The Coral Reef Early Warning System (CREWS)

A Marine Expert System for Near Real-Time Monitoring of Conditions Conducive to Coral Bleaching, and Other Biological Events

Jim Hendee, Ph.D.
Atlantic Oceanographic and Meteorological Laboratory
National Oceanic and Atmospheric Administration
4301 Rickenbacker Causeway
Miami, Florida 33149-1026
Email: jim.hendee@noaa.gov

A true interagency, international collaborative effort!

The Florida Institute of Oceanography

Australian Institute of Marine Science

More Marine Laboratory

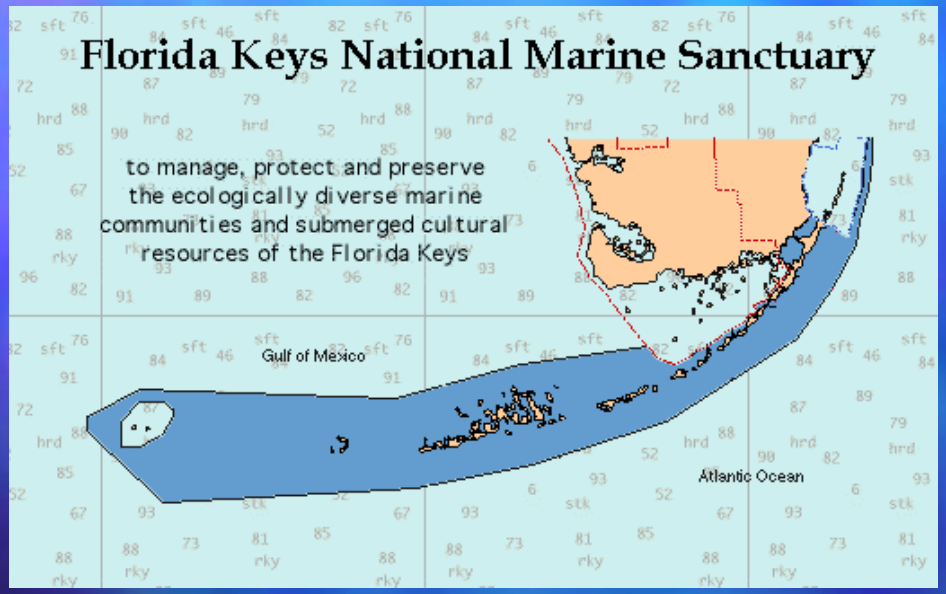
National Oceanic and Atmospheric Administration

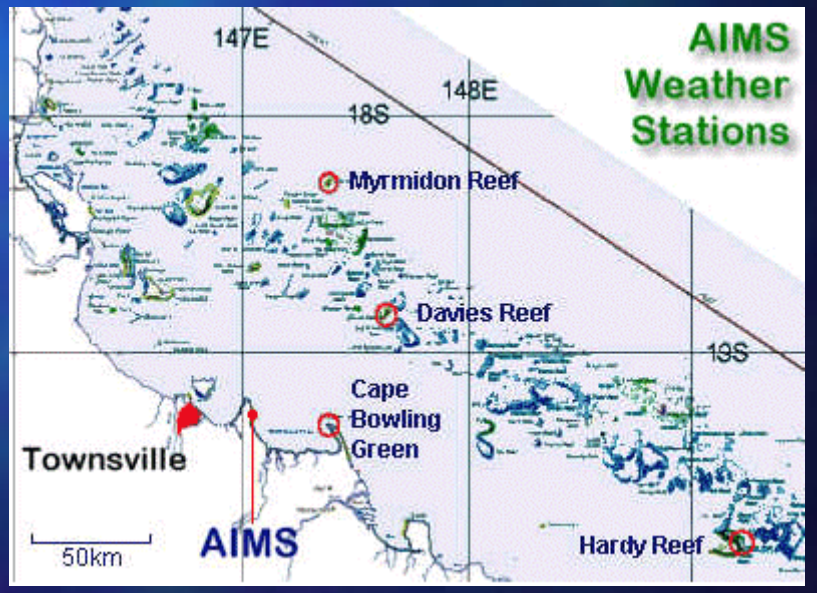
- Ocean and Atmospheric Research
- National Environmental Satellite, Data, and Information Service
- National Undersea Research Program
- The Florida Keys National Marine Sanctuary
- National Ocean Service
- National Data Buoy Center

CREWS was developed as a value-added software product for the SEAKEYS network (Florida Keys), which was developed by by John Ogden, James Porter, Ned Smith, Alina Szmant, Walt Jaap and Dave Forcucci in the early 1990s.

CREWS monitors data quality, but also monitors conditions conducive to coral bleaching and other events of interest to researchers.

CREWS is currently deployed in the Florida Keys and the Great Barrier Reef, but...

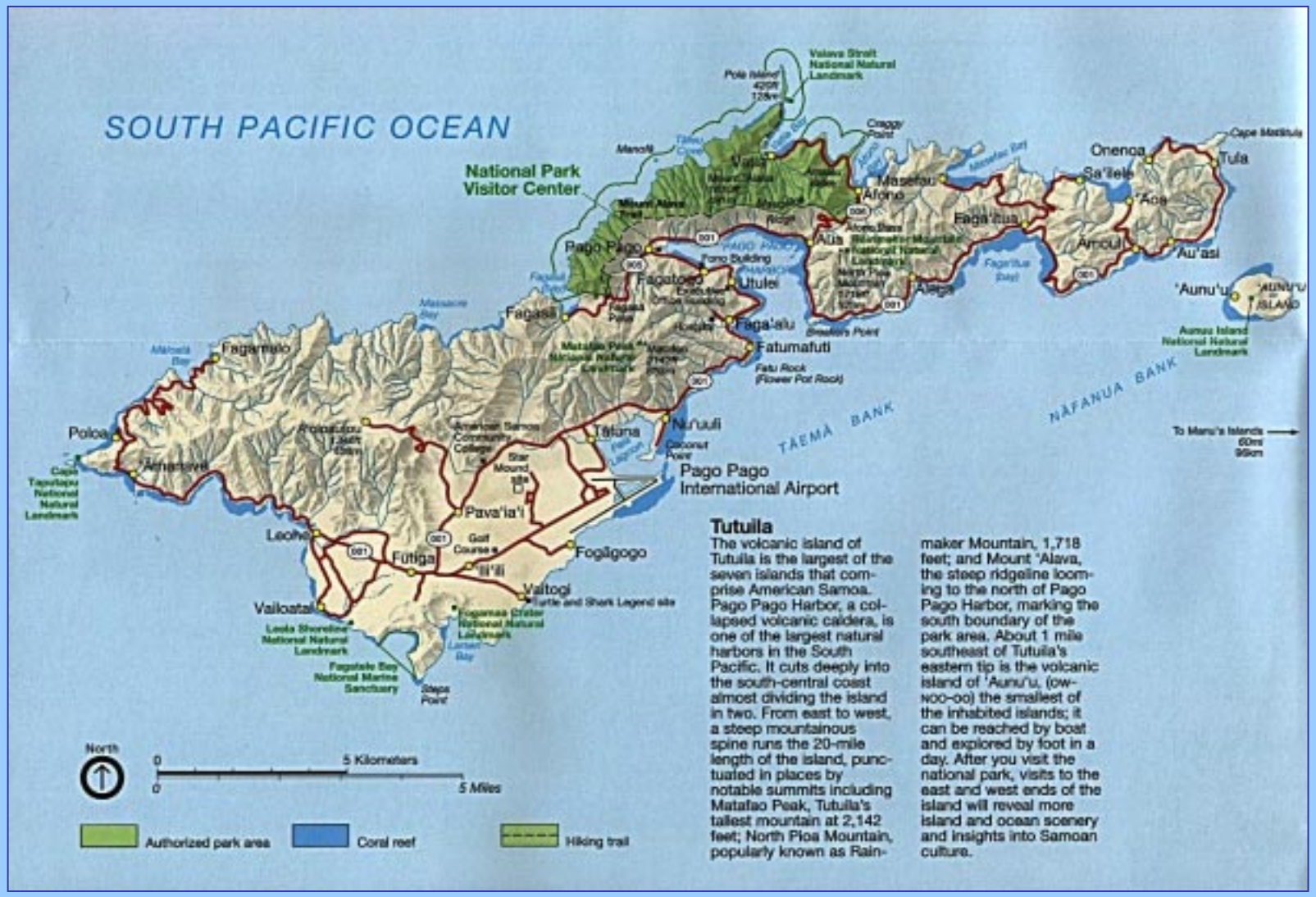




...new stations are currently being added near Lee Stocking Island, Bahamas, and...

...at St. John, US Virgin Islands National Park, and...

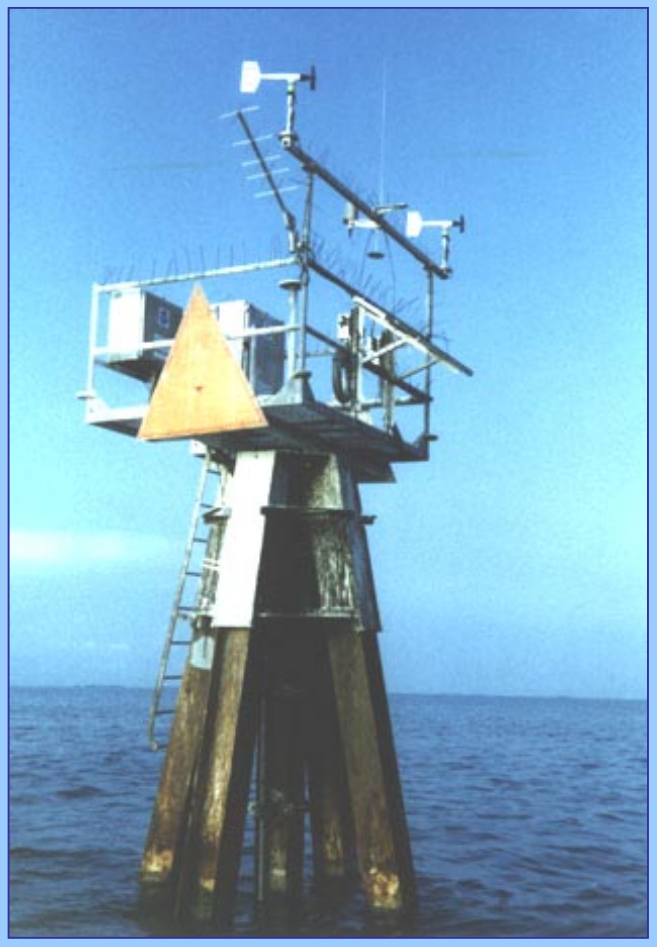
...at American Samoa.



Tutuila

The volcanic island of Tutuila is the largest of the seven islands that comprise American Samoa. Pago Pago Harbor, a collapsed volcanic caldera, is one of the largest natural harbors in the South Pacific. It cuts deeply into the south-central coast almost dividing the island in two. From east to west, a steep mountainous spine runs the 20-mile length of the island, punctuated in places by notable summits including Matafao Peak, Tutuila's tallest mountain at 2,142 feet; North Pioa Mountain, popularly known as Rainmaker Mountain, 1,718 feet; and Mount 'Alava, the steep ridgeline looming to the north of Pago Pago Harbor, marking the south boundary of the park area. About 1 mile southeast of Tutuila's eastern tip is the volcanic island of 'Aunu'u, (ow-NOO-oo) the smallest of the inhabited islands; it can be reached by boat and explored by foot in a day. After you visit the national park, visits to the east and west ends of the island will reveal more island and ocean scenery and insights into Samoan culture.

Existing Platform Types



Meteorological data types (AIMS and SEAKEYS):

- Barometric pressure
- Wind Speed
- Wind Gust
- Wind Direction
- Air Temperature

Oceanographic data types:

- Photosynthetically Active Radiation (AIMS, SEAKEYS)
- Sea temperature (AIMS, SEAKEYS)
- Salinity (SEAKEYS)
- Tide (SEAKEYS)
- Fluorometry (SEAKEYS)
- Transmissometry (SEAKEYS)

CREWS derives its input from data files retrieved in near real-time from remote stations. Here is an example from Sombrero Key, near Marathon, in the Florida Keys:

Sombrero Key SEAKEYS/C-MAN Report--Meteorology (NOAA/NDBC)

Date	Time	Baro	WD	WSp	WGu	DewP	AirT	SeaTemp
02/24/99	0900	1017	8	16.3	18.2	13.7	17.0	23.4
02/24/99	0800	1016	340	13.3	14.1	13.4	18.1	23.3
02/24/99	0700	1017	329	11.7	13.1	13.7	18.3	23.3
02/24/99	0600	1017	334	11.3	12.0	13.3	18.3	23.3
02/24/99	0500	1018	341	9.5	10.7	13.3	18.3	22.8
02/24/99	0400	1018	337	10.2	10.9	13.0	18.1	23.0
02/24/99	0300	1018	343	13.8	14.8	12.9	18.1	23.1
02/24/99	0200	1018	346	13.7	14.7	13.1	18.1	23.3
02/24/99	0100	1018	336	12.1	13.4	12.7	18.1	23.5
02/24/99	0000	1017	337	14.1	16.1	12.5	18.0	23.6

Expert Systems use Production Rules

- If/then statements represent knowledge
- Domain experts' heuristics encapsulated in production rules
- When conditions are met, most important rules are fired first (concept of "salience")
- Decision tables used for many production rules

Effectiveness of CREWS vitally dependent upon field team:

- Field maintenance
  - High boat maintenance
  - Instruments to swap-out for bad ones
  - Trouble-shooting in the field
- Personnel are experienced divers and rugged individuals
- Feedback on biological event (*e.g.,* coral bleaching)

Coral Bleaching Models Using CREWS

Complex pattern matching, which occurs in RAM using the Rete Algorithm, is one of the great strengths of expert systems.

CREWS can model specific environmental conditions (*i.e.*, meteorological and oceanographic patterns), for purposes of coral bleaching, as they occur:

- **Very high sea temperature only.**
- **Very high sea temperature, and very low winds during midday.**
- **Very high sea temperature, very low winds, and very low tide during midday.**
- **Very high sea temperature, high illumination (through PAR) and high water clarity (through transmissometry) during midday.**
- **Very high sea temperature, high illumination, high water clarity and very low tide during midday.**
- **Very high sea temperature, high illumination, high water clarity, very low tide and very low winds during midday.**
- **Very low salinity or very high salinity.**
- **High or low salinity, high illumination, high water clarity, very low tide and very low winds during midday.**
- **Very high or very low salinity, high illumination, high water clarity, very low tide and very low winds during midday.**

How do you match data types throughout the day?

If you want to match low wind speeds with high temperatures, do you average the whole day's worth then match them, or do you average certain periods of a day, then match them? What if you want to match something that happens all morning (say low wind speeds) with something that happens around noon (say high temperature)? And what if you want to match a low, low tide to high temperature at noon and the low wind speeds all morning?

And besides, what is "low" and doesn't it matter what time of year it is, anyway?

Data Grouping in CREWS

Subjective Data Ranges:

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

Subjective Periods of the Day:

Abbrev	Period	GMT Time	Local (5 hours)	Local (4 hours)
(Large Groupings)				
all	all-day	0300 - 0300	2200 - 2200	2300 - 2300
dayl	daylight-hours	0900 - 2400	0400 - 1900	0500 - 2000
nite	night-hours	0000 - 0900	1900 - 0400	2000 - 0500
dayb	dawn-morning	0900 - 1500	0400 - 1000	0500 - 1100
aftn	afternoon	1800 - 2400	1300 - 1900	1400 - 2000
(Basic Periods)				
midn	midnight	0300 - 0600	2200 - 0100	2300 - 0200
pdaw	pre-dawn	0600 - 0900	0100 - 0400	0200 - 0500
dawn	dawn	0900 - 1200	0400 - 0700	0500 - 0700
morn	morning	1200 - 1500	0700 - 1000	0800 - 1100
midd	mid-day	1500 - 1800	1000 - 1300	1100 - 1400
psun	pre-sunset	1800 - 2100	1300 - 1600	1400 - 1700
suns	sunset	2100 - 2400	1600 - 1900	1700 - 2000
even	evening	0000 - 0300	1900 - 2200	2000 - 2300

See 3D decision table...

As specified environmental conditions are met, coral bleaching "alerts" are posted to the World-Wide Web and emailed to coral bleaching researchers and sanctuary management.

SEAKEYS:
http://www.coral.noaa.gov/sferpm/seakeys/es

AIMS:
http://www.coral.noaa.gov/gbr/es

~~~~ Coral Bleaching Alert for Sombrero Key, 08/12/1998 ~~~~

Rule-T4 (9)
Conditions possibly favorable for bleaching night-hours on 08/12/1998,
because FIO sea temperature was very high (about 31.2).

Rule-TWT1 (48)
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-T5 (6)
Conditions possibly favorable for bleaching afternoon on 08/11/1998,
because FIO sea temperature was very high (about 31.5).

Rule-T8 (3)
Conditions possibly favorable for bleaching evening on 08/11/1998,
because FIO sea temperature was very high (about 31.0).

Rule-T8 (3)
Conditions possibly favorable for bleaching morning on 08/11/1998,
because FIO sea temperature was very high (about 31.0).

Rule-T5 (6)
Conditions possibly favorable for bleaching afternoon on 08/10/1998,
because FIO sea temperature was very high (about 31.3).

... [etc.] ...

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High temperature points:	**138**
High temperature, low wind points:	**0**
High temperature, low wind, low tide points:	**48**
Number of rules triggered:	**18**

CREWS for the Great Barrier Reef

- Very reliable data output from Hardy, Davies, Cleveland Bay, Agincourt and Myrmidon Reefs
- Good PAR (light), sea temperature, and wind data, but no tidal information
- Data are automatically uploaded to coral workstation at AOML every day
- CREWS effectively parsed data and produced coral bleaching alerts during February, 1998 and 2000 for Myrmidon Reef

~~~~ Coral Bleaching Alert for Myrmidon Reef 02/15/1998 ~~~~

Rule-TWP2 (24)
Conditions favorable for bleaching on 02/15/1998, because in situ sea temperature was very high (about 29.9) during mid day, and PAR was high (about 1663) during mid-day.

Rule-TWP1 (24)
Conditions favorable for bleaching on 02/12/1998, because in situ sea temperature was very high (about 29.8) during mid-day, wind speed was very low (about 3.0), during mid-day, and PAR was high (about 1864) during mid-day.

[etc.]

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High temperature only points:	**0**
High temperature, low wind points:	**24**
High temperature, low wind, low tide points:	**0**
High temperature, low wind, high PAR points:	**120**
High temperature, high PAR points:	**48**
High temperature, low wind, high PAR, low tide points:	**0**

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Total points triggered:	**192**
Number of rules triggered:	**9**

Effectiveness of CREWS vitally dependent upon field team:

- Field maintenance
  - High boat maintenance
  - Instruments to swap-out for bad ones
  - Trouble-shooting in the field
- Personnel are experienced divers and rugged individuals
- Feedback on biological event (*e.g.,* coral bleaching)

Solution: Remote Video!

If instruments are very reliable, field maintenance is rarely necessary, and is expensive when it is. Remote video could tell us when corals begin to bleach.

Obvious problems:

a) Fouling of lens might be a big problem; hence, maintenance might be necessary anyway.
b) Data transmission is expensive and difficult.
c) Local sports fans might steal the $15K camera!

Satellite data and CREWS

- Data from satellite can directly be processed by CREWS, too, just as for *in situ* instruments
- Data streams from *in situ* temperature sensor and satellite sensor can be merged for CREWS processing (see next)
- CREWS can report on differences in measurements, and can make recommendations, based on experts' production rules

Example output from Long Key station's temperature comparison production rule:

Rule-T1 (sea temp difference)
Day 149 (dawn)

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FIO sea temperature was about 21.1 (somewhat-low)
NDBC sea temperature was about 31.0 (high)
Difference: FIO - NDBC was -9.9
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Bloom detection production rule at Long Key (prototype):

Rule Flu-Wind-PAR-1 (high fluoro, low wind, high PAR)
Day 146
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Fluorometry was about 0.082 (very-high mid-day)
Wind Speed was about 4.4 (low mid-day)
Wind Direction was from NE-ENE direction (mid-day)
PAR was about 969 (high mid-day)

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This type of algorithm may eventually be useful in harmful algal bloom and/or bloom conditions detection.
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~~~~ Sombrero Key Conch Larval Drift Alert for 08/25/2000 ~~~~

Rule: Dawn/morning (6 points)
Winds were approximately easterly at 91 degrees,
during dawn/morning hours on day 08/24/2000.

Rule: Dawn/morning (6 points)
Winds were approximately easterly at 90 degrees,
during dawn/morning hours on day 08/22/2000.

Rule: Afternoon (6 points)
Winds were approximately easterly at 89 degrees,
during dawn/morning hours on day 08/21/2000.

Rule: Afternoon (6 points)
Winds were approximately easterly at 95 degrees,
during dawn/morning hours on day 08/20/2000.

Rule: Dawn/morning (6 points)
Winds were approximately easterly at 85 degrees,
during dawn/morning hours on day 08/19/2000.

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Easterly wind count points: 39
Number of rules triggered: 5

What does all this mean?

- Expert systems can automatically do a lot of work the experts can.
- CREWS can synthesize *knowledge* from data.
- CREWS can work with *in situ* instruments, or satellite instruments, or both.
- CREWS can send alerts when prescribed conditions are met.

Plans for the future

- Deploy CREWS for the Bahamas, the US Virgin Islands, Puerto Rico, and American Samoa
- Add new instruments: UV-B, pCO_2, nutrients, etc.
- Reconfigure for additional event alerts besides coral bleaching (e.g., fish or invertebrate migrations, larval survival, harmful algal blooms, etc.)


Photo courtesy of Ray Berkelmans