A Data-Driven Expert System for Producing Coral Bleaching Alerts*

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Abstract

As a recent enhancement to the SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape) environmental monitoring network, an expert system shell was employed to provide daily interpretations of near real-time acquired combinations of meteorological and oceanographic parameters as they meet criteria generally thought to be conducive to coral bleaching. These interpretations were automatically posted to the World-Wide Web and emailed to FKNMS managers and scientists so they could witness and study bleaching events as they might happen, and so that a model could be developed with greater precision in identifying physical factors conducive to coral bleaching. The expert system, as a model, was successful in showing that certain assumptions by experts regarding coral bleaching apparently do not hold at Sombrero Reef.

1 Introduction

1.1 Background

The Florida Keys National Marine Sanctuary (FKNMS) was established to provide protection for a unique marine ecosystem in the Florida Keys so that generations of visitors could enjoy the beauty of coral reefs and the enjoyment of water sports such as skin and scuba diving, boating and fishing. “Protection” entails not only the policing of the Sanctuary to prevent plundering of its natural resources by poachers, but also monitoring the status or condition of the ecosystem so that appropriate steps may be taken in the event anthropogenic stressors threaten the environment. The FKNMS also seeks to support basic research of the marine ecosystem to further understand its mysteries, and, where applicable, to apply the findings of that research not only to the general fund of knowledge, but toward greater enjoyment for its visitors. Conservation and understanding of the Florida Keys natural marine resources are its prime directives.

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At the National Oceanic and Atmospheric Administration's (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML), in Miami, Florida, environmental data are acquired from remote sites on lighthouses and navigational aids situated at reefs and other strategic locations within and near the FKNMS via a satellite data archival site at Wallups Island, Virginia. The data are collected at the sites continuously then transmitted hourly. Oceanographic instruments (measuring sea temperature and salinity) are maintained by the Florida Institute of Oceanography (FIO), and meteorological instruments (for measuring wind speed, wind gust, wind direction, air temperature, dew point and barometric pressure) are maintained by the National Data Buoy Center (NDBC) of NOAA. There are currently six sites, which have been termed the SEAKEYS (Sustained Ecological Research Related to Management of the Florida Keys Seascape; Ogden et al [1]) network: Fowey Rocks (in Biscayne National Park), Molasses Reef (near Key Largo), southern Florida Bay (near Long Key), Sombrero Reef (near Marathon), Sand Key (near Key West), Dry Tortugas (at the very end of the Florida Keys), and northwestern Florida Bay (near Cape Sable).

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 of course 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. Except in very critical cases, however, the truth is that large volumes of data are generated by instruments at such sites, as in the SEAKEYS network, and no one has the time to look at every printout of data from every station, every day, seven days a week. It is highly desirable to have an automated system that can monitor meteorological and oceanographic parameters and produce specialized alerts of specific events, as indicated by abnormally high ranges or combinations of parameters. The expert system described here collects data from one station (Sombrero Reef) in the SEAKEYS network and produces automated email and World-Wide Web alerts when conditions are thought to be conducive to coral bleaching. The present expert system, which we have dubbed the Coral Reef Early Warning System (CREWS), represents a first step in the construction of a larger coral reef specific expert system, and the first of many applications for marine environmental monitoring utilizing the methodology described in Hendee [2] and herein.

1.2 Expert Systems

Expert systems, or knowledge-based systems, are a branch of artificial intelligence. Artificial intelligence is 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 & Dologite [3]). An expert system is a computer program that attempts 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 when the expert might not be, and so that the knowledge can be available at all times and in many places, as necessary. Expert systems derive their input for decision making from prompts at the user interface, or from data files stored on the computer, as in the presently described system. 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 with the domain expert to approximate the expert's reasoning. The degree of belief the expert has in her conclusion may be represented as a confidence factor (CF) in the expert system. For instance, the expert may feel that the conclusion based upon the input has a 95% probability of being correct, so the CF would equal 95. Conclusions may also be represented in fuzzy terms such as "possibly," "probably," or "almost certainly."

For a review on expert systems in oceanography, see Hendee [2].

1.3 Coral Bleaching

Coral bleaching may be described as the general whitening of coral tissues due to the release of symbiotic zooxanthellae and/or reduction in photosynthetic pigment concentrations in the zooxanthellae residing within the tissues of the host coral (Glynn [4]). Bleaching can 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 [4], Kushmaro et al [5]). In most reported incidences of mass coral bleaching, however, locally high sea temperature is in evidence and appears to be the chief environmental stressor (Brown & Ogden [6]), whether those temperatures may be considered “abnormal” or not (see, for example, Atwood et al [7]). One other event that is thought to induce bleaching, in the presence of high sea temperatures, is the presence of low wind speed, as this is thought to favor localized heating and a greater penetration of solar radiation (Glynn [4]; Causey [8]; Jaap [9,10]; Lang [11]).

1.4 The Utility of CREWS

The use of an expert system is designed to allow researchers to model and further understand the coral bleaching phenomenon, and also to give the FKNMS managers and researchers some immediate feedback on one facet of the status or condition of the sanctuary. An additional benefit is that it automatically alerts volunteers and researchers so that they may travel to the site for further study, and provide feedback to the knowledge engineer for further fine-tuning of the system (e.g., whether or not bleaching is beginning to occur or not). CREWS screens near real-time incoming wind speed and sea temperature data to determine if conditions are optimal for abiotic-induced coral bleaching at Sombrero Reef, based on a working notion, gleaned from coral researchers that temperatures over 30°C (B. Causey, W. Jaap, A. Szmant, personal communications), together with low winds (B. Causey, W. Jaap, personal communications), represent optimal conditions to induce abiotic coral bleaching.

2 Methods

The basic structure of the expert system was described in Hendee [2]. The production rules were drawn from consultations with experts (B. Causey, W. Jaap, J. Porter, A. Szmant, J. Lang, A. Strong) in the field of coral bleaching, and from discussions in the literature, as cited above and below. It should be noted, however, that there is still controversy in the literature as to exactly what physical conditions are responsible for coral bleaching (for reviews, see Brown [12] and Glynn [4]), but they generally agree 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 at the time of the present study. Essentially, CREWS excepts as input wind speed, wind gust and sea temperature derived from the instruments at the station. Thus, depending on how high the sea temperature was, in combination with low winds and low wind gusts, or how high the sea temperature was without low winds or gusts, conditions conducive to a coral bleaching event were described in fuzzy terms through automated “alerts,” broadcast as email messages and via the World-Wide Web early each morning, as one of the following:

Conditions extremely favorable for bleaching
Conditions very favorable for bleaching
Conditions favorable for bleaching
Conditions probably favorable for bleaching
Conditions possibly favorable for bleaching

If a combination of parameters was considered favorable, and that combination occurred all day, then the combination was considered more favorable (e.g., “very favorable”), rather than if the combination occurred only during one period of the day (e.g., during the afternoon). 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. At the end of each alert, the number of production rules triggered was calculated and presented.

To verify whether coral bleaching had occurred after the alerts began to be posted, visits were made every seven to ten days to Sombrero Reef and a representative reef spur was surveyed to determine the extent of coral bleaching, if any.

3 Results

The incidence of high sea temperature with low winds, in the context of possible coral bleaching, was reported automatically to researchers on June 1, 1998—17 days before another remote sensing effort (see Strong et al [13] for description) recognized high sea temperatures in the area for the purpose of possible coral bleaching episodes. Over the four weeks after the first alert, dives at Sombrero Reef by coral reef experts (W. Jaap, E. Mueller; personal communications), as well as by ourselves and other experienced local divers (L. Benvenuti, S. Mishmash, personal communications), revealed no significant signs of bleaching, as happened at Sombrero Reef during the previous year (E. Mueller and B. Haskell, personal communication) when temperatures were over 30°C. During the four weeks of the present study, winds were predominately low (average 7.5 knots, range 0 knots to 21.2 knots), and the sea temperatures were high (average 30.2°C, range 27.6 to 32.1°C).

4 Discussion

The experts' heuristic for coral bleaching used in the current study states that temperatures over 30°C together with low winds for about two to three weeks must occur before coral bleaching will begin to occur. A heuristic by A. Szmant (based on her data, personal communication) states two to three weeks of continuous temperatures greater than 30°C, or three to four weeks of intermittent high temperatures, is required. Since the conditions were met for all of these heuristics for the four weeks of the study (i.e., the month of June, 1998), yet bleaching did not ensue, the prescribed conditions must be reevaluated for Sombrero Reef, even though they may hold true for other coral reef areas.

It is our belief that other physical factors should be taken into account. First, the effect of ultraviolet radiation (UV) may play an important role in the bleaching response. Jaap [9] discussed the apparent contribution of low tides and low winds in more rapid solar heating to induce coral bleaching at Middle Sambo Reef in the sourthern part of the Florida Keys. However, in light of the work of Lessor et al [14], and of Gleason & Wellington [15], who presented convincing evidence of the effect of UV in inducing coral bleaching in *Montastrea annularis* within three weeks, irrespective of water temperature, it may be that the effect of low tides is more a result of greater penetration of UV than of solar heating. Also, low winds result in greater water clarity, due to the reduced effect of wave diffraction of light; hence, a greater penetration of UV. During visits to Sombrero Reef it was noted by local dive shop owners, who frequent the area often, that visibility was reduced during the outgoing tide, when water from Florida Bay washed over the reef, but cleared during the incoming tide; however, they noted that the water generally was more turbid than what is optimal for that area. We also noted that water exhibited less clarity than usual during our visits, as did E. Mueller, S. Mishmash and L. Benveuti (personal communications). Since suspended organic or inorganic materials can reduce the penetration of UV (Brown [14], Gleason & Wellington [15]), it is worth considering that corals at Sombrero Reef were not yet stressed to the point of bleaching because of the reduced effect of stressful UV levels. Secondly, acclimation to wide temperature fluctuations, as discussed by Cook et al [16], Ware et al [17], and others, may result in less sensitivity to bleaching than by the same species located in areas of less annual fluctuation. This may be occurring at Sombrero Reef, which is for the most part shallower than 10 m, influenced greatly by water from Florida Bay, and has experienced temperature ranges from about 16.5°C to 32.5°C (range of 16.0°C; July, 1992 through December, 1996; unpublished preliminary SEAKEYS data). These data may be compared to Molasses Reef, which is more influenced by oceanic Gulf Stream water, and which has an annual range (based on the same period of time, and from the same data source) of about 19.1°C to 31.5°C (range of 12.4°C). It is very interesting to note, however, that the mean temperature for both of these reefs is 26.7°C.

New heuristics will be encoded in a more complex version of CREWS, which will screen measurements from new instrumentation to measure transmissometry (for water clarity), tide level, photosynthetically active radiation (light intensity) and fluorometry (chlorophyll *a*, which can contribute to increased water column turbidity), all of which are scheduled for installation during summer, 1998. Until the new instrumentation is installed, however, the CREWS knowledge base will be updated to reflect an upper "safe" sea temperature of 31°C, rather than 30°C.

It is anticipated that further development of the expert system described herein might provide alerts such as conditions conducive to the onset of harmful algal blooms (e.g., "red tide"), conditions conducive to the arrival of commercially important fisheries stocks (such as pink shrimp, *Penaeus duorarum*), conditions conducive to larval fish (and other animal) survival or death (e.g., extended high or low temperatures), incidences of extended duration of clear or turbid water (via optical density measurements), phytoplankton blooms (measured directly through fluorescence), influx of hypo- or hypersaline waters from Florida Bay through the Florida Straits, excessive dissolved nutrient encroachment (reflected in sustained high levels of fluorescence), and the influx of cool or warm water from Florida Bay through the Florida Straits. Such predictive models, through iterative development with domain experts, will help environmental managers and scientists understand natural cycles in Florida Bay, and serve as a backdrop for feedback on, and development of, environmental regulations.

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5 References

[1] Ogden, J., Porter, J., Smith, N., Szmant, A., Jaap, W. & Forcucci, D. A long-term interdisciplinary study of the Florida Keys seascape. *Bulletin of Marine Science*, **54(3)**, pp.1059-1071, 1994.

[2] Hendee, J., An expert system for marine environmental monitoring in the Florida Keys National Marine Sanctuary and Florida Bay. *Proceedings of the Second International Conference on the Coastal Environment*; C.A. Brebbia, Ed., Cancun, Mexico, September 8-10, 1998. Computational Mechanics Publications, UK., 1998 (in press).

[3] Mockler, R.J. & Dologite, D.G., *Knowledge-Based Systems. An Introduction to Expert Systems*, Macmillan Publishing, New York, 1992.

[4] Glynn, P., Coral reef bleaching: ecological perspectives. *Coral Reefs* **12**, pp 1-17, 1993.

[5] Kushmaro, A., Rosenberg, E., Fine, M. & Loya, Y., Bleaching of the coral *Oculina patagonica* by Vibrio K-1. *Marine Ecology Progress Series* **147(1-3)**, pp. 159-165, 1997.

[6] Brown, B.E & Ogden, J.C., Coral bleaching. *Scientific American*, **268**, pp. 64-70, 1993.

[7] Atwood, D.K., Hendee, J.C., Mendez, A., An assessment of global warming stress on Caribbean coral reef ecosystems. *Bulletin of Marine Science*, **51(1)**, pp. 118-130, 1992.

[8] Causey, B.D., Observations of environmental conditions preceding the coral bleaching event of 1987—Looe Key National Marine Sanctuary. *Proceedings Association of Island Marine Laboratories of the Caribbean*, **21**, pp. 48, 1988.

[9] Jaap, W.C., Observations on zooxanthellae expulsion at Middle Sambo Reef, Florida Keys. *Bulletin of Marine Science*, **29(3)**, pp. 414-422, 1978.

[10] Jaap, W.C., The 1987 zooxanthellae expulsion event at Florida reefs. *NOAA's Undersea Research Program Research Report* **88(2)**, pp. 24-29, 1988.

[11] Lang, J.C., Apparent differences in bleaching responses by zooxanthellate cnidarians on Colombian and Bahamian reefs. *NOAA's Undersea Research Program Research Report* **88(2)**, pp. 30-32.

[12] Brown, B. (1996). Coral bleaching: Causes and consequences. *Proceedings 8th International Coral Reef Symposium* **1**, pp. 65-74.

[13]Strong, A. (1996). Improved satellite techniques for monitoring coral reef bleaching. *Proceedings 8th International Coral Reef Symposium* **2**, pp. 1495-1498.

[14] Lesser, M.P., Stochaj, W.R., Tapley, D.W. Shick & Shick, J.M. (1990). Bleaching in coral reef anthozoans: effects of irradiance, ultraviolet radiation, and temperature on the activities of protective enzymes against active oxygen. *Coral Reefs* **8**, pp. 225-232.

[15] Gleason, D.F. & Wellington, G.M. (1993). Ultraviolet radiation and coral bleaching. *Nature* **365**, pp. 837-838.

[16] Cook, C.B., Logan, A., Ward, J. Luckhurst, B. & Berg, C.J., Jr. (1990). Elevated temperatures and bleaching on a high latitude coral reef:: the 1988 Bermuda event. *Coral Reefs* **9**, pp. 45-49.

[17] Ware, J.R., Fautin, D.G. & Buddemeier, R.W. (1996). Patterns of coral bleaching: modeling the adaptive bleaching hypothesis. *Ecological Modelling* **84,** pp.199-214.