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Ecological forecasting for coral reef ecosystems

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Abstract. Assessment of coral reef ecosystems implies the acquisition of precision data and observations appropriate for answering questions about the response of multiple organisms to physical and other environmental stimuli. At the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory, we model marine organismal response to the environment in terms of a Stimulus/Response Index (S/RI). S/RI is computed using an approach called heuristic programming, from parameters bounded in subjective terms, which are defined numerically by comparing historical data with expert opinion, so as to match research and our understanding of the process in question. The modeled organismal response is called an ecological forecast, or ecoforecast, and relative possibility and intensity of the response is reflected in a rising S/RI. We have had success to date in modeling coral bleaching response to high sea temperatures plus high irradiance and other parameters. The approach requires, a) highly robust instrumentation (in situ, satellite, or other) deployed for long periods and producing high quality data in near real-time, b) a basic understanding of the process, behavior and/or physiology being modeled, and, c) a knowledge of approximate threshold levels for single or synergistically acting environmental parameters that elicit the phenomenon in question.

Key words: coral reef · artificial intelligence · bleaching/stress model · data integration · NOAA

Introduction

As stewards of the marine environment in US territorial waters, the National Oceanic and Atmospheric Administration (NOAA) must continually strive to understand how marine ecosystems respond to environmental and anthropogenic change so as to protect its fisheries resources, shorelines, and areas of high biodiversity and intrinsic beauty, such as the many square miles of coral reefs, sea grass and kelp meadows, and other ecosystems. Because of the accumulating stresses through global warming, toxic and eutrophying effluent, and opportunistic and introduced invasive species, detecting early change in the environment becomes not just desirable but critical to the well-being of ecosystems and humans alike, especially when remedial action can only be taken less expensively at an early stage. At the Atlantic Oceanographic and Meteorological Laboratory (AOML), the Integrated Coral Observing Network (ICON) has since 1998 (Hendee et al. 1998) improved upon a series of artificial intelligence techniques to produce near real-time data-driven models of how organisms or events are influenced by meteorological and oceanographic stimuli acting singly and synergistically. These models, when validated and used to provide decision support for Marine Protected Area (MPA) managers, or to add to researchers' knowledge of stimulus by the environment (as well as response by organisms or ecosystems), are called ecological forecasts or "ecoforecasts," and are more formally defined as predicting "the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components" (CENR 2001; Brandt et al. 2006).

Thus, the ICON program has developed a numerical measure of the response by organisms and ecosystems to these impacts called a Stimulus/Response Index, or S/RI. The S/RI can also serve double-duty by informing station maintainers and AOML researchers of any drifting or otherwise errant environmental data when those values are found to be outside acceptable ranges as defined by ecoforecast models.

Measuring the Environment

Sensors in the marine environment have to be routinely maintained and calibrated to ensure quality data or the whole exercise of producing ecoforecasts would be fruitless. Stations we at AOML produce for deployment are called Coral Reef Early Warning System (CREWS) stations, named after the early ecoforecasting software developed by Hendee et al. (1998), and later improved (Hendee et al. 2006; 2007).

CREWS stations have been deployed near Lee Stocking Island, Bahamas; Salt River Bay, St. Croix, US Virgin Islands (USVI); La Parguera, Puerto Rico; and Discovery Bay, Jamaica; with new stations over the next two years currently being planned for Brewer's Bay, St. Thomas, USVI; Little Cayman, Cayman Islands; Managaha Bay, Saipan, Commonwealth of the Northern Marianna Islands; and Kenting National Park, Taiwan. These stations produce meteorological and oceanographic data: wind speed and direction, barometric pressure, precipitation, light (above and below water), sea temperature, salinity and tide height. Research specific instruments have also been deployed: partial pressure of CO_2 and pulse amplitude modulating (PAM) fluorometry. Realizing the goal of maintained and calibrated instruments requires participation of field scientists and technicians, who also provide necessary support by validating ecoforecasts produced from AOML. The instrumental architecture (data acquisition and transmission) for CREWS stations has been elaborated elsewhere (Jankulak et al. in press).

The ICON program also produces ecoforecasts from data received from other in situ networks: the SEAKEYS Network of stations in the Florida Keys (Ogden et al. 1994); NOAA AOML's South Florida Ecosystem Research and Monitoring Program stations also in the Keys (SFP 2008); NOAA's National Marine Fisheries Service (NMFS) network of buoys maintained by the Coral Reef Ecosystem Division (Hawaii) in the Pacific; and the Australian Institute of Marine Science's Weather Network of eight stations on the Great Barrier Reef (Berkelmans et al. 2002) Most of these stations are well maintained, but some are so remote it is difficult to do this in a timely way.

On the assumption that sea-surface data derived from satellites are relatively good, considering their well studied and proven algorithms, data are also received from latitude/longitude pairs representing target sites for multi-parameter data collection, and called "virtual stations" (Hendee et al. 2008). Satellite data have been collected from 111 virtual and in situ station sites to date, from all three major oceans, with more planned for the future. Ecoforecasts produced from these data are always compared with in situ stations when there are some nearby, but that is not always the case. In all cases, field validation of ecoforecasts is necessary to improve or correct them.

Finally, there is one other source of data for ecoforecasting at Molasses Reef and nearby sites in the Florida Keys National Marine Sanctuary (FKNMS): Wellen Radar (Shay et al. 2002). This source of data continuously tracks surface currents, which are useful in onshore flux (Gramer et al. 2008) and larval drift ecoforecasts (L. Gramer, unpublished).

Information Architecture

Fig. 1 displays the flow of satellite and other data from a site, through a data clearing hub, and finally back to AOML for posting to a Web page which displays the most recently transmitted Web data, as well as any ecoforecasts operational for the day.

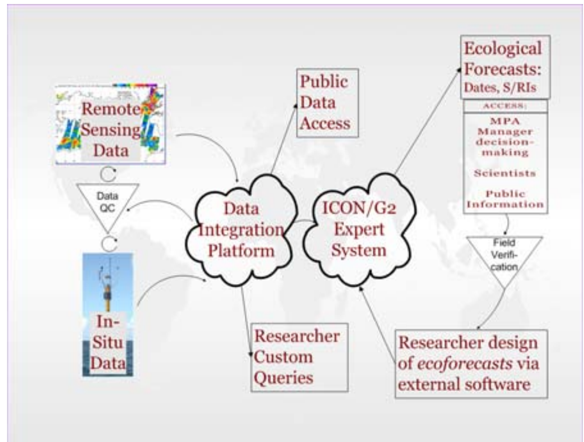

Figure 1. ICON information architecture.

Reducing Environmental Complexity

The CREWS approach to ecoforecasting seeks to reduce the extreme complexity of modeling the contributions of multiple environmental factors on eliciting behavioral and ecosystem response. Organisms respond rarely to one environmental factor; rather, they respond to a complex and often synergistic combination of factors, for instance temperature and light. One of the most complex concepts to study and understand is how the physiology of an organism that responds to, say, sea temperature and light, responds differently to a range of values for each parameter, but in combination. For instance, consider reaction to a high sea temperature and low irradiance value vs. a high sea temperature and a high irradiance value. Ideally, one would construct an index of response to an arbitrarily fine series of gradations of each of these parameters (e.g. for sea temperature, 29.01, 29.08, 29.11, etc.) in various combinations. Obviously, the number of combinations and permutations for more than one parameter quickly becomes very large. What we have done is to adopt a heuristic modeling approach. In computer science, a heuristic is "a technique designed to solve a problem that ignores whether the solution can be proven to be correct, but which usually produces a good solution or solves a simpler problem that contains or intersects with the solution of the more complex problem" (Wikipedia entry: "Heuristic" 2008). Utilizing an expert system tool called G2 (Gensym, Inc.) we use subjective terms to describe data levels and times of day, then use those terms in "production rules" (basically, if/then constructs) to model cause and effect scenarios. To do this, we first subdivide the continua of each parameter into discrete subjective levels ("bins"), based on what historical data show are minima and maxima, and according to what researchers and users of data consider appropriate. For instance, in the open ocean, salinity readings of 34-36 psu would be considered "average" or normal, while a reading of 23 psu would be considered "unbelievably low." Table 1 lists the subjective terms we use for levels of many sensor data, along with the abbreviations utilized within the software.

Table 1. CREWS/G2 subjective data ranges.

Abbrev	Description
ul	unbelievably low
dl	drastically low
vl	very low
lo	low
sl	somewhat low
av	average
sh	somewhat high
hi	high
vh	very high
dh	drastically high
uh	unbelievably high

Table 2.
CREWS/G2 subjective daily periods.

Abbrev	Period	GMT Time	Local (@5 hrs)
(Basic Periods)			
midn	midnight	0300 – 0600	2200 – 0100
pdaw	pre-dawn	0600 - 0900	0100 - 0400
dawn	dawn	0900 - 1200	0400 - 0700
morn	morning	1200 - 1500	0700 - 1000
midd	mid-day	1500 - 1800	1000 - 1300
psun	pre-sunset	1800 - 2100	1300 - 1600
suns	sunset	2100 - 2400	1600 - 1900
even	evening	0000 - 0300	1900 - 2200
(Large Groupings)			
all	all-day	0300 - 0300	2200 - 2200
dayl	daylight-hours	0900 - 2400	0400 - 1900
nite	night-hours	0000 - 0900	1900 - 0400
dayb	dawn-morning	0900 - 1500	0400 - 1000
aftn	afternoon	1800 - 2400	1300 - 1900

Naturally, data change with time, and so does the response of an ecosystem or an organism. Table 2 shows various subjective assignments for periods of the day, following the same sort of logic as for data ranges. An additional advantage of this approach is that organisms most often are active at periods we can more easily identify with. For instance, a nocturnal animal is active during "night-hours," a diurnal animal during "daylight-hours," and a crepuscular animal during "dawn" or "sunset," and so on. This helps in the descriptive phrasing of our final ecoforecast product.

Calculating the Stimulus/Response Index

The final pre-processing of data before their utilization in an ecoforecast model is the assignment of "points" to reflect the duration of the received value at the subject level and for the subjective time of day. The points accrue to a relatively simple indexing method which assigns one point to each hour that the parameter remains in one of the subjective daily periods (Table 2), multiplied by the subjective data range (Table 1), with the latter being the key determinate of the degree of stimulus or "stress." Thus, values near "average" values are treated with a multiplier of 1, while the "very low" and "very high" designations use 2, and the "drastic" levels a multiplier of 2.5.

A decision table is a complex if/then statement which allows the knowledge engineer (a person who constructs expert systems) to weigh different input levels in the decision making process. Fig. 2 shows the use of a decision table to explain our approach in an example of a coral bleaching model, and shows how the stimulus/response index is formulated.

Rule: High Sea Temp + High Noon Irradiance + Low Winds (Julian Day: 172 to 264)

		ul	vl	lo	sl	av	sh	hi	vh	dh	uh
IF											
	sea temp								all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)	all (48) dayl (30) nite (18) dayb (12) aft (6) basic (6)	
and:	irradiance								mid (6)	mid (12)	
and:	wind speed		all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)	all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)							

THEN
Conditions are [probably/possibly] conducive to mass coral bleaching.

Figure 2. A decision table for coral bleaching, modeling input of sea temperature, irradiance and low winds as parameters of stress. Refer to Tables 1 and 2 as reference to the use of the abbreviations (e.g. ul, lo, dayl, basic, etc.).

To facilitate understanding, the figure may first be interpreted in a simple fashion thus: if sea temperature is high, and irradiance is high, and wind speed is low, then conditions are likely conducive to mass coral bleaching. However, the use of our point (index) system is to assign points for the duration and time of day. Therefore, the most extreme limits of stimulus (or stress) are assigned a point level of 2X or even 2.5X the number of hours of duration. So, though a 24 hour duration of "high" sea temperature would accumulate 24 points, one that is "very-high" would accumulate 48 points, and a "drastically-high" duration rates 60 points. This point system is assigned to reflect the rarity of the "drastic" levels for each particular parameter. In the end calculation, the stimulus (or, in this case, stress) points are added up for each of the conducive parameters (e.g. sea temperature, light, winds) to arrive at a Stimulus/Response Index (S/RI).

In summary, utilizing this approach, the data process, from acquisition at the sensor to preparation of the data for a heuristic model challenge, is:

- Data are received as hourly averages from the collection site and "tagged" as to the appropriate parameter (e.g. "sea-temp").
- Data are categorized as to one of the subjective levels, as in Table 1.
- Depending upon what time of day the data are collected, they are further categorized according to Table 2 into one of the Basic Periods (three hours in length each).
- If the subjectively categorized data continues in that range beyond its originally assigned three hour period, it is further re-categorized according to the next larger period as appropriate, up to possibly "all-day."
- If the data persist at a level of stimulus (or stress) qualitatively beyond the basic threshold, they are assigned a multiplier great than unity to indicate numerically the greater stress.
- Indices from all the stimuli are added to come up with a final S/RI value, which indicates the relative intensity of the modeled response, and the relative likelihood of any response of the modeled type, to the environment at the time it is monitored.

Ecological Forecasting

Once the number of points is assigned in a heuristic model, an assessment is made as to whether those points reach a threshold level for reporting as an ecoforecast, either via an email message or Web posting to decision makers, researchers, field technicians or the knowledge engineers. Once these ecoforecasts are received, then the desirable outcome is for the field personnel (technicians maintaining a station, researchers, interested public, etc.) to give timely feedback as to whether the ecoforecast was correct as to the outcome. If it is was not correct, feedback to the knowledge engineers allows further fine-tuning of the model until, through time, it becomes a reliable ecoforecast for decision makers.

There are now many types of ecoforecasts produced as part of the ICON project, accessible via the project's Web presence (ICON 2008) which provides both hourly data from various sources at coral reef areas around the world, and ecological forecasts produced from those data. The structure of the ecoforecasts reflects one of the hallmarks of a true expert system, namely, that results are explained (i.e. "because") so that those who use the output can follow the reasoning and agree or not, and thus give feedback to the knowledge engineer so that proper refinement of the rules can take place. Figs. 3 and 4 show this approach and illustrate a current experimental coral bleaching ecoforecast being produced at Salt River Bay, St. Croix in the U.S. Virgin Islands.

Results

Early in the history of the CREWS software, the ecoforecasts were called "alerts" and were produced for the SEAKEYS Network (e.g. Hendee et al. 2001), the AIMS stations on the Great Barrier Reef (Berkelmans et al. 2002; Hendee and Berkelmans 2003), and in St. Croix (Manzello et al. 2006). With the current addition of more complex coral bleaching models reproduced at over one hundred sites around the world, as well as new types of ecoforecasts, it is now important to gain more feedback from researchers and collaborators in the field to validate and utilize them for decision support for MPA managers, and to help researchers understand how coral reef ecosystems respond to a changing climate.

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Ecoforecast Rule #4: Coral-Bleaching-Itlw
  Description: Mass coral bleaching (high in-situ sea temperature + high light + low wind)
  This rule will produce a forecast *IF* . . .
      'Photosynthetically Active Radiation At Ocean Surface (parsurf)' has any of these values:
           High Very-High Drastic-High
      (Within any of these 3-hour or longer periods: Mid-Day Pre-Sunset Daylight-Hours Afternoon All-Day)
  AND . . .
      'Hourly Average Wind Speed (windsp)' has any of these values:
           Drastic-Low Very-Low Low
      (Within any of these 3-hour or longer periods: Morning Mid-Day Pre-Sunset Daylight-Hours Dawn-Morning Afternoon All-Day)
  AND . . .
      'Depth-Averaged Sea Temperature (seandbc)' has any of these values:
           High Very-High Drastic-High
      (Either throughout the day, or during any 3-hour or longer subperiod thereof.)
```

Figure 3. Representation of the decision reasoning on the Web site for a coral bleaching ecoforecast, considering high sea temperature, high irradiance and low winds.

Ecological forecast: 'Mass bleaching', for 2005-Sept-28, Salt River, St. Croix, US Virgin Islands
Model rule: 'Mass coral bleaching (high in-situ sea temp + high light + low wind)'
Stimulus/Response Index (S/RI) = 9, because:
Photosynthetically active radiation at ocean surface (PARsurf) was drastic HIGH (1827) during period Mid-Day
Hourly averaged wind speed (Windsp) was LOW (1.8) during period Morning
Sea temp at 1 m (SeaT1m) was HIGH (30.7) during period Pre-Sunset

Figure 4. Coral bleaching ecoforecast output, considering high sea temperature, high irradiance and low winds.

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