

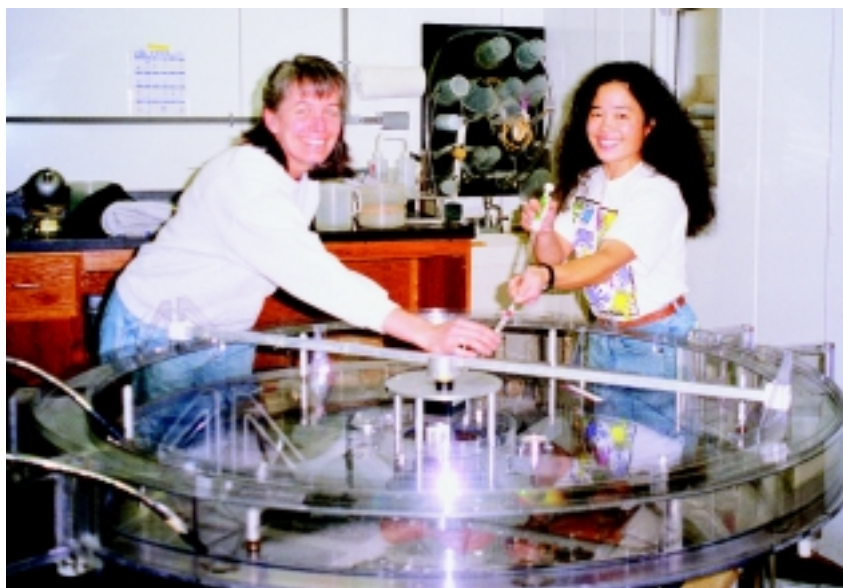
Flume Studies Identify Physical and Chemical Processes That Control Larval Dispersal and Settlement

Contributed by Cheryl Ann Butman and Richard Zimmer

Most animals—worms, snails, and crabs—associated with sediments as adults have a planktonic larval stage. Dispersing in the water column for hours to months, the larvae then settle onto the seabed and metamorphose into benthic juveniles. Knowledge of the factors determining when and where larvae settle on the bottom is critical for understanding the life cycle of a species and ultimately for predicting adult population sizes and distributions.

Evaluating the physical and chemical factors that establish larval distributions in the water column and on the seafloor is a major research focus in our laboratories at Woods Hole Oceanographic Institution and the University of California, Los Angeles. We are conducting an extensive series of experiments in two recirculating flumes at the Coastal Research Laboratory, the 17-Meter Flume (60 centimeters wide with a 17-meter-long channel) and a smaller annular flume (1.5-meter-diameter ring, 10-centimeter-wide channel). Combining several new technologies for

monitoring the movements of individuals within a flow field, these experiments address the relative importance of passive transport versus larval behavior in response to chemical or hydrodynamic cues in determining suspended and benthic larval distributions.



Vicke Starczak (left) and Nan Trowbridge introduce larvae to the annular flume.

Estuarine parasitic trematodes (wormlike organisms) can significantly affect both the population dynamics and community structure in salt marshes through castration or by inducing behaviors in their hosts (snails, fish, crabs). To determine factors that control the transfer of infection from one host to the next, Jonathan Fingerhut and Damion Gastelum are quantifying the emergence,

transport, and settlement of the cercaria larval stage. For one species (*Himasthla rhigedena*), still-water assays indicate that vertical swim speeds can double over a temperature change of only 6° C (18 to 24° C, bracketing the range that occurs in the field). Temperature-dependent swim speeds may

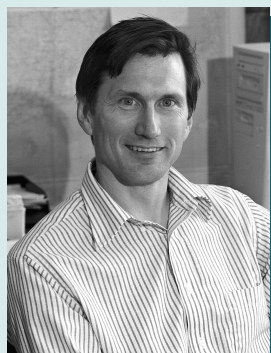
generate two different vertical distributions of cercaria in the water column. Such distributions could affect the probability of cercaria encountering a suitable host (such as fish in the water column or snails on the seabed) and thus the spread of infection.

To quantify the interaction between larval behavior and

hydrodynamics, we are using the 17-Meter Flume to study vertical distributions of cercaria in flow. We use an infrared laser light for illumination because the larvae cannot detect it. The laser beam is reflected and then spread to create a very thin sheet in the along-channel direction. This technique specifies a defined

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A Message from the RCRC Director:



Back in the early days of the Woods Hole Oceanographic Institution, there were just oceanographers. There was no separate department for physical oceanographers or chemical oceanographers or engineers—in fact, it wasn't until 1963 that WHOI Director Paul Fye managed to organize the scientific ranks of the Institution into separate departments.

With the ever-increasing complexity of our science over the last several decades, such specialization was inevitable and valuable for increasing the sophistication and rigor of oceanographic research. But...what goes around comes around.

I participated in the Mid-Atlantic Bight Physical Oceanography and Meteorology Workshop in Woods Hole this fall (see article on page 5), where probably the most exciting talk was given by a *geologist* talking about *clams*. It turns out that these lowly mollusks have been keeping faithful track of the salinity of the coastal ocean for the last hundred years, with a temporal resolution as fine as one week! It took some fancy analysis, precision machinery, and a sophisticated model of the partitioning of stable isotopes to yield this interpretation of clam shells, which indeed speaks to the great strides that oceanographic science has made within the individual disciplines.

The reason this clam research is exciting is not, however, the technical virtuosity of the measurements, but rather the assimilation of ideas across different disciplines to arrive at a new view of how the physical, biological, and chemical processes in the ocean interact.

That's Oceanography. Period.

A handwritten signature in dark ink, which appears to read "Roddy Gezy". The signature is fluid and cursive, with a long, sweeping underline.

RCRC Calendar for January – June 2000

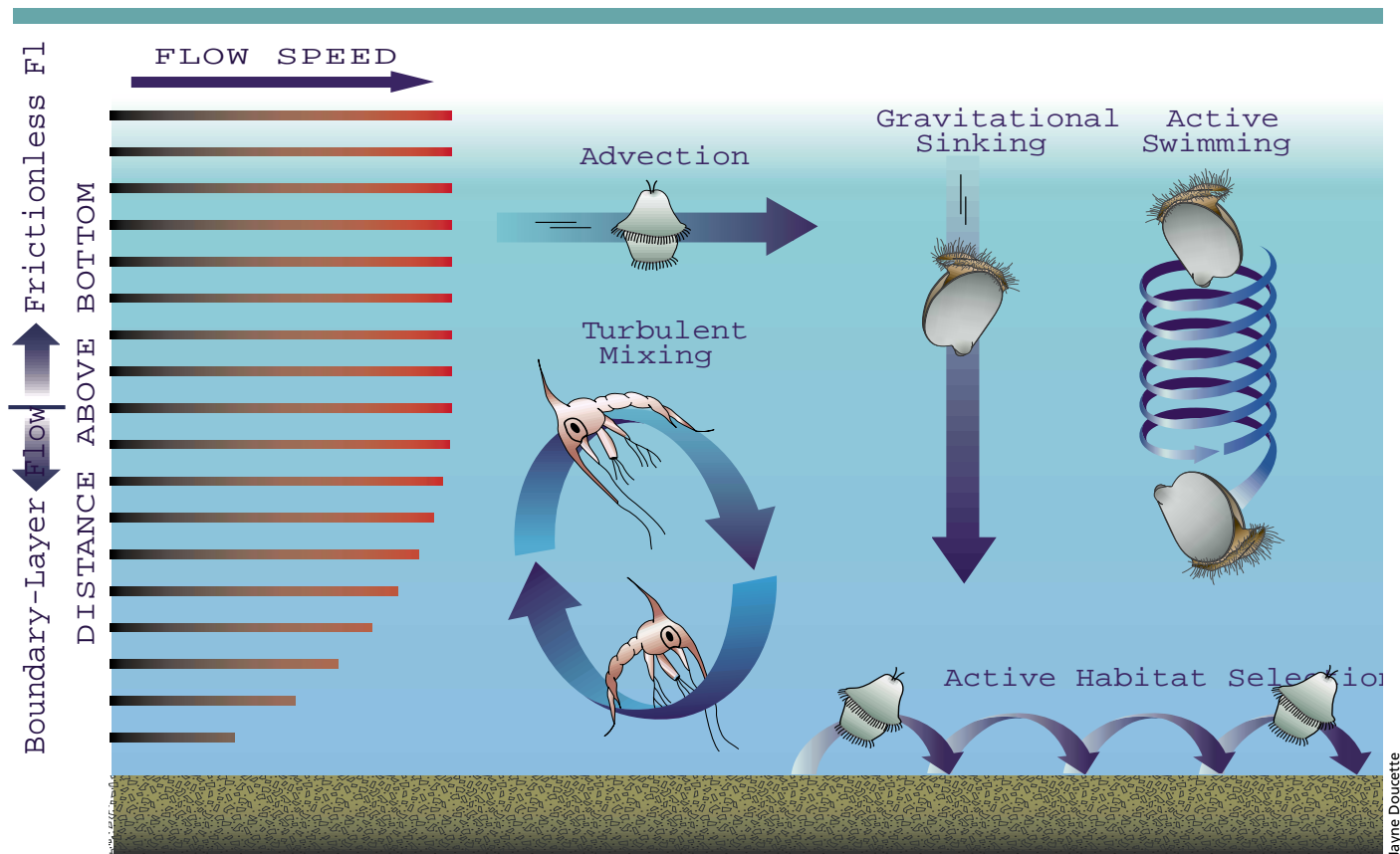
April 14	-----	Annual RCRC Proposal Deadline
April 25	-----	Nearshore Processes Symposium
June	-----	RCRC Open House

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volume for determining larval concentrations. Two highly sensitive video cameras record the images of larvae transported by or swimming in flow. The field of view spans the entire water column. Recorded images are processed in near-real time on a custom-built Computer Assisted Video Motion Analysis System. This analysis generates vertical concentration profiles, swimming speeds, and trajectories of cercaria.

Experiments in the annular flume are designed to quantify larval behaviors and settlement in three-dimensional flows. Cross-stream (“secondary”) circulations are a direct result of the continuously curving channel and simulate aspects of the more complicated near-bed flows that occur in nature. Surprisingly, although secondary flows are weak relative to the along-channel flow, larvae of certain species are easily entrained in these sluggish cross-stream circulations.

Victoria Starczak and Nan Trowbridge are studying larval settlement behavior of a small worm (*Capitella* sp. I) that is very abundant in organic-rich muds and thus indicative of disturbed or polluted conditions. Previous studies in a large recirculating flume showed that larvae of this species were highly selective for the high organic muds of the adult habitat. Whereas selectivity was not affected by current speed, settlement rate was about a factor of two greater in relatively fast versus slow flow. Consequently, studies of near-bed swimming and settlement in the small annular flume are designed to evaluate how behaviors at the scale of the individual might



Diagrammatic representation of physical factors and behaviors affecting larval transport within near-bottom waters and settlement on the seabed. In addition, settlement may be influenced by dissolved or substrate-adsorbed chemical cues.

explain flow-dependent settlement rates.

In addition, Patrick Krug is conducting research on larval behavior and settlement rate in response to dissolved and adsorbed chemical cues for a small sea slug (*Alderia modesta*). Still-water studies suggest that *Alderia* is induced to settle by both water-borne and substrate-adsorbed cues produced by the benthic yellow-green alga *Vaucheria longicaulis*. Adsorbed molecules have long been highly favored as the dominant inductive compounds for larval settlement.

Work in author Zimmer's lab indicates, however, that dissolved cues may also play an important role, particularly under conditions where high concentrations of the inductive solution are maintained very close to the surface of the inductive substrate. We are exploring the effects of

such conditions on settlement rate in the annular flume studies.

We quantify larval settlement of both *Capitella* and *Alderia* larvae on substrates (mud for the worms and algae for the slugs) placed in depressions at 10 equidistant locations around the annulus. During the experiments, larval swimming in flow is video recorded using a set-up similar to that described above for the 17-Meter-Flume studies. We analyze the video tapes using the same Computer Assisted Video Motion Analysis System that tracks the locations of the larvae in time and space, and also computes swim trajectories and speeds.

This research should greatly improve current understanding of the interplay between animal behavior and hydrodynamics in determining patterns of larval settlement. It could lead to improved theory on the mecha-

nisms that control larval supply to established populations and new habitat, and that help regulate benthic community structure.

Cheryl Ann Butman is a Senior Scientist, Victoria Starczak a Research Associate, and Nan Trowbridge is a Research Assistant in the WHOI Applied Ocean Physics and Engineering Department. Richard Zimmer is a Professor in the Department of Biology at the University of California, Los Angeles, where Patrick Krug is a Postdoctoral Fellow, Jonathan Fingerut a Graduate Student, and Damion Gastelum a Research Assistant.

Coastal Groundwater Discharge on Cape Cod

Contributed by Matt Charette and Ken Buesseler

The fate of contaminants and natural compounds in estuarine and near-shore environments is determined by a complex set of biological, geochemical, and physical interactions. Scientists have at least a basic understanding of the major sources, sinks, and transformations for many substances. However, the importance of coastal groundwater discharge in delivering dissolved nutrients, such as nitrate and phosphate, to coastal waters has often been overlooked, primarily because it is difficult to estimate.

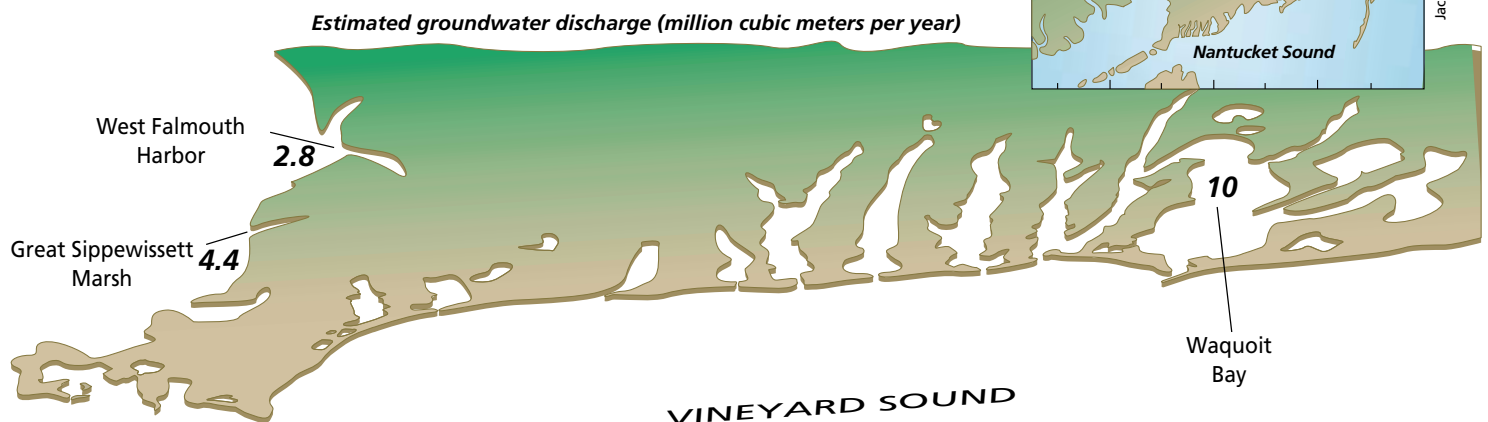
In the last RCRC newsletter (Vol. 3, No.1), we reported a new approach to studying groundwater discharge in the coastal ocean. It is based on radium isotopes (radium 226, radium 228, radium 223, radium 224), a set of naturally occurring nuclides that are enriched in groundwater. These four isotopes, with half-lives ranging from four days to 1,600 years, allow us to examine this process over a wide range of time and spatial scales. In addition, the short-lived radium isotopes show promise for estimating flushing times of local estuaries.

With support from the Rinehart Coastal Research Center, the WHOI Education Office, and the Office of Naval Research, we set out to estimate groundwater discharge to three local estuaries—West Falmouth Harbor, Great Sippewissett Marsh, and Waquoit Bay (see figure below). By constructing a simple mass-balance model for a long-lived radium isotope (radium 226) and using a short-lived isotope (radium 223) to gauge estuarine water residence times, we were able to estimate groundwater fluxes of 2.8, 4.4, and 10 million cubic meters per year, respectively.

The magnitude of these fluxes is large considering that these estuaries are only three of the many inlets that line the southern and eastern coasts of Falmouth. For example, the annual water use for the town of West Falmouth is less than 20 percent of discharge to the harbor from natural sources. In Waquoit Bay, direct groundwater discharge to the bay comprises roughly one-third of the total freshwater budget for the entire watershed.

The key biogeochemical problem associated with coastal

groundwater flow on Cape Cod is the introduction of “new” nitrogen, entrained by groundwater plumes as they pass through septic tank fields located along the coastline. In several groundwater samples taken from around Waquoit Bay, total dissolved inorganic nitrogen (DIN) concentrations ranged from 100 to 125 micro-moles per liter. Using our calculated groundwater flux, this translates to a DIN flux of about 15,000 kilograms of nitrogen per year, a value much greater than the potential contribution from precipitation. Since summer DIN concentrations in the bay are three orders of magnitude less, much of the nitrogen is either stored as particulate nitrogen (such as macroalgae) or exported to Vineyard Sound.





Glen Crossin

Matt Charette and John Andrews prepare R/V Mytilus for field sampling in local Cape Cod estuaries. Radium isotopes used to trace groundwater discharge are concentrated from 100 liter samples onto manganese-coated acrylic fibers (inset).



Matt Charette

As radium isotopes are introduced to an estuary via groundwater discharge, they are subject to mixing and radioactive decay. The two short-lived radium isotopes are useful because they have half-lives (4 and 11 days) that are on the same order as the flushing times of many estuaries. The flushing rate of an estuary is important because it is a proxy for the amount of time a contaminant spends in the system; for example, estuaries with rapid flushing rates may be less impacted by contaminant inputs than systems with slower exchange rates.

The distribution of the short-lived radium isotopes in Waquoit Bay reveals that the flushing process is more complex than previously believed. Previous estimates of flushing based on a water balance differ by factors of two to three when compared to the radium approach. These estimates

may have been biased by failing to account for the large groundwater input at the head of the bay as well as a strong salinity front located mid-bay. The built-in "clocks" provided by these radioisotopes are thus improving our understanding of both the inputs and circulation processes of these harbors.

This work is critical for the future management of our estuaries in the event that groundwater-borne organic contaminant plumes from the Massachusetts Military Reservation outcrop into local harbors and along the Cape Cod coastline. Our results can help environmental managers identify specific problem areas and the potential resulting impact on local ecosystems.

Matt Charette is a Postdoctoral Investigator and Ken Buesseler an Associate Scientist in the Marine Chemistry and Geochemistry Department.

Mid-Atlantic Bight Research Workshop

Contributed by Jim Churchill

Since the time of the Nixon Administration, an autumn rite of scientists interested in physics of the Mid-Atlantic Bight (the oceanic region between Georges Bank and Cape Hatteras) has been the MABPOM (Mid-Atlantic Bight Physical Oceanography and Meteorology) Workshop. This is unique among scientific meetings in that it is sustained solely by the volunteer efforts of the science community. This year's workshop was held in the newly revamped top-floor Clark Laboratory conference room on WHOI's Quissett Campus.

During the one-and-a-half day meeting span (October 25–26), the roughly 50 attendees were treated to a broad range of presentations as well as a traditional New England style clam boil. The mix of talks included some slick high-tech presentations given by students and young investigators, and more traditional fare served up by MABPOM old-timers. This year's meeting also continued the recent MABPOM trend of expanding disciplinary boundaries, with a number of talks directed to the effects of currents on biological communities and chemical distributions.

Interest in interdisciplinary marine science was exemplified by a spirited discussion regarding the use of radiocarbons to infer shelf circulation, including a question on the possibility of cross-shelf clam transport by fishermen.

For further information, check <http://www.whoi.edu/MABPOM/>
Jim Churchill is a Research Specialist in the Physical Oceanography Department.

Reconstructing Climate with Coral

Contributed by Anne Cohen

It's after hours at Falmouth Hospital's X-ray Department, and I'm at the controls. My patient: a brain coral (*Diploria labyrinthiformis*) collected from the southern reefs of the Bermuda platform. The X-ray image reveals details of the coral's skeletal structure invisible to the naked eye: pairs of alternating light and dark bands that reflect changes in skeletal density in response to seasonal changes in light and water temperature (see figure above right).

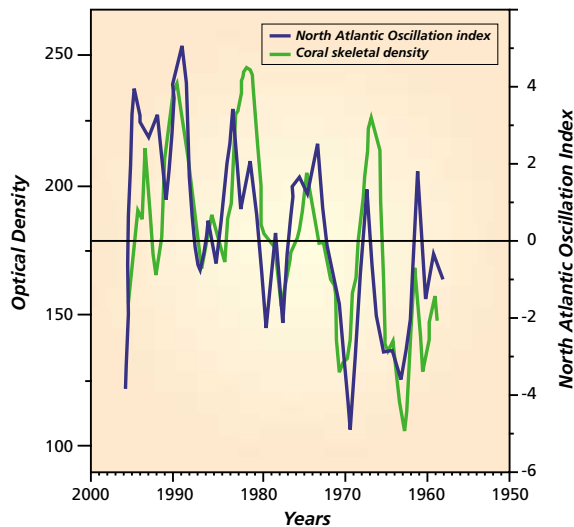
Because each high- and low-density couplet represents one year of growth, I can tell immediately that the colony is 40 years old and that it grew, on average, 3 millimeters per year. The second specimen is older, 79 years. On it, I can pinpoint the year I was born, the year of the first moon landing, the invention of the Frisbee, and the introduction of television.

This built-in chronology is one of several unique characteristics that make reef corals valuable to understanding and reconstruction of climate of the recent past. Beginning in the 1950s, instrument recordings provide reliable data on short term climate change. They show that the earth's climate has undergone fairly significant changes, reflected in both air and sea surface temperatures, the frequency of Pacific El Niño/Southern Oscillation events (ENSO), the behavior of the North Atlantic Oscillation (NAO), and the frequency and intensity of hurricanes, floods, and droughts.

However, these records are too short to tell us whether these

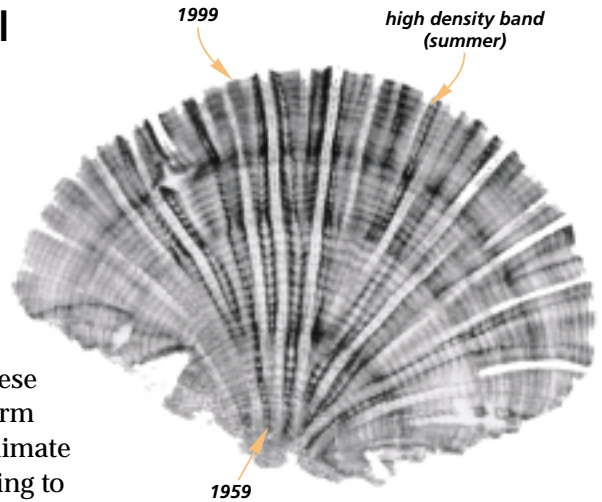
changes are unprecedented or part of a naturally varying climate system, whether they're to be expected or whether they're unusual and caused by human activities. To put these changes into a longer-term perspective and to aid climate predictions, we are turning to proxy data.

Massive reef corals are just one of many paleoclimate archives that we tap for information, but they're particularly well-suited to the reconstruction of continuous, multi-century records of conditions in the surface oceans, with



Quantification of low-frequency variability in a Bermuda brain coral (*Diploria labyrinthiformis*) indicates a strong correlation between density and the North Atlantic Oscillation Index (NAO). This may prove to be a valuable tool in reconstructing NAO variability over the past several centuries.

seasonal resolution. As corals grow, the structure, isotope composition, and trace element chemistry of their calcium carbonate skeletons change in response to small variations in light, sea surface temperature, salinity, turbidity, runoff, and upwelling intensity.



An X-ray image reveals seasonal and decadal-scale changes in coral skeletal density. Seasonal banding is used to age the colony and establish long chronologies.

We are developing techniques to measure these changes with greater precision. Using relationships established in calibration studies, we can re-interpret the chemistry as an environmental signal. For example, the oxygen isotope composition (ratio of oxygen 18 to oxygen 16) of the skeleton is sensitive to water temperature and salinity, while the strontium/calcium ratio varies with temperature. By measuring both the isotope and elemental ratios using mass spectrometry, a history of temperature and salinity changes in the waters surrounding the coral colony can be reconstructed for the period in which it grew. Because reef corals grow rapidly, up to 22 millimeters per year, the skeleton can be subsampled at monthly intervals to achieve seasonal resolution. Using Bermuda corals we are reconstructing winter-time sea surface temperatures to study long-term variability in the North Atlantic Oscillation. Despite the relatively low growth rate of the Bermuda brain coral, I am able to extract 12 samples per growth band us-

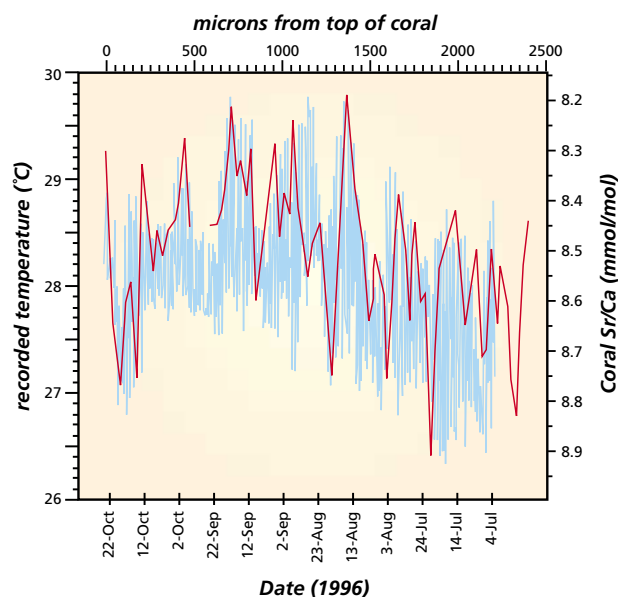
ing a super-fine, diamond-tipped dental drillbit, a microscope—and a very steady hand.

Corals accrete skeleton continuously until the colony dies. For some of the massive species, this may mean several hundreds of years. In fact, the oldest known living colony reached 1,000 years before it was removed from Bermuda in the early 1980s for paleoclimate reconstruction. Today, we seldom remove entire colonies. Instead a special underwater hydraulic drill is used to remove core samples, often several meters long and up to 10 centimeters in diameter. After coring, the hole is closed with a cement plug to prevent infection by boring organisms, and new growth eventually covers the plug.

Worldwide, there are now 15 to 20 coral-based climate records extending back further than the mid-1800s. All have been generated by subsampling coral cores at monthly or annual resolution. At WHOI, we're pushing that envelope, striving for even greater resolution in order to extract the signals left by short-lived, cata-

strophic events. Using petrographic thin-sections and scanning electron microscopy, we recently identified daily growth bands in coral from the north-central Pacific, each band about 30 microns wide (see figure below). We're even able to distinguish night-time and day-time skeletal accretions! Measurement of skeletal chemistry at this micro-scale requires a quite different technique, one that has been used by hard-rock geochem-

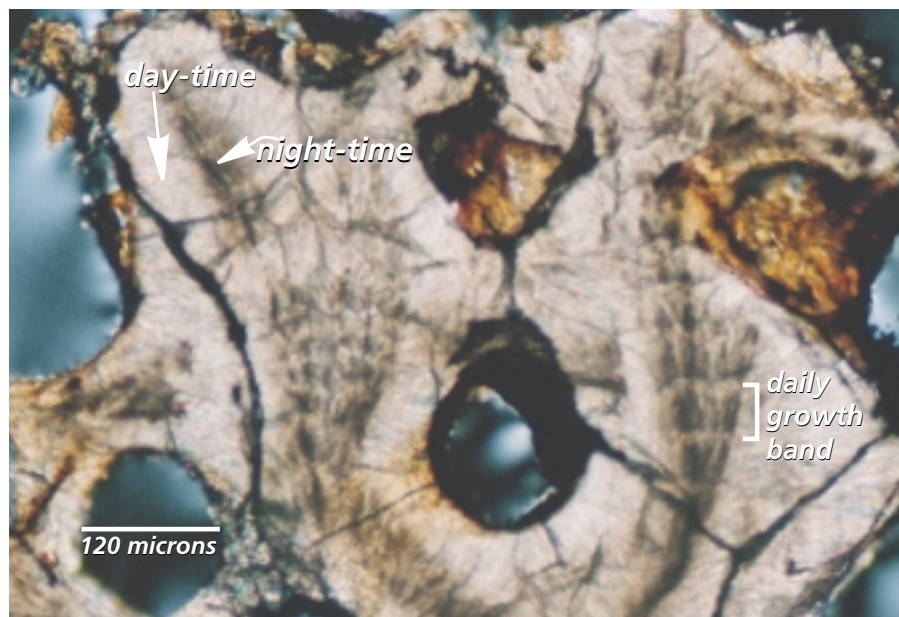
ists at WHOI for decades but only recently applied to corals. With the ion microprobe, the surface of the coral is "sputtered" with a continuous stream of oxygen ions, leaving a tiny cavity about 5 microns deep. The ion beam—as small as 10 microns in diameter—can be focused on specific regions of the coral



Micro-scale analysis of the section pictured below using the ion microprobe yields high-frequency variability in the strontium/calcium ratio (red), which tracks the real daily sea surface temperature variability with remarkable precision (blue).

sample. The figure above shows the results of our first attempt to reconstruct ultra-high resolution strontium/calcium-based sea surface temperature variability recorded in the daily growth bands of a colony collected in late October. A temperature logger placed near the base of the coral recorded half-hourly temperature, with large biweekly oscillations coincident with the phase of the moon. Strontium/calcium ratio variability in the top 2,400 microns of skeleton correlates remarkably well with these high-frequency sea surface temperature changes, indicating that we can extract information with at least sub-weekly resolution. Over the next year we'll be developing this capability for oxygen isotope analysis in order to track pulsed signals of hurricane rainfall in Caribbean corals, a project funded by the RCRC.

Anne Cohen is a Visiting Investigator in the Geology and Geophysics Department at WHOI.



*A polished thin-section of skeletal elements in *Porites lutea* viewed in polarized, transmitted light shows daily growth bands and regions of night- and day-time skeletal accretion.*

Published semi-annually by the
Rinehart Coastal Research Center
Woods Hole Oceanographic Institution
193 Oyster Pond Road, MS#2
Woods Hole MA 02543-1525
Telephone: (508) 289-2418
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