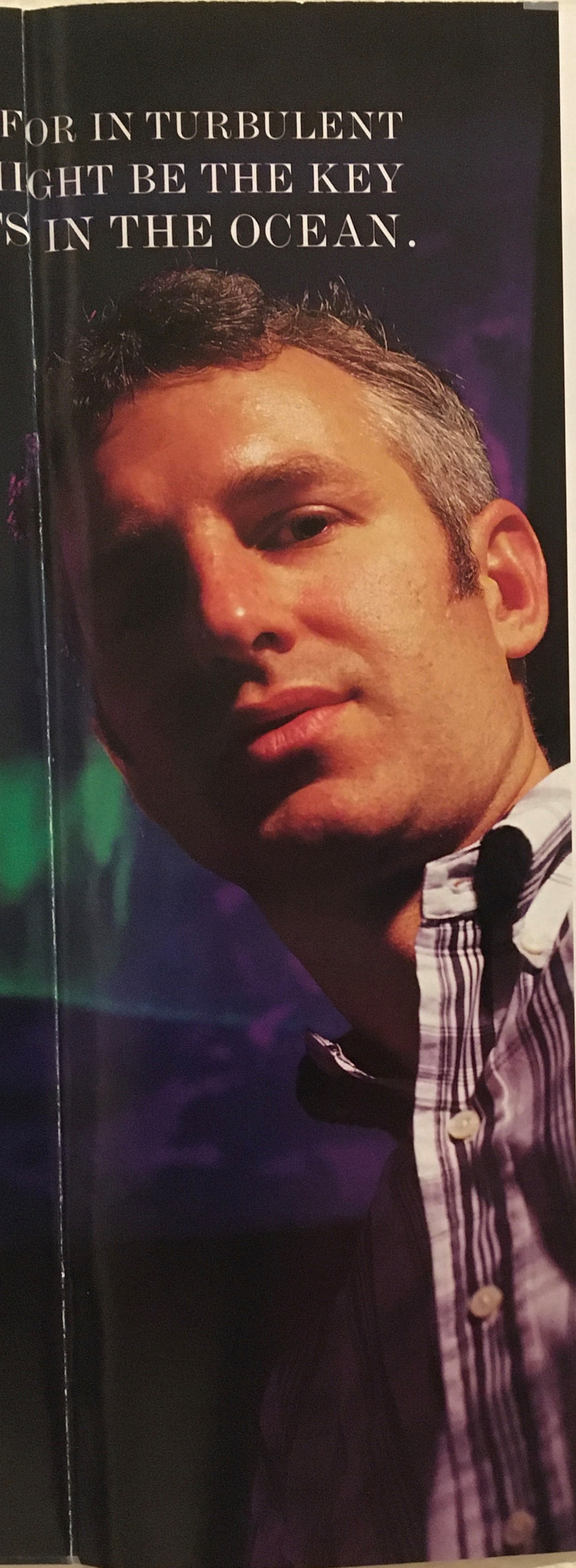
HOW DOES A LOBSTER FIND WHAT IT'S LOOKING FO
WATER? TODD COWEN THINKS THE ANSWER MIG
TO TRACKING THE SOURCE OF POLLUTANTS I

HOW WATER TURBULENCE WORKS: Qian Liao, graduate student in environmental fluid mechanics and hydrology, observes dye markers of a concentration plume illuminated by a laser light sheet in a glass tank above his head. Asst. Prof. Todd Cowen (right) conducted these experiments to observe how chemicals might be disbursed in turbulence in the DeFrees Hydraulics Lab in Hollister Hall.



NICOLA KOUNTOUPES / UP

Going with the Flow

BY LEILA BELKORA

A few steps from the College Avenue bridge over Cascadilla Creek, behind the round window in Hollister Hall that looks like a porthole in the prow of a ship, water churns and bubbles in a kind of laboratory counterpart to Ithaca's famous waterways.

Outside, rocky terraces and deep plunge-pools shape the courses of Cascadilla, Fall, and Six Mile creeks, and wind-driven breakers pound Cayuga Lake's south shore. Inside turbines and tilting water tanks reproduce some of nature's hydrodynamic complexities in a variety of test conditions. Waves roll over a ripple bed. An artificial stream tumbles down the gentle slope of a flume. A turbulent, meandering current surges through a broad channel. Lasers flash as high-speed cameras record the scattered light from test particles in the tanks.

The facility is the DeFrees Hydraulics Laboratory, the focal point of experimental studies in the environmental fluid mechanics and hydrology program in the School of Civil and Environmental Engineering. (The lab is named after engineer and benefactor Joseph DeFrees '29 CE.)

Edwin "Todd" Cowen, assistant professor, assumed the directorship of the laboratory when he joined the Cornell faculty in 1998. The term "hydraulics," he noted, is slipping as a descriptor of what he and his colleagues do; it doesn't take into account the study of such problems as how pollutants disperse in the environment or how waves re-suspend sediments.

"Hydraulics is, classically, man's attempt to make water do what civilization needs it to do: open channel flow and delivering aqueducts with water, managing reservoirs, dissipating energy as water falls off a spillway," Cowen said. "Even lake source cooling, to a degree, is a hydraulics project," he continued, referring to a plan underway to use cold water from the depths of nearby Cayuga Lake in a heat exchange to cool campus buildings. "The Army Corps of Engineers comes to mind when you say hydraulics. Environmental fluid mechanics I think of as including that, but also extending to the natural environment's flows. So one of the things I'm interested in is, for example, not only how do we take advantage of the lake to cool a body of buildings on campus, but what is the big transport picture, everything going on in the lake under its natural circulation, which maybe you wouldn't normally consider to be part of hydraulics. That's the direction I think environmental fluid mechanics is heading."

A Lobster Tale

Cowen's current research certainly stretches the traditional boundaries of fluid mechanics. One of his projects, sponsored by the Office of Naval Research, will add a potentially key lobster clause to the annals of research on chemical plume tracing.

The Navy's problem is to find the sources of chemicals that are detected in turbulent waters in coastal zones. The chemicals might be explosives leaking from unexploded ordnance on the sea floor, for example, or pollutants escaping from lost 55-gallon drums. In any case, the challenge is to start at the downstream end of a plume of chemicals and follow it back to the source.

"If you look at a turbulent patch of a chemical in water, it's not at all clear what direction is upstream," said Cowen. "Our goal is to understand the mechanisms, the physics by which local, naturally evolving turbulence will disperse a pollutant plume. Then we can look at those turbulent structures and try to understand what sort of algorithms would be effective at searching for a source."

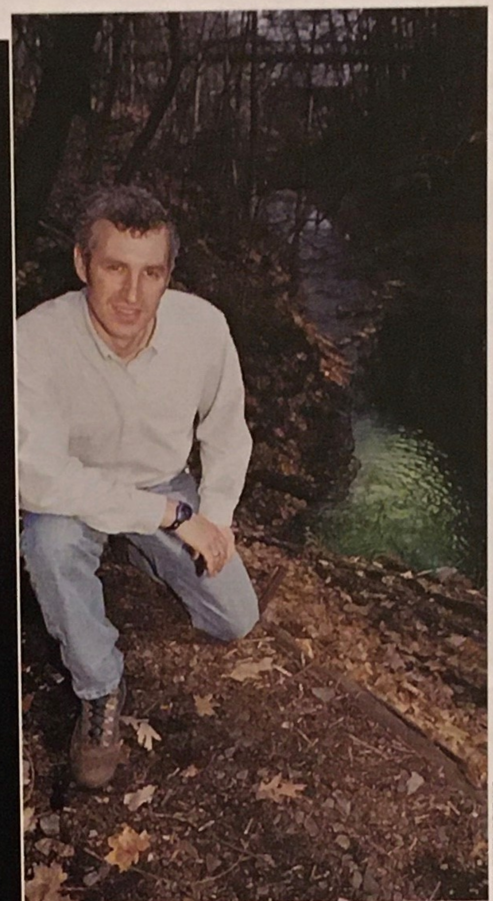
As part of a multi-pronged effort to develop such algorithms, the government is funding studies of the lobster, which hunts very effectively for food or sources of sexual pheromones in choppy water. The Navy paired Cowen with biologists at the Marine Biological Laboratory in Woods Hole, Mass., whose expertise is in lobster behavior and olfactory capabilities. The biologists study how the lobster reacts to odorants it picks up through antennules, small antennae protruding from under the eyes.

"The lobster is the dog of the sea," Cowen noted. "They have very good olfactory capabilities. They have developed quite fine abilities to measure the concentrations of things they're interested in."

The biologists' understanding of lobster chemo-orientation leaves Cowen and his students free to tackle the question of what structures in turbulent water a lobster might be able to use in tracking the source. That depends on what data is available to the lobster, and it appears that the chemical concentration and the basic flow pattern in a small area in front of the lobster are significant.

"They have a crude ability to measure velocity, it looks like," Cowen said. "They do a little spatial sampling—they keep their two antennules about nine centimeters off the bed, spaced apart some standard distance. They flip them a little bit as they're sampling out there in a certain plane, in two different spots in space. So, to a degree they may be developing spatial gradients. They also have some sort of memory capacity, and it turns out that the dynamic range of their sensors is quite large. It's like the iris of our eye: they can tune it down when it's being saturated by a strong concentration and amplify it for a weak

The Greening of Cascadilla



MATTHEW FONDEUR / UP

ON A RECENT DAY COWEN LED students in CEE 655, a class on mixing and transport processes, on a field trip out the back door of Hollister Hall. He carried a vial of fluorescein dye, a benign but lurid green pigment, in his pocket—"hopefully not leaking," as he commented to the class. At a narrowing in Cascadilla just upstream from the footbridge to Collegetown, in the center of the channel, he placed a submersible pump; this he connected to a fluorometer and laptop computer on the footpath. The fluorometer would monitor the concentration of dye as a function of time. A few hundred meters upstream, Cowen tipped the contents of the vial into the creek. As the dye spread down the stream and lingered in pockets at the water's edge, students saw the gist of his latest lecture confirmed: the pockets, eddies, plunge pools, and all of the other mechanisms in the stream act to delay mass transport downstream. Not even a waterfall hurries things along.

—*L.B.*

concentration."

In the lab, Cowen's group runs a physical simulation of the lobster's hunting conditions. A plume of fluorescent dye issues from a source in the upstream end of a tank. A current moves the water downstream. Waves, too, propagate down the tank, and a weir and waterfall at the downstream end act to prevent reflections from traveling back into the test section. On top of this already elaborate model, the researchers can impose a certain kind of large-scale turbulent structure—a vertically oriented vortex—that results in nature when three-dimensional deep-water structures move into shallow regions.

"That flow is one of the most complex we've ever tried to model," Cowen said.

The dye plume itself does not contribute to the turbulence in the flow; that's inherent in the definition of a plume as a momentum-less jet. What Cowen and his group will be looking for are the various ways the passive plume interacts with the turbulent flow.

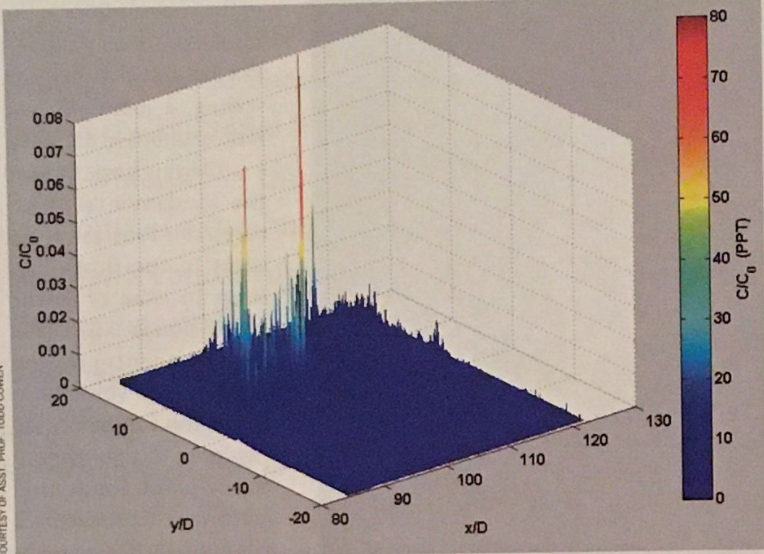
At the source of the plume, interaction between the source and the flow can generate a series of swirls with alternating sense of rotation, known as a von Karman vortex street. Further from the source, the dye may spread in all directions under turbulent "Fickian" diffusion, evening out gradients in concentration. As the plume widens it develops similar structures on a range of spatial scales, just as a jagged coastline may look similar whether one is looking at the walls of a fjord, rocks along the beach, or pebbles at the water margin. Depending on the scale of the plume relative to the scale of the largest eddies in the turbulence, it may also follow a so-called Richardson scaling, a more efficient form of turbulent diffusion.

Cowen hopes to see the fundamental structures the lobster recognizes in the flow—patterns in time or in the spatial domain. He tracks both dye concentration and particle velocity in the region a lobster could explore, a two-dimensional plane about nine centimeters off the bed. His data-gathering technique is based on his own innovations to the field of particle tracking, introduced over the last decade. In the first step, a laser flashes and a camera records the scattered light from the test particles—neutrally buoyant glass spheres—in the flow. In the second step, another laser flashes and stimulates the emission from the fluorescent dye, so that the concentration field can be recorded. In the third step, the first laser flashes again and records the new position of the test particles. Cross-correlating the first and third images yields the vector velocity field at the time corresponding to the dye measurement. These concentration and velocity field measurements are repeated at 20 Hz.

The newest tanks in the DeFrees lab are marine-tolerant and might occasionally host a lobster showing off his squid-juice tracking prowess. Cowen's primary task, however, is to provide his colleagues with the concentration and velocity field data under a range of conditions and with insight into the fundamental turbulence structures that appear in the

Measuring Turbulence

A THREE-DIMENSIONAL RENDERING OF PLUME CONCENTRATION IN A HORIZONTAL PLANE 9 CM ABOVE THE BED OF A WIDE OPEN CHANNEL FLOW.



COURTESY OF ASST. PROF. TODD COWEN

The vertical coordinate is the concentration. The source, 1.4 cm in diameter (D=1.4 cm), is flush mounted in the bed at (x,y) = (0,0) and slowly leaks fluorescent dye into the flow. There is a mean current of about 9 cm/s in the positive x direction (left to right in the image). This image was collected using the laser induced fluorescence (LIF) technique.

The x/D axis is the non-dimensional coordinate in the direction of flow (streamwise direction), where D is the source diameter (1.4 cm) and x/D=0 is at the center of the source. The y/D axis is the non-dimensional coordinate perpendicular to the flow direction and at a constant elevation of 9 cm (z/d=6.4) above the bed which contains the flush mounted source. y/D=0 is at the center of the source. C/Co is the non-dimensional concentration where Co is the source strength (hence C/Co can be thought of as the dilution ratio).

data. The biologists, in turn, will run synthetic algorithms on the data sets. From previous experience they know what physical cues cause a lobster to turn or move forward; they'll try different algorithms based on these rules to see which are most effective at locating the source in Cowen's simulated environment.

After The Lobster Shift

The investigation into lobsters' chemical plume tracing is just one of several pots boiling, so to speak, under Cowen's supervision. His ability to identify and isolate important aspects of complex problems in fluid mechanics and to turn them into manageable laboratory investigations keeps him busy with several students and colleagues.

A project involving jets, for example, takes a new look at a classic problem. Clams and other bivalves, such as scallops and mussels, take in food-rich water through an intake siphon and expel clear water through the second siphon. The canonical form of the flow around this second siphon is that of a turbulent round jet, which is well known. Cowen and his students found, however, that the problem had not been well studied for the conditions that prevail in the bivalves' environment. They are reexamining the problem, considering the flow as a function of Reynolds number (a gauge of the relative importance of viscous and inertial forces in the fluid) and including the effects of mass transport in the two different jets.

In collaboration with Philip Liu, a professor of civil engineering with expertise in the propagation and transformation of waves in complex ocean environments, Cowen is proposing a new use for the tank developed for the lobster project. The ability to study three-dimensional waves shoaling in shallow water would help address the questions of how tsunamis, often destructive waves generated by seismic activity, interact with buildings on shore, and what is the best way to mitigate the damage. Other projects involve modeling breaking waves, in particular the entrainment of bubbles in salt water versus fresh water, and research on problems in coastal engineering that have implications for industries.

In the future, Cowen sees a good opportunity to study natural systems around Ithaca. He's especially keen on a campus-wide, multi-disciplinary proposal to study Cayuga Lake, taking into account the various physical and social factors affecting water quality and hydrodynamics: urbanization, dairy farming, erosion, the use of the lake as a source of water.

"Lake source cooling has brought a lot of interest in the lake from the community, both Cornell and at large. But also in coming here I was thinking I wanted to look at transport phenomena on the lake," he said.

"Already we—it's the royal we, as in, 'me,' unfunded, no students—have a crude model of circulation on the lake, looking at internal wave structure. The goal is a three-dimensional circulation model, fitting in a watershed model."

His eyes light up as he contemplates the potential for innovative hydrodynamical modeling coupled with fieldwork practically in his back yard.

"We have a lot of great environmental fluid mechanics around."

Leila Belkora is on leave from the University of Illinois at Chicago, where she works in the news bureau and teaches astronomy. She is currently living in Ithaca, freelancing and writing a history of astronomy.