Integrating Near Real-Time Data for Coral Reef Ecological Forecasting

HENDEE, J.[1], L. GRAMER[2], D. MANZELLO[3] and M. JANKULAK[2]

[1]*Atlantic Oceanographic and Meteorological Laboratory*
National Oceanic and Atmospheric Administration
4301 Rickenbacker Causeway, Miami, FL 33149-1026
jim.hendee@noaa.gov

[2]*Cooperative Institute for Marine and Atmospheric Sciences*
Rosenstiel School for Marine and Atmospheric Sciences
University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149

[3]*School of Marine Biology and Fisheries*
Rosenstiel School for Marine and Atmospheric Sciences
University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149

Abstract

The National Oceanic and Atmospheric Administration (NOAA) has committed to integrating ocean data from a variety of sources into an Integrated Ocean Observing System, and to work towards operational ecological forecasting as part of its Ecosystem Approach to Management. Consistent with this, NOAA's Coral Reef Conservation Program has committed to integrating coral data from a variety of sources for the specific benefit of coral reef researchers and Marine Protected Area (MPA) managers; and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), together with its NOAA and academic research partners, is contributing to this goal through their Integrated Coral Observing Network (ICON) project. ICON provides Web-based software to integrate satellite, monitoring station (*in situ*), and radar data sources in near real-time; and utilizes an inference engine (artificial intelligence software) to provide ecological forecasts using some or all of these data. The capabilities of ICON software were initially focused upon one area in particular, Molasses Reef in the Florida Keys National Marine Sanctuary, to provide proof-of-concept, and to provide a "discovery prototype" for consideration by the MPA managers assembled at the GCFI conference. Since GCFI 59, this focus has expanded to stations throughout the Caribbean, as well as those on the Great Barrier Reef and Ningaloo Reef in Australia. Feedback to ICON developers from MPA managers – based upon their own specific management requirements and priorities, and knowledge of the prototype capabilities – is essential to set priorities and enable additional ICON software engineering specifically tailored to MPA managers' needs. Featured in the prototype are several levels of user access: layperson, researcher, site maintainer, MPA manager, and software developer colleague. Depending upon user access, information products can include recent and historical single-source and integrated data output, custom graphics output, and ecological forecasts for coral bleaching, coral spawning, upwelling, pollution impacts, meteorological extremes, and larval drift.

KEY WORDS: coral, MPA, integration, data, in situ, NOAA, ICON, software, artificial intelligence, Florida Keys National Marine Sanctuary, Molasses Reef

La administración para el océano y la atmósfera de los E.U. (NOAA) esta haciendo esfuerzos para integrar datos oceanográficos provenientes de diferentes fuentes en un sistema unico integrado para la observación de los océanos y desarrollar un sistema de pronostico ecológico operacional como parte de su enfoque para el manejo de los ecosistemas. De cuerdo a esto, el Programa de Conservación de Arrecifes de Coral de NOAA (CRCP) se ha comprometido a integrar datos sobre corales provenientes diversas fuentes para el beneficio directo de investigadores y administradores de Áreas Marinas Protegidas. El Laboratorio del Atlántico para las investigaciones del océano y la atmósfera de NOAA (AOML) en colaboración con investigadores de las universidades y de otras dependencias de NOAA se ha unido a este esfuerzo con la creación del proyecto "Red Integrada para la Observación de Corales" (ICON). El mismo proporciona programas accesibles en la Internet para integrar datos satelitales, datos tomados en el campo (*in situ*) y datos de radar en tiempo real; que usando un mecanismo de inferencia (inteligencias artificiales) proporciona pronósticos ecológicos utilizando alguna o toda la información disponible. Las funcionalidades del programa ICON se enfocaron inicialmente en un área en particular, el arrecife Molasses en el Santuario Marino Nacional de los Cayos de la Florida, para ofrecer prueba-de-concepto y un "prototipo de descubrimiento", sometido a consideración de los administradores de AMP participantes en la reunión de GCFI. Desde GCFI 59, este enfoque se ha expandido a estaciones en todo el Caribe, así como a estaciones en la Gran Barrera de Coral y en el Arrecife Ningaloo en Australia. Los comentarios que proporcionen los administradores de áreas marinas protegidas a los diseñadores del ICON de acuerdo a sus prioridades y requerimientos específicos del manejo, servirán para implementar cambios al diseño de los programas del ICON que respondan a las necesidades del manejo por parte de los administradores de las AMP. En el prototipo se ofrecen varios niveles de acceso a usuarios: empleado, investigador, encargado, administrador del AMP y colaborador para la programación. En dependencia del tipo de usuario, se tendrá acceso a información integrada reciente o histórica de una sola fuente o de varias, gráficos, pronósticos ecológicos para blanqueamiento de corales, desoves, afloramientos, contaminación, transporte de larvas y otros.

PALABRAS CLAVES: coral, AMP, integración, datos, in situ, NOAA, ICON, inteligencia artificial, Florida Keys National Marine Sanctuary, Molasses Reef

Introduction and Background

The Integrated Coral Observing Network (ICON), based at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, is dedicated to continuous environmental monitoring of coral reef sites, to provide scientists and Marine Protected Area (MPA) managers with data critical to understanding the complex physical, chemical, and biological processes that influence these complex ecosystems. ICON stations are currently operational at North Norman's Reef near the Island of Exuma, Bahamas; at Salt River, St. Croix in the U.S. Virgin Islands; at La Parguera, Puerto Rico; and at Discovery Bay, Jamaica, with plans for additional stations in the Caribbean and Indo-Pacific.

The ICON project focuses its efforts in two primary areas: (1) integration of data from many sources, and the ability to draw automated, near real-time inferences about ecologically important events on the basis of those data; and, (2) continued deployment of new stations and innovative new *in situ* environmental sensors, as well as maintenance of existing stations and *in situ* sensors (Hendee *et al*, 2006). Data are also gathered and analyzed from monitoring networks of partner organizations, including the SEAKEYS Network (Florida Keys National Marine Sanctuary), the Australia Institute of Marine Science (AIMS) Weather Network, and NOAA's Coral Reef Ecosystem Division network in the Pacific islands. As an integral part of data integration efforts, ICON gathers satellite-derived data products for these monitored reef sites, and for other "virtually monitored" reef sites around the world where no in situ monitoring is yet done.

The resulting near real-time, reef site-specific integrated data streams are then used as input to an expert systems (artificial intelligence) inference engine. Rules based on current research are defined in this expert system, to recognize in real time, environmental conditions that are likely to be conducive to, respectively, coral bleaching events, upwelling and other nutrient delivery onto the reef, and reproductive activities of corals and other reef organisms. The resulting ecological forecasts ("ecoforecasts") are then distributed via email alerts and via the NOAA ICON Ecoforecast Website (see References), to researchers, resource management decision makers, and the public. Continuous baseline data collection, in conjunction with real-time monitoring tools like ICON/G2, allows scientists and managers to better understand and predict processes that drive coral reef ecosystems. Such tools provide information that is necessary to properly manage and protect these unique and valuable natural resources. Many US governmental, academic and international partners are involved in this ongoing research effort.

Data Integration

In 2005, ICON began development on a robust commercial expert systems platform called G2 (Gensym, Inc.). G2 allows a scientific programmer to implement artificial intelligence applications, using object oriented design and a combination of natural- and visual-language programming tools. The newly developed ICON/G2 software system automatically combines observations from *in situ* instruments such as pCO2 and pH sensors, visible- and ultraviolet-light instruments, meteorological and hydrographic instruments, together with data from satellite sensors including MODIS, AVHRR, AMSR-E, TRMM and QuickSCAT, as well as data from other remote sensing systems, such as ocean surface currents derived from a Wellen Radar (WERA) High-Frequency radar operated on the East Florida Shelf by the University of Miami's Rosenstiel School for Marine and Atmospheric Sciences (see References). All monitoring sites, as well as instrument packages and individual environmental sensors at each site, are all represented in ICON/G2 by appropriate "object icons".

Collaborators around the world partner with ICON to provide near real-time data from other networks of *in situ* monitoring stations (e.g., the SEAKEYS Network, the AIMS Weather Network, etc.), and from these satellite- and radar-derived data products. Data are acquired through automated uploads and downloads, or through the use of scripting techniques to acquire values posted on partner Web sites. *In situ* data, when it is available, is automatically matched with pixel data from satellites, and in some cases with spatially averaged data from WERA radar, based on geographic coordinates and dates and times. At reef locations where no *in situ* monitoring occurs, "virtual monitoring sites" are established to gather and monitor satellite data for wind speed and direction, sea surface temperature (SST), color-derived chlorophyll *a* concentration, precipitation, and other conditions of ecological interest.

All integrated data streams are then available via query and last-report summary, at the ecoforecasting Web site previously mentioned. Simple tabular output of integrated data is available both hourly and as daily averages, for those who wish to conduct their own research. The integration of data for various purposes is a stated goal of the U.S. Commission on Ocean Policy as part of its Integrated Ocean Observing System (U.S. Commission on Ocean Policy, 2004, Ch. 26), of which NOAA has taken the lead in management authority. The ICON Program is one of the leaders in data integration specifically for marine ecological forecasting.

Ecological Forecasting

Improving on previous efforts to apply artificial intelligence to ecological forecasting (Hendee, 1998), data quality control, analysis and ecosystem modeling for the ICON Program are automatically performed by the ICON/G2 system. ICON/G2 thus serves as a single platform both for integration of environmental data from many sources, and for rule-based data quality control on these integrated data streams, using value range checks and sensor cross-comparisons. Email and online alerts are then provided in near real-time by the system, whenever sensors report apparently anomalous values.

The ICON/G2 system also serves as the platform for creating ecological forecast models based on these near real-time integrated, quality-controlled data streams. Ecological forecasts predict the impacts of physical, chemical, biological, and human-induced stimuli on ecosystems and their components (CENR, 2001). Within coral reef ecosystems, the best examples of ecological forecasts in the published literature are those for coral bleaching (based on high sea temperatures; Hendee, 1998; Liu *et al*, 2003), and coral spawning (based on moon phase and sea temperature; Harrison *et al*, 1984).

However, recent research shows that light is involved in chronic photo-inhibition within the coral/endosymbiont relationship, related to bleaching. Light is also indicated as the underlying mechanism of thermally induced bleaching (Warner *et al*, 1999). Similarly, recent research by van Woesik *et al* (2006) shows that accumulating hours of daylight appear to play a role in the inducement of spawning in at least some coral species. Finally, research has shown that local and regional circulation and mixing processes in the water column play a critical role in the primary productivity and ecology of coral reefs (Leichter *et al*, 2003; Sponaugle *et al*, 2005).

To further explore the complex interactions of physical parameters that govern coral ecosystem response, the ICON Program is utilizing the wider sources of data now available through data integration. The table below summarizes ecoforecasting models that the ICON Program is currently advancing.

A Summary of ICON Operational and Developmental Ecological Forecasts

Name	Description	Model variables	Assumptions
Coral bleaching	Recognizes potential physical stressors capable of causing coral bleaching	Sea temperature; light [sea surface and sub-surface light – Photosynthetically Active Radiation (400-700nm), UV-A and UV-B]; wind speed; tidal height.	Thermal stress leading to coral bleaching can be modified by other factors (i.e., light, wind, wave action, water clarity)
Coral spawning	Recognizes potential physical cues for coral spawning	Sea temperature, light accumulation (PAR), lunar phase.	Local environmental conditions (in addition to lunar phase) may be important in the timing of planulae release by brooding or broadcast spawning coral spp.
Nutrient / larval delivery	Recognizes hydrodynamic events that may be ecologically important	Sea temperature, wind speed and direction, chlorophyll *a* (from satellite or *in situ* measurements); model is also refined by current data (e.g., ADCP, or WERA radar ocean surface returns) where available	Simple environmental indicators (i.e., wind variability, satellite chlorophyll *a*, sea temperature variability, etc.) are sufficient to distinguish anomalous water properties as being caused by wind forcing, frontal / topographic interaction, or local nutrient load
Fish spawning aggregation	Recognizes potential physical cues for spawning aggregations	Sea temperature, light (PAR), tidal height, onshore currents and internal wave breaking, lunar phase.	Local environmental conditions (in addition to lunar phase) may be important in the timing of spawning aggregations
Data quality	Recognizes “out-of-range” or mutually inconsistent data that may indicate sensor disturbance	Any	Sensor drift and malfunction can be identified by values outside of predefined range, combined with inter-comparison of values from similar sensors

References

Refereed literature:

Harrison, P. L., R. C. Babcock, G. D. Bull, J. K. Oliver, C. C. Wallace, B. L. Willis, 1984: Mass spawning in tropical reef corals. *Science*, **223**, 1186–1189.

Hendee, J., 1998: An expert system for marine environmental monitoring in the Florida Keys National Marine Sanctuary and Florida Bay. Proceedings, 2nd International Conference on the Coastal Environment, Cancun, Mexico, September 8-10, 1998. Computational Mechanics Publications/WIT Press, Southampton, 57-66.

Hendee, J., E. Mueller, C. Humphrey, T. Moore, 2001: A data-driven expert system for producing coral bleaching alerts at Sombrero Reef in the Florida Keys. *Bulletin of Marine Science*, **69(2),** 673-684. (Presented at the National Coral Reef Institute's International Conference on Scientific Aspects of Coral Reef Assessment, Monitoring, and Restoration. Fort Lauderdale, FL, USA, April 14-16, 1999.

Hendee, J., E. Stabenau, L. Florit, D. Manzello, C. Jeffris, 2006: Infrastructure and capabilities of a near real-time meteorological and oceanographic in situ instrumented array, and its role in marine environmental decision support. *In*: Richardson, L.L., and E.F. LeDrew, eds., *Remote sensing of aquatic coastal ecosystem processes*. Kluwer Academic Press, 135-156.

Leichter, J. J., H. Stewart, S. L. Miller, 2003: Episodic nutrient transport to Florida coral reefs. *Limnol. Oceanogr.*, **48**, 1394–1407.

Liu, G., W. Skirving, A. E. Strong, 2003: Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. *Eos*, **84(15)**, 137-144.

Sponaugle, S., T. N. Lee, V. Kourafalou, D. Pinkard, 2005: Florida Current frontal eddies and the settlement of coral reef fishes. *Limnol. Oceanogr.*, **50(4)**, 1033–1048.

van Woesik, R., F. Lacharmoise, S. Koksal, 2006: Annual cycles of solar insolation predict spawning times of Caribbean corals. *Ecol. Lett.*, **9**, 390-398.

Warner, M. E., W. K. Fitt, G. W. Schmidt, 1999: Damage to photosystem II in symbiotic dinoflagellates: A determinant of coral bleaching. *Proc. Nat. Acad. Sci.*, USA, **96**: 8007-8012.

Reports and online data:

Committee on Environmental and Natural Resources [CENR], 2001: Ecological Forecasting, Washington, D.C., 12 pp.

NOAA ICON Ecological Forecasting Website. Available online as of September 15, 2007 at http://ecoforecast.coral.noaa.gov

University of Miami / Rosenstiel School of Marine and Atmospheric Sciences, Eastern Florida Shelf High Frequency Radar Operations. Available online as of September 15, 2007 at http://iwave.rsmas.miami.edu/wera/

An Ocean Blueprint for the 21st Century: Final Report of the U.S. Commission on Ocean Policy, 2004: Available online as of September 15, 2007 at http://www.oceancommission.gov/documents