-point rule fired three times in a week, that rule would tally 36 points by the end of the week. In theory, as bleaching is verified in the field, the model which had the greatest number of points at the time of bleaching would represent the most likely conditions which resulted in coral bleaching. These are the models which were programmed into CREWS for reviewing Sombrero Reef data:

* Very high or drastically high sea temperature only.
* Very high or drastically high sea temperature; and low, very low or drastically low winds.
* Very high or drastically high sea temperature; low, very low or drastically low winds; and very low or drastically low tide.

The expert system proceeds in three different stages.

Stage 1--Data Parsing

Every day at 4:05 am, an automated data acquisition program is initiated. The program uses communications software and a modem to call a location at Wallups Island, Virginia, which holds the archived raw data. The data held are those which were collected five minutes earlier via a satellite from the SEAKEYS/C-MAN stations in the FKNMS, which transmit the data on the hour, every hour. From the archived site, a caller can acquire data for the last 72 hours' worth of transmissions (including the those most recently acquired) from the stations. After the program makes contact with the archival site, using a password, a special prearranged data suite identifier is supplied. The required data are then supplied to the screen, and the program captures the whole session in a file. The data represent values recorded from instruments designed to measure barometric pressure, wind speed, wind gusts, wind direction, air temperature, sea temperature, salinity, photosynthetically active radiation (PAR), and sensor depth, which provides an indirect measurement of the state of the tide or, where applicable, water level. These sensors are not present at all stations, or they may be inoperable at certain times of the year. With the data are also sent the station name, date and time (GMT).

The raw data file captured by the data acquisition module is parsed to extract the data of interest, which are written to an ASCII text file in a format that can be read and interpreted by Stage 2, described below. This parsed file is easier to work with than the complex raw file. CLIPS is used as the data parser, as programming language classes for each SEAKEYS/C-MAN station are the same, and code changes due to data stream changes at each station are more easy to effect without having to recompile an executable, as in a language like C. Also, the ASCII programming code is directly portable across operating systems and immediately executable when using CLIPS. Thus, programming code was often developed on a PC, then implemented on a UNIX workstation.

Stage 2--Data Subjectification: Information Synthesis

ASCII data files produced in Stage 1 are screened against production rules to determine whether the values for the instruments are within realistic ranges, or whether the instrument appears to be malfunctioning or off-line (garbled or no data). To aid in the analysis of data, which may vary widely depending upon the time of day and the season of the year, values are averaged for eight three-hour periods per day, termed midnight (2200 to 0100 hrs local time), pre-dawn (0100 to 0400 hrs), dawn

(0400 to 0700 hrs), morning (0700 to 1000 hrs), mid-day (1000 to 1300 hrs), pre-sunset (1300 to 1600 hrs), sunset (1600 to 1900) and evening (1900 to 2200 hrs). These groupings are convenient because meteorological phenomena quite often show predictable fluctuations during these periods of the day, for instance the change of wind direction and wind speed with sunrise and sunset. The averaged values within each of these categories are then subjectively assigned to fall within one of eleven categories: unbelievably low, drastically low, very low, low, somewhat low, average, somewhat high, high, very high, drastically high, and unbelievably high. These groupings are arbitrary terms, of course, and parameters such as wind direction are further translated to different regions of the compass (e.g., NE-ENE). The assignment of values to these categories depends upon what the season of year is (spring, summer, fall or winter), so, for instance, what might be considered "somewhat high" in winter might otherwise be considered to be "average" during summer. Values which are determined to be "unbelievably high" or "unbelievably low" represent values which are considered to be totally unrealistic for the parameter in question. However, should it happen that these values begin to represent real-life values, the ranges may be easily reset to encompass the newer values.

FIO personnel visit the sites generally twice a month (except for Dry Tortugas, visited generally once a month) so corrective maintenance of the oceanographic sensors can be attended to as necessary. For instance, oceanographic instruments may become biofouled by encrusting marine organisms and such, and must be cleaned periodically. Sea temperature and salinity sensors are "sea-truthed" during the station visits. That is, calibrated instruments are taken into the field and measured at the same time the in situ instruments make their automated measurements to see if the in situ instrument needs to be replaced, or its data need to be corrected. This sea-truth information is compiled in an FIO maintenance database. Analysis of this database is used in instrument replacement and data correction decisions. Meteorological instruments are maintained by NDBC. If any of the instruments are malfunctioning, the expert system code is easily adjusted so that those values are not accounted for in the process. Under Stage 3 (below), production rules requiring measurements from the malfunctioning instrument simply do not fire, but the fact of a malfunctioning instrument is sent via email to the field team office for maintenance review.

The status of the parameters, that is, where they are on the continuum from unbelievably low to unbelievably high, and when these values occurred (i.e., the period of the day), are saved as "facts" in a text file, which is loaded into the expert system under Stage 3 processing. These facts thus represent subjective interpretations of the measured data, and therefore represent information, not just columns of numbers.

Stage 3--Information Processing

The information synthesis in Stage 2, proceeding according to how experts view the ranges of data, makes the further processing for the benefit of determining environmental trends and events easier in the context of an expert system. At this point, information represented as occurring through time (since the "facts" show data progress through the previous 72 hours, or longer still, if desired), presents an enormous range of possibilities for further processing, limited only by the skill of the knowledge engineer, the experts, and the time required for coding.

There is an excellent chance that environmentally-induced (i.e., not by pathogens) coral bleaching can be predicted; however, research indicates that bleaching occurs under different conditions for different species, and at different localities for each species (e.g., CARICOMP 1997). As mentioned above, high sea temperature alone, or in combination with low wind speeds and/or high solar radiation, appear to be the chief stressors involved for most species, whether they are the sole causative agents or not. The following pseudocode represents one of the production rules of the coral bleaching module of CREWS:

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IF sea temperature is drastically high all day,
AND wind speed is very low all day,
AND the tide is drastically low during midday,
THEN output alert:
        "Conditions are probably favorable for coral bleaching."
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This particular production rule has a higher salience than other rules because it represents more extreme environmental stress--drastically high temperatures together with conditions probably allowing high solar irradiation. It would be the first to "fire" when the prescribed conditions are met. This particular rule would also carry more points commensurate with its higher salience. Thus, if higher salience rules fire a number of times throughout a week's time, a greater number of points would be accumulated for these particular conditions, and if bleaching did occur at this time, a greater weight to the validity of this particular model would accrue. On the other hand, if bleaching did not occur during this time, less validity would accrue, and the model (i.e., the production rules) would be adjusted as advised by the expert(s). If a parameter is missing because the instrument is malfunctioning, rules which depend on that parameter will not fire. For instance, in the example rule immediately above, if tide measurements were not forthcoming, only rules which matched low wind speed and high temperature would fire. Since several models can be coded at one time, and the resulting points tabulated for these models at the end of each week, the expert can gain a fuller understanding of which environmental conditions were more conducive to coral bleaching.

The production rules were drawn from consultations with experts (B. Causey, W. Jaap, J. Porter, A. Szmant, J. Lang) in the field of coral bleaching, from discussions in the literature, as cited above and below, and from the experience and education of one of us (EM). It should be noted, however, that there is still controversy in the literature as to all the physical conditions responsible for coral bleaching (for reviews, see Brown 1996, and Glynn 1996), but generally there is agreement that high sea temperature is a major contributing or coincident factor. Although one of the experts (J. Porter, personal communication) stressed high irradiance to be an important factor, the SEAKEYS station at Sombrero Reef was not capable of monitoring irradiance (PAR) at the time of the present study. We could, however, infer that other conditions would be right to allow for a greater penetration of light. If wind speed was low we would expect that wave action would be less and allow for less refraction of light as it entered the water. If the tide was very low, light would be expected to have a greater penetration. However, tide measurement was not in place during June and most of July, 1998.

If a combination of parameters was considered favorable, and that combination occurred all day, then the combination was considered more favorable (e.g., "probably favorable"), rather than if the combination occurred only during one period of the day ("favorable," e.g., during the afternoon). If drastically high sea temperatures occurred during any period of day (three hours or longer), along with low wind speeds and low tide, conditions were considered "probably favorable" for bleaching.

The system was configured so that alerts were only kept for the previous seven days' worth of alerts, so that if no new production rules were triggered for a whole week, the alerts would no longer be sent after a week's time.

During June and most of July, coral bleaching alerts reported only on the number of production rules triggered. During the last week of July and thereafter, the system was re-configured so that the number of production rules triggered and the number of accumulated points were calculated and presented. For sea temperature, one point was totalled for every hour "very high" conditions were met, or two points for every hour "drastically high" sea temperature conditions were met. For all wind and tide events, one point accumulated for each hour conditions were met.

Field Validation

To verify whether coral bleaching had occurred after the alerts began to be posted, visits were made by FIO personnel every seven to ten days to Sombrero Reef and a representative reef spur was surveyed to determine the extent of coral bleaching, if any. Also, one of us (EM) visited the site from time to time in conjunction with conducting a college class on coral disease etiology. We also accumulated reports on coral bleaching posted on the Internet listserver coral-list (Coral Health and Monitoring Program, NOAA, 1998), and via personal enquiries with colleagues diving in the area. Using feedback from the field, the production rules were adjusted during July, 1998, to reflect which conditions appeared to be more likely to be conducive to coral bleaching than during June, 1998.

Results

CREWS was successful in matching patterns prescribed in production rules designed to alert users of conditions conducive to coral bleaching. The alerts were emailed and posted to the Web reliably and continually without intervention by the knowledge engineer. After feedback from the first alerts, CREWS was adjusted to send alerts after higher temperatures, together with low winds and low tide, were achieved.

Table 1 depicts the ranges and averages of sea temperature and wind speeds during June, July and August, 1998. During June, the sea temperature ranged from 27.6°C to 32.1°C (average 30.2°C), while wind speed averaged 7.5 knots with a range of 0 to 21.2 knots. During July, the sea temperature ranged from 29.6°C to 32.4°C (average 30.8°C), while wind speed averaged 10.5 knots with a range of 0 to 27.8 knots. During August, the sea temperature ranged from 29.8°C to 32.5°C (average 31.1°C), while wind speed averaged 8.7 knots with a range of 0 to 22.9 knots. Figure 1 depicts running three-day averages in sea temperature and wind speed. Figure 2 depicts the number of incidences of sea temperature readings over 31.8°C during the previous 72 hours.

The following reports were assembled from observations by ourselves and experienced divers who are knowledgable in coral identification and provided us with their field notes (please see Acknowledgments), or announced their findings on the coral-list listserver (Coral Health and Monitoring Program, NOAA, 1998).

The incidence of high (i.e., over 30°C) sea temperature with low winds, in the context of possible coral bleaching, was reported automatically to researchers via email and the Web on June 1, 1998. This was 17 days before another remote sensing effort (see Strong et al 1996 for description) recognized high sea temperatures in the area as possibly being conducive to coral bleaching (Strong 1998, unpublished data). Over the four subsequent weeks, no significant (i.e., "mass") bleaching occurred at Sombrero Reef. At nearby Delta Shoals, a few colonies of *Millepora alcicornis* were bleached, and a few other corals and the zoanthid *Palythoa caribaeorum* colonies were a bit pale and exhibited signs of stress (i.e., all individuals of the colonies completely contracted). It is noteworthy that June, 1998, was reported as the hottest June on record in Florida (National Climate Data Center, NOAA, 1998), yet bleaching did not occur.

An example coral bleaching alert for June is depicted in Fig. 3; however, since no bleaching occurred, the expert system was adjusted upward after July 14 to begin sending alerts when sea temperatures reached over 31.0°C instead of over 30.0°C. Example alerts for July and August are given in Figs. 4 and 5, respectively.

During mid-July, several colonies of Millepora sp. were observed to exhibit bleaching, while *Diploria* spp., *Montastrea* spp., *Siderastrea* spp., and other corals were in fairly good shape with dark coloration. *P. caribaeorum* had not yet bleached but continued to exhibit the aforementioned signs of stress.

Some time around August 15, 1998 (we did not visit the reef on that particular day), a significant increase in bleaching began to ensue at Sombrero Reef. Most colonies of *Colpophyllia natans* were well bleached, while *Diploria strigosa* exhibited light to moderate bleaching. There was very little to fairly extensive bleaching of *Montastrea annularis* and *M. faveolata*, yet none were completely bleached. Many colonies of *Agaricia agaicites* were completely bleached, while *Acropora palmata* was light on top but not extensively bleached. A number of large colonies of *Siderastrea siderea* were not bleached at all, although other species around them were. One colony of *S. siderea* possessed a band around its base moderately bleached but normal on top. Several *Millepora complanata* and many *Millepora alciconis* were completely bleached. Some unidentified species of *Erythropodium* were very bleached. *P. caribaeorum* exhibited patchy bleaching; that is, some areas were very white but otherwise normal colored areas all around. We estimated the coral bleaching at Sombrero Reef during this period was a little greater than 50% of the entire coral coverage.

Discussion

In mid-August, 1998, coral bleaching ensued at Sombrero Reef only after sea temperatures averaged greater than 31.5°C and the incidences of hourly temperature readings over 31.8°C were greater than about 15 during a 72 hour period. Although coral bleaching occurred coincident with these high sea temperatures, low winds, and a very low tide, there is no experimental field evidence (i.e., no direct measurements of light in situ) to conclude that high irradiance was partially responsible for the event. It is our conclusion, then, that the high 72 hr average temperature of 31.5°C, representing chronic stress, was important in elucidating the bleaching response, but that the acute stress of hourly very high temperatures was also important, and that the contribution of high irradiance, facilitated by low winds and at least one very low tide, may also have played a role.

Bleaching episodes in 1982 (Fisk and Done 1985; Harriott 1985; Oliver 1985) and 1987 (Causey 1988; Jaap 1988; Lang 1988; Goenaga et al 1989) were described as possibly attributable to high sea temperatures together with low winds, which presumably allowed high insolation; however, no light measurements were taken in these studies. Coles and Jokiel (1978) and Glynn et al (1992) discovered that interactive effects of high temperature and ambient light moderated the degree of bleaching in certain species of corals. Gleason and Wellington (1993, 1995) have offered convincing evidence that UVB (280 to 320 nm) radiation has an effect on coral survival, but these studies should be reviewed in light of Dunne's (1994) critique. For comprehensive reviews on the subject see Glynn (1996) and Brown (1996). Whether the conditions encoded as production rules in CREWS were in fact responsible for coral bleaching will require further laboratory studies on the effect of single and multiple stressors on corals, especially for corals found at Sombrero Reef.

The use of satellite remote sensing of the environment for purposes of detecting high temperatures conducive to coral bleaching has begun only in the 1990s (McCormack and Strong, 1990; Strong, et al 1996), but there has been no effort to date at real-time remote sensing using in situ instrumentation to detect multiple conditions conducive to coral bleaching. CREWS has been designed to afford the researcher the capability of modeling multiple stressors and their effect on coral bleaching in the field. Reconfiguring the production rules in response to feedback from the field was relatively easy. As laboratory work elucidates the probable synergistic effect of multiple stressors, and as field evidence and validation efforts accrue, CREWS will be reconfigured and should prove to be a valuable tool for sanctuary management. Now that the difficult work of building the expert system infrastructure (mainly, Stage 2) has been accomplished, many other subdomain expert systems (e.g., possibly those for harmful algal blooms and fisheries dynamics), hence ecosystem models, should be relatively easy to configure and implement.

CREWS will eventually be implemented at the other SEAKEYS/C-MAN monitoring sites and will thus provide a means for the near real-time synoptic modeling of monitored parameters in the Florida Keys and Florida Bay. This will give FKNMS management further input for decision support during times of environmental stress when time to decision may be critical.

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Table 1

Sea Temperatures (Celcius) and Wind Speeds (knots)
at Sombrero Reef During Summer, 1998.

Figure 1. Three-day running average sea temperatures (Celcius, solid line) and wind speeds (knots, hashed line) from day 150 (May 20, 1998) through day 270 (September 27, 1998) at Sombrero Reef, Florida Keys. Mass bleaching began around August 15 (day 227).

Figure 2. Number of hourly readings over 31.8^{o}C during each 72 hour period from day 150 (May 20, 1998) through day 270 (September 27, 1998) at Sombrero Reef, Florida Keys.

Figure 3. Example coral bleaching alert from June 21, 1998. Notice that the most recent records are added at the top of each report. Each record stays on the list for a week, but will be moved toward the bottom of the list as other records are added. Some records have been deleted from this figure.

Figure 4. Example coral bleaching alert from July 29, 1998. During the later part of July, the expert system was reconfigured so that temperatures over 31.0^{o}C were considered “very high” and so that points were accummulated and presented for each model.

Figure 5. Example coral bleaching alert for Sombrero Reef, August 16, 1998.

Table 1

Sea Temperatures (Celcius) and Wind Speeds (knots)
at Sombrero Reef During Summer, 1998.

	Sea Temp Range	Sea Temp Mean	Wind Speed Range	Wind Speed Mean
June	27.6 - 32.1	30.2	0 - 21.2	7.5
July	29.6 - 32.4	30.8	0 - 27.8	10.5
August	29.8 - 32.5	31.1	0 - 22.9	8.7

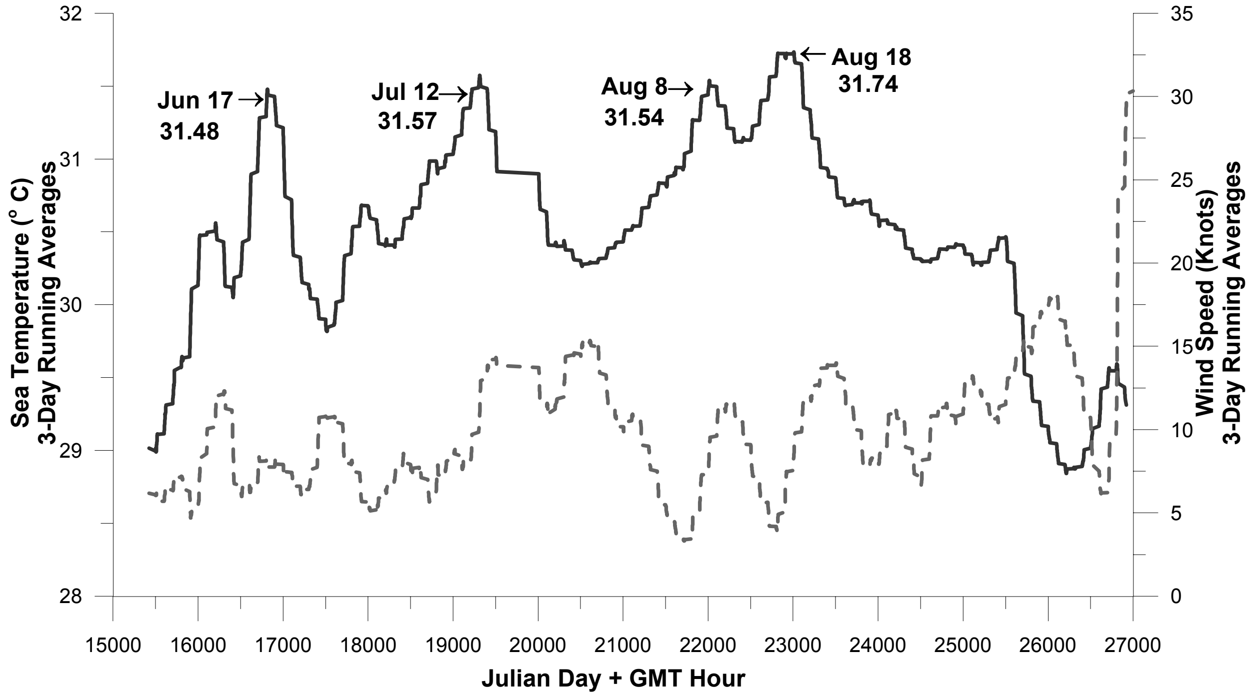

Figure 1. Three-day running average sea temperatures (Celcius, solid line) and wind speeds (knots, hashed line) from day 150 (May 20, 1998) through day 270 (September 27, 1998) at Sombrero Reef, Florida Keys. Mass bleaching began around August 15 (day 227).

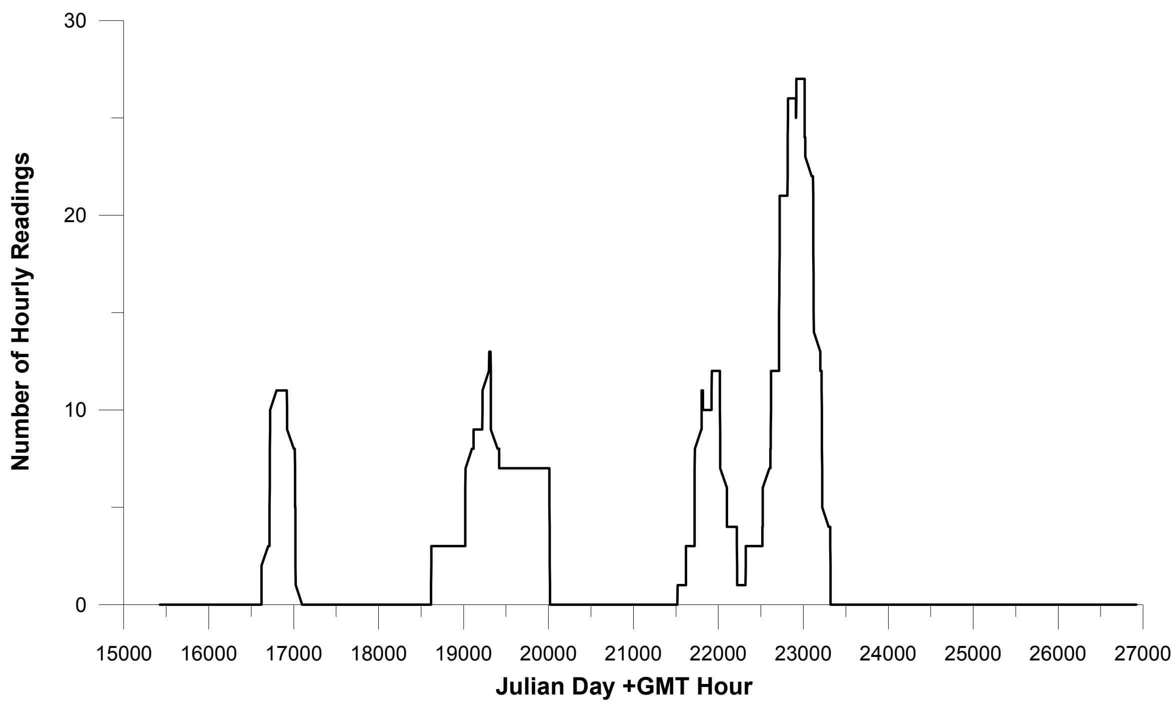

Figure 2. Number of hourly readings over 31.8°C during each 72 hour period from day 150 (May 20, 1998) through day 270 (September 27, 1998) at Sombrero Reef, Florida Keys.

~~~~ Coral Bleaching Alert for 06/21/1998 ~~~~

Rule-B9
Conditions probably favorable for bleaching midnight on 06/21/1998, because
FIO sea temperature was very high (about 30.2),
and wind speed was low (about 6.9).

Rule-B9
Conditions probably favorable for bleaching evening on 06/21/1998, because
FIO sea temperature was very high (about 30.4),
and wind speed was low (about 7.4).

Rule-B27
Conditions possibly favorable for bleaching mid-day on 06/21/1998, because
FIO sea temperature was high (about 30.0),
wind speed was low (about 7.4),
and wind gusts were low (about 8.4).

Rule-B29
Conditions possibly favorable for bleaching pre-dawn on 06/21/1998, because
FIO sea temperature was high (about 30.0),
and wind speed was low (about 4.9).

Rule-B7a
Conditions probably favorable for bleaching mid-day on 06/20/1998, because
FIO sea temperature was very high (about 30.2),
wind speed was low (about 5.4),
and wind gusts were low (about 6.3).

[etc.]

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Number of rules triggered: 26

Figure 3. Example coral bleaching alert from June 21, 1998. Notice that the most recent records are added at the top of each report. Each record stays on the list for a week, but will be moved toward the bottom of the list as other records are added.

~~~~ Coral Bleaching Alert for 07/29/1998 ~~~~

Rule-T8 (3)
Conditions possibly favorable for bleaching sunset on 07/27/1998, because FIO sea temperature was very high (about 31.0).

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High temperature points:	3
High temperature, low wind points:	0
High temperature, low wind, low tide points:	0
Number of rules triggered:	1

Figure 4. Example coral bleaching alert from July 29, 1998. During the later part of July, the expert system was reconfigured so that temperatures over 31.0°C were considered “very high” and so that points were accummulated and presented for each model.

~~~~ Coral Bleaching Alert for 08/16/1998 ~~~~

Rule-T4 (9)
Conditions possibly favorable for bleaching night-hours on 08/16/1998, because
FIO sea temperature was very high (about 31.6).

Rule-TW6 (18)
Conditions probably favorable for bleaching afternoon on 08/15/1998 because
FIO sea temperature was extremely high (about 32.3),
and wind speed was very low (about 4.1) during afternoon
(but PAR not measured).

Rule-TW8 (9)
Conditions probably favorable for bleaching mid-day on 08/15/1998 because
FIO sea temperature was extremely high (about 32.1),
and wind speed was very low (about 2.4) during mid-day
(but PAR not measured).

[...records deleted...]

Rule-TWT1 (9)
Conditions favorable for bleaching on 08/11/1998, because
FIO sea temperature was very high (about 31.2) during mid-day,
wind speed was very low (about 5.9), during mid-day,
and tide was very low (about -4.40) during mid-day.

Rule-T8 (3)
Conditions possibly favorable for bleaching evening on 08/10/1998, because
FIO sea temperature was very high (about 31.2).

Rule-T8 (3)
Conditions possibly favorable for bleaching midnight on 08/10/1998, because
FIO sea temperature was very high (about 31.0).

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High temperature points:	114
High temperature, low wind points:	39
High temperature, low wind, low tide points:	9
Number of rules triggered:	24

Figure 5. Example coral bleaching alert for Sombrero Reef, August 16, 1998.