The Integrated Coral Observing Network: Sensor Solutions for Sensitive Sites

Conference Paper · January 2007

DOI: 10.1109/ISSNIP.2007.4496923

6 authors, including:

J. Hendee
National Oceanic and Atmospheric Administration

Lew Gramer
University of Miami

Joan Kleypas
National Center for Atmospheric Research

Derek P Manzello
National Oceanic and Atmospheric Administration

The Integrated Coral Observing Network: Sensor Solutions for Sensitive Sites

#James C. Hendee[1], Lew Gramer[2], J.A. Kleypas[3], Derek Manzello[2], Mike Jankulak[2], Chris Langdon[4]
[1] Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration (NOAA)
4301 Rickenbacker Causeway; Miami, FL 33149, USA; Jim.Hendee@noaa.gov
[2]Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami FL, 33149, USA
Lew.Gramer@noaa.gov, DManzello@rsmas.miami.edu, M.Jankulak@miami.edu
[3]National Center for Atmospheric Research,
Boulder CO 80307 USA, kleypas@ucar.edu
[4]Rosenstiel School for Marine and Atmospheric Science, University of Miami
Miami FL, 33149, USA, CLangdon@rsmas.miami.edu

Abstract

The National Oceanic and Atmospheric Administration's (NOAA) Integrated Coral Observing Network (ICON), has been operational since 2000 and works closely with most US Government and many international environmental partners involved in coral reef research. The ICON program has pioneered the use of artificial intelligence techniques to assess near real-time data streams from environment sensor networks such as the SEAKEYS Network (Florida Keys), the Australia Institute of Marine Science Weather Network, NOAA's Coral Reef Ecosystem Division network in the Pacific, and its own Integrated Coral Observing Network (ICON) of stations in the Caribbean. Besides its innovative approach to coral monitoring station deployments, the ICON program recently pioneered techniques for the near real-time integration of satellite, in situ and radar data sources for purposes of ecological forecasting of such events as coral bleaching, coral spawning, upwelling and other marine behavioral or physical oceanographic events. The ICON program has also ushered in the use of Pulse-Amplitude-Modulating fluorometry to measure near real-time physiological recording of response to environmental stress during coral bleaching, thus providing even better ecological forecasting capabilities through artificial intelligence and data integrative techniques. Herewith, we describe these techniques, along with a report on new coral calcification instrumentation augmenting the ICON Network sensor array.

1. INTRODUCTION AND BACKGROUND

Through continuous data collection and real-time monitoring, the ICON Program, located at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, provides scientists and Marine Protected Area (MPA) managers with data critical to understanding the complex physical, chemical, and biological processes influencing coral reef ecosystems. ICON stations are currently installed 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, Pacific and Indo-Pacific regions.

The project continues to focus its efforts in two primary areas: (1) integration of data and the ability to draw automated, real-time inferences about ecological and physical events on the basis of those data; and, (2) continued deployment of new stations, and maintenance of existing stations and *in situ* sensors, based on a continually evolving structural hardware design that offers incrementally increased stability and reliability of the instrumentation at each new (or updated) study site [1]. Data are analyzed from partner environmental sensor networks besides the ICON Network, including the SEAKEYS Network (Florida Keys), the Australia Institute of Marine Science Weather Network, NOAA's Coral Reef Ecosystem Division network in the Pacific, and various "virtual sites" (i.e., latitude/longitude pair data gained via satellite) in all three oceans.

A new (over previous efforts; [2,3]) robust expert system shell called G2 (Gensym, Inc.) now combines station observations from instruments such as pCO_2 sensors, multi-spectral light instruments, temperature loggers, meteorological and hydrographic instruments and others, 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 Wellen Radar (WERA) High-Frequency radar operated by the University of Miami's Rosenstiel School for Marine and Atmospheric Sciences. The resulting high-resolution, near real-time integrated data streams are used to predict conditions conducive to coral bleaching events, upwelling and other hydrodynamic events affecting ecosystem productivity, as well as reproductive activities of corals and other reef organisms. These ecological forecasts ("ecoforecasts") are then distributed via email to researchers and via the ICON/G2 Ecoforecast Website [4]. Continuous baseline data collection, combined with real-time monitoring tools allow scientists, modellers and managers to understand the processes that drive coral reef ecosystems and provide the necessary information to properly manage and protect these unique and valuable natural resources. Many US governmental and international partners are involved in this ongoing research effort.

2. DATA INTEGRATION FOR ECOLOGICAL FORECASTING

A. Computing Architecture

The ICON computing architecture makes use of four main servers: Web hosting, applications, database and mail. The servers run supported versions of Red Hat Enterprise Linux 4 and 5 and are updated regularly with security patches. The database server houses an Oracle database. The Apache web server and the G2 server are each installed within isolated "chroot jail" environments to minimize the impact of any possible server compromise, and all systems are kept behind the AOML firewall with access limited to a small subset of ports and, in many cases, originating Internet Protocol addresses. All four systems are provided with redundant power supplies, a hurricane plan and daily backup support.

The G2 server interfaces with the Web server via Gensym's G2-WebLink bridge, and interfaces with the database server via the G2-Oracle Bridge. Data from the ICON stations are collected within minutes of each hourly satellite transmission and are uploaded to the G2 server. From there, they are propagated into the Oracle database for archival and reporting purposes, and hourly transmission reports are sent directly to the Web server, as well. Once a day, 72 hours' worth of data is processed by the ICON program's original C Language Integrated Production Systems (CLIPS) routines [2] and summarized as sensor "facts." These facts, which are the raw material of the expert system's ecological forecasts, are uploaded to the G2 server, which creates its own set of sensor facts, some as a check on the facts output by CLIPS and some additional facts not supported by the CLIPS routines.

A subset of sensor data is also shared with AOML's Hurricane Research Division for forecasting purposes, and a new data feed will soon make ICON data available at the National Data Buoy Center and be incorporated into the U.S. National Weather Service operational data stream.

B. Data Integration

A group of collaborators from around the world work with the ICON project by supplying near real-time data from in situ networks (e.g., the SEAKEYS Network, the AIMS Weather Network, etc.), satellite and radar data. These data are either acquired through automated uploads or downloads, or through the use of scripting techniques to acquire values posted on partner Web sites. Where possible, the *in situ* data are matched with latitude and longitude pixel data from satellites, and in some cases with WERA radar data, at matching dates and times for output to the ecoforecasting Web site mentioned previously. Where in situ monitoring stations are not located, "virtual sites" are monitored using satellite data for wind, sea temperature and other conditions of interest to ecological forecasting. In all cases, simple tabular output via the Web of integrated data is available hourly and/or daily 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 [5]), of which NOAA has taken the lead in management authority. The ICON Program is one of the leaders in data integration and marine ecological forecasting.

Improving on previous efforts to apply artificial intelligence to ecological forecasting [2], data quality control, analysis and ecosystem modelling for the ICON Program are performed automatically by a software system known as ICON/G2, developed at NOAA using the commercial G2 expert-systems platform. G2 allows a scientific programmer to implement artificial intelligence applications, using object oriented design and a combination of natural- and visual-language programming tools. Monitoring sites, instrument packages and individual environmental sensors at a site are all represented in ICON/G2 by appropriate class definitions.

The ICON/G2 system thus serves as a platform for integration of environmental data from many sources, at each of hundreds of monitored reef sites globally. The ICON/G2 system then utilizes the rule-based inferencing capabilities of the G2 expert systems platform to implement data quality control on integrated data streams. Value range checks and sensor cross-comparisons provide email and online alerts in near real-time whenever sensors report apparently anomalous values.

C. Ecological Forecasting

The ultimate goal of creating ecological forecast models based on these near real-time integrated, quality-controlled data streams is also encompassed by the ICON/G2 system. Ecological forecasts predict the impacts of physical, chemical, biological, and human-induced change on ecosystems and their components [6]. Within coral reef ecosystems, the best examples of ecological forecasts are coral bleaching alerts (based on high sea temperatures [7]), and coral spawning (based on moon phase and sea temperatures [8]). However, research shows that light is involved in chronic photo-inhibition within the symbiotic relationship (resulting in bleaching), and is the underlying mechanism of thermally-induced bleaching [9]. Also, recent research [10] shows that accumulating hours of daylight appear to play a role in spawning, at least in some species. Thus, the ICON Program is delving further into the complex interactions of physical parameters that govern coral ecosystem response, utilizing the wider sources of data that are now available through data integration techniques.

Table 1 displays several ecoforecasting models that the ICON Program is currently advancing.

3. PHYSIOLOGICAL MONITORING OF CORAL STRESS

Researchers of coral reef ecosystems now recognize that mass coral bleaching, (i.e., the loss of coral color due to mass expulsion of their endosymbiotic zooxanthellae), is primarily due to the presence of extended exposure to high sea temperatures [11] . However, as mentioned above, light has a significant and fundamental role in the response.

One line of research that has elucidated this physiological process utilizes a Pulse-Amplitude-Modulating (PAM) fluorometer (a "PAM") to detect photosynthetic efficiency of the zooxanthellae through night-time fluorescence, and although some keystone work has been done on this in the past [8], there had never been a continuous measuring of the physiological response coincident with comprehensive monitoring of the physical environment to better understand the ecological drivers. Such an approach is fundamental to understanding the processes that are now causing stress and mortality to corals globally [12].

To pursue the applicability of this approach, a specially constructed PAM was deployed on the ICON station near Lee Stocking Island, Exuma, Bahamas, for monitoring two species of corals, *Siderastrea siderea* and *Agaricia tenuifolia*, during summer, 2005. The PAM utilized was manufactured by Gademann Instruments, Inc. of Belgium and consisted of a central canister with four light guns connected to the central canister by 7m cables. The canister itself was connected to the station data logger via a cable running from the top of the station, down through and out the side of the pylon, and then out to the two target species of corals. The nature of PAM-fluorometry requires that the light gun be positioned a fixed distance from the target species, so specially constructed holders held the guns firmly against the strong local currents and were positioned utilizing a special spacer. Every hour, each light gun emitted a series of light flashes of 0.6 sec duration.

Results obtained through the summer, 2005 coral bleaching incidence indicated that chronic photo-inhibition was sustained beginning August 3, 2005. These data indicate that the endosymbionts of the of *S. siderea* colony began undergoing biochemical damage responsible for bleaching over a month prior to the issuing of satellite-based bleaching alerts, and thus show promise for a better understanding of the multiple and interacting physical factors involved in coral bleaching [13].

4. OCEAN ACIDIFICATION STUDIES

Ocean acidification has become increasingly recognized as an important consequence of increasing atmospheric carbon dioxide (CO_2) concentration [14,15,16,17]. Ocean acidification refers to the progressive decrease in seawater pH due to the ocean's absorption of much of the excess CO_2 emitted into the atmosphere from fossil fuel burning. Laboratory studies illustrate that corals and other reef-building organisms are particularly susceptible to the changes in seawater carbonate chemistry associated with decreasing pH, because they cause a reduction in calcification rates (skeletal building through precipitation of calcium carbonate) by up to 50% by the middle of this century [18,19]. Because calcium carbonate production is the base process of reef building, these changes not only threaten reef organisms, but entire reef structures and the ecosystems they support [20].

These revelations are relatively new, however, and field studies of coral reef response to changing seawater carbonate chemistry have been few and limited in scope. Field research of carbonate chemistry and calcification rates on coral reefs is challenging for a few important reasons. First, measurements of the carbonate system in seawater are difficult to do. At least four measurements must be obtained: temperature, salinity, and two of the following: total dissolved inorganic carbon (DIC), partial pressure of CO_2 (pCO_2), pH, and total alkalinity (TA) [21]. Second, the carbonate system on coral reefs is highly variable both temporally and spatially, mainly because of the direct effect that coral reef metabolism (calcification, dissolution, photosynthesis, and respiration) has on reef water chemistry [22, 23, 24, 25, 26, 27]. Seawater carbonate chemistry can thus change hourly and will vary at the scale of tens of meters. This is further complicated by the complex hydrodynamic environment of reefs, where currents, waves, and winds can strongly affect the carbonate system as well as the organisms changing it!

The ICON field stations provide an ideal platform for examining the effects of ocean acidification on reefs because they provide high-resolution data of temperature, salinity, winds, and a suite of other variables that are relevant to carbonate chemistry research, along with other data that directly relate to the metabolic state of the coral reef community.

To further support ocean acidification studies, the ICON Program has supplemented their stations with several important sensors. Over the past two years, automated pCO_2 sensors (Submersible Autonomous Moored Instrument or SAMI™ by Sunburst Sensors, LLC) have been installed at stations of the ICON network. SAMIs have been deployed in the Bahamas, the Florida Keys, Puerto Rico and Jamaica, and data are now included in the near-real-time suite of data provided via the ICON Web site. Recently, one of us (CL) has deployed a second automated sensor to measure pH at the La Parguera site, thus completing the suite of measurements needed to completely characterize seawater chemistry changes at this reef site.

These ICON-based high resolution and long-term data provide a foundation of field measurements to support future, integrated research on the effects of ocean acidification on coral reefs. The stations are thus ideal sites to fully characterize the carbonate system on a coral reef. These enable research projects that integrate hydrographic measurements and modelling, and direct measurements of coral calcification rates and other metabolic parameters that are badly needed if we are to understand the full biogeochemical and ecological responses of coral reef ecosystems to ocean acidification.

.

5. TABLE 1.

A Summary of Integrated Coral Observing Network Operational and Developmental Ecological Forecasts.

Name	Description	Application	Model variables	Scale	Assumptions
Coral stress	Recognizes potential physical stressors capable of causing coral bleaching	Decision support for MPA managers; research in coral biology and ecology.	Sea temperature; light [sea surface and sub-surface light – Photosynthetically Active Radiation (400-700nm), UV-A and UV-B]; wind speed; tidal height.	From 3 h to 150 d	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	Decision support for MPA managers; research in coral biology and ecology.	Sea temperature, light (PAR), lunar phase.	From 3 h to 90 d	Local environmental conditions (in addition to lunar phase) may be important in the timing of spawning
Fish spawning aggregation	Recognizes potential physical cues for spawning aggregations	Decision support for MPA managers; research in reproductive biology and ecology.	Sea temperature, light (PAR), tidal height, onshore currents and internal wave breaking, lunar phase.	From 1 d to 14 d	Local environmental conditions (in addition to lunar phase) may be important in the timing of spawning
Hydrodynamic anomaly	Recognizes hydrodynamic events that may be ecologically important	Water quality and coastal resource management; research in nutrient dynamics and larval recruitment.	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 radar surface returns) where available	From 12 h to 30 d	Environmental indicators (i.e., wind, chlorophyll *a*, variance in sea temperature etc.) are sufficient to distinguish anomalous water properties as being caused by wind forcing, frontal / topographic interaction, or local nutrient load
Data quality	Recognizes “out-of-range” or mutually inconsistent data that may indicate sensor disturbance	Quality control of data feeds	Any	Hourly to monthly	Sensor drift and malfunction can be identified by values outside of predefined range, combined with inter-comparison of values from similar sensors

6. ACKNOWLEDGEMENTS

NOAA’s Coral Reef Conservation Program, and the High Performance Computing and Communications office are gratefully acknowledged for support of the ICON Project and related research. The authors thank M. Shoemaker, J. Craynock, N. Ash, H. Casanova, J. Halas, L. Florit, C. Jeffris, E. Roque-Rodriguez, J. Tomczuk, K. Puglise and others for their work on the ICON Project.

7. REFERENCES

[1] J. Hendee, E. Stabenau, L. Florit, D. Manzello, C. Jeffris. 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, Editors, Remote sensing of aquatic coastal ecosystem processes. Kluwer Academic Press, pp 135-156, 2006.

[2] J. Hendee. 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, 1998.

[3] J. Hendee, E. Mueller, C. Humphrey, and T. Moore. 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; 2001.

[4] http://ecoforecast.coral.noaa.gov.

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

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

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

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

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

[10] R. van Woesik, F. Lacharmoise, and S. Koksal. Annual cycles of solar insolation predict spawning times of Caribbean corals, Ecol. Lett., 9, 390-398; 2006.

[11] P. W. Glynn. Coral reef bleaching: ecological consequences. Coral Reefs, 12, 1-17; 1993.

[12] W. K. Fitt, B. E. Brown, M .E. Warner, R. P. Dunne. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. Coral Reefs 20: 51-65; 2001.

[13] J. C. Hendee, D. Manzello, E. Stabenau, M. Lesser, M. Warner, and M. Jankulak. Remote, hourly physiological monitoring of two corals during the summer, 2005 bleaching event at Lee Stocking Island, Exuma, Bahamas. *In prep.*

[14] R.A. Feely, C. L. Savine, K. Lee, W. Berelson, J. Kleypas, V. J Fabry, and F. J. Millero. Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans, Science, 305, 362-366; 2004.

[15] J. C. Orr, V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G. K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M. F. Weirig, Y. Yamanaka, A. Yool. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, Nature, 437, 681-686; 2005.

[16] Royal Society. Ocean acidification due to increasing atmospheric carbon dioxide, 223 pp, The Royal Society, London; 2005.

[17] Ruttiman, J. Sick Seas, Nature, 442, 978-980; 2006.

[18] J.A. Kleypas and C. Langdon. Coral reefs and changing seawater chemistry, in Coral Reefs and Climate Change: Science and Management, edited by J. T. Phinney, O. Hoegh-Guldberg, J. Kleypas, W. Skirving and A. Strong, pp. 73-110, Am. Geophys. Union, Washington, DC; 2006.

[19] C. Langdon, W. S. Broecker, D. E. Hammond, E. Glenn, K. Fitsimmons, S. G. Nelson, T. H. Peng, I. Hajdas, and G. Bonani. Effect of elevated CO_2 on the community metabolism of an experimental coral reef, Global Biogeochem. Cycles, 17, art. no. 1011; 2003.

[20] J. A. Kleypas, R. W. Buddemeier, and J.-P. Gattuso. The future of coral reefs in an age of global change, Int. J. Earth Sci., 90, 426-437; 2001.

[21] R. E. Zeebe and D. Wolf-Gladrow. CO_2 in Seawater: Equlibrium, Kinetics, Isotopes, 346 pp., Elsevier Science, B.V., Amsterdam; 2001.

[22] N. R. Bates.. Seasonal variability of the effect of coral reefs on seawater CO_2 and air-sea CO_2 exchange, Limnol. Oceanogr., 47, 43-52; 2002.

[23] N. R. Bates, L. Samuels, and L. Merlivat. Biogeochemical and physical factors influencing seawater fCO_2, and air-sea CO_2 exchange on the Bermuda coral reef, Limnol. Oceanogr., 46, 833-846; 2001.

[24] J.-P. Gattuso, M. Frankignoulle, and R. Wollast. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry, Am. Zool., 39, 160-183; 1999.

[25] J.-P. Gattuso, M. Pichon, B. Delesalle, and M. Frankignoulle. Community metabolism and air-sea CO_2 fluxes in a coral reef ecosystem (Moorea, French-Polynesia), Mar. Ecol. Prog. Ser., 96, 259-267; 1993.

[26] K. Kawahata, A. Suzuki, and K. Goto. Coral reef ecosystems as a source of atmospheric CO_2: evidence from PCO_2 measurements of surface waters, Coral Reefs, 16, 261-266; 1997.

[27] H. Kayanne, A. Suzuki, and H. Saito. Diurnal changes in the partial pressure of carbon dioxide in coral reef water, Science, 269, 214-216; 1995.