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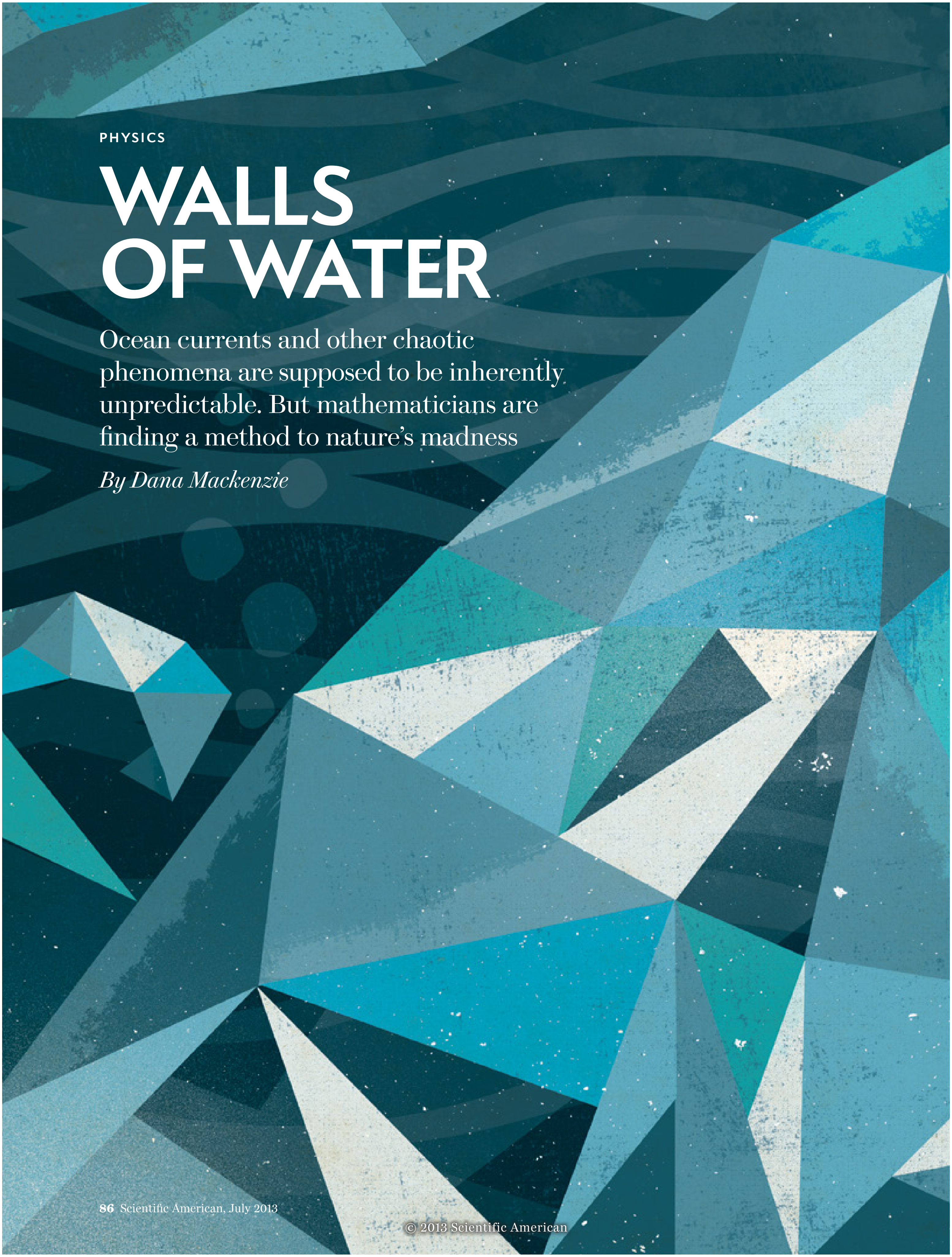
WALLS OF WATER

Ocean currents and other chaotic phenomena are supposed to be inherently unpredictable. But mathematicians are finding a method to nature’s madness

By Dana Mackenzie



ALL ALONG THE GULF OF MEXICO, 2010 WAS THE SUMMER OF THE Oil Spill. As BP's uncapped Deepwater Horizon oil well gushed away off of Louisiana, tourists stayed away from the Gulf Coast in droves, convinced by news reports that oil was coming ashore or would do so imminently. As far away as Fort Myers and Key Largo in Florida, beaches were deserted and hotel occupancy rates were down.

In reality, the situation was never so dire—especially on the western coast of Florida. This part of the Gulf Coast was protected for the duration of the oil spill by a persistent, invisible divide. Lying above the continental shelf off of Florida was an unseen line that directed the oil and prevented it from spreading farther east. It was not a solid object, but a wall of water that moved around as ocean currents shifted. Nevertheless, this wall was just as effective as any seawall or containment boom.

Scientists call these invisible walls "transport barriers," and they are the maritime equivalent of continental divides. They separate water flowing in one direction from water flowing in another. In a chaotic ocean, they provide a road map to tell you where the traffic is going. Although water currents often appear to be almost completely unpredictable, transport barriers restore a measure of order and structure to their chaotic flow.

The study of these structures has blossomed in recent years, and their importance is still not fully appreciated by the scientific community. But already researchers have shown how their study may help explain why the surface oil from the Gulf spill disappeared more rapidly than expected and why none of it escaped through the Strait of Florida into the Atlantic. During future disasters, understanding these flows could make cleanup efforts more efficient. The research could also elucidate how blood flow affects the formation of plaques in arteries and help to predict how allergy-causing spores migrate in the atmosphere.

The study of chaos came of age in the 1970s, when scientists discovered that in certain natural phenomena, even tiny perturbations could lead to profound changes. The proverbial refrain is that the flutter

Illustration by Andrew Bannecker

of a butterfly's wing on one side of the globe could make subtle changes in air currents that cascaded, to the point of causing a tornado on the other side weeks later.

Flowing fluids—which include gases such as air and liquids such as seawater—are in fact the quintessential example of chaotic systems and one of the most ubiquitous: the dynamics of fluids govern phenomena from the Gulf Stream to the flow of air through a wind turbine to curving penalty kicks in soccer. The mathematical equations describing fluid flow were unveiled nearly 200 years ago, by Claude-Louis Navier (in 1822) and George Stokes (in 1842). Yet knowing the equations is not the same thing as solving them, and the Navier-Stokes equations remain among the most challenging problems in mathematics.

In principle, an exact solution of the Navier-Stokes equations would yield a detailed prediction of the future behavior of a fluid. But the precision of the answer would depend on exact knowledge of the present—or what scientists call the initial conditions. In reality, you can never know where every molecule of water in the ocean is going, and in a chaotic system any uncertainties—like the effects of a butterfly's motions—grow exponentially over time. Your exact solution to the Navier-Stokes equations will rapidly become moot.

And yet "chaotic" does not mean "random" or "unpredictable," at least in principle. In the past decade or so mathematicians have created a theoretical framework for understanding the persistent structures such as transport barriers that are hidden in chaotic fluids. In 2001 George Haller, a mathematician now at McGill University, gave these structures the rather unwieldy name "Lagrangian coherent structures." More poetically, Haller calls the intricate structure of transport barriers "the skeleton of turbulence." Once you have identified these structures in a body of fluid, you can make useful short- to medium-term predictions of where the fluid flow will carry an object, for instance, even without a perfect, precise solution of the Navier-Stokes equations.

What does a transport barrier look like? You are looking at one every time you see a smoke ring. At its core lies an *attracting* Lagrangian coherent structure—a curve toward which particles flow, as if they were attracted by a magnet. Ordinarily you cannot see such a structure, but if you blow smoke into the air, the smoke particles will concentrate around it and make it visible.

Much harder to visualize are the *repelling* Lagrangian coherent structures—curves that, if they were visible, would appear as if they were pushing particles away. If you could run time backward, they would be easier to see (because they would attract particles); failing that, the only way to find them is to tease them out by computer analysis. Though difficult to observe, repelling structures are particularly important because, as Haller has proved mathematically, they tend to form transport barriers.

An experiment conducted in the summer of 2003 in Monterey Bay off the coast of California showed that Lagrangian coherent structures could be computed in real time and in real bodies of water. Mathematician Shawn C. Shadden of the Illinois Institute of Technology and his collaborators monitored surface currents in the bay using four high-frequency radar stations deployed around the bay.

Dana Mackenzie is a freelance mathematics and science writer who lives in Santa Cruz, Calif. He received his Ph.D. in mathematics at Princeton University and is a U.S. Life Master at chess. His most recent book is *The Universe in Zero Words* (Princeton University Press, 2012).

Analyzing the radar data, the researchers discovered that most of the time a long transport barrier snakes across the bay from Point Pinos, at the southern edge, almost all the way to the northern side. Waters to the east of the barrier circulate back into the bay, whereas those on the western side go out to sea. (Occasionally the barrier detaches from Point Pinos and drifts farther out to sea.) Such information could be vital in case of a pollutant spill.

To confirm that the computed structures did actually behave as advertised, Shadden's team tracked the motion of four drifting buoys they deployed in collaboration with the Monterey Bay Aquarium Research Institute. When they placed drifters on opposite sides of the transport barrier, one drifter would follow the water circulating back into the bay, and the other one would hitch a ride on the currents heading southward along the coast. They also showed that a drifter placed on the recirculating side of the structure would stay in the bay for 16 days—even though they had used only three days of data to compute it. This robustness of their results testified to the strength and persistence of the transport barrier. For 16 days, it really was like an invisible wall in the water.

CLOSE CALL IN THE GULF

THE MOST DRAMATIC demonstration of the transport barrier concept came in the aftermath of the 2010 Gulf oil spill. Oceanographers and mathematicians have analyzed the huge volumes of data on the spill and shown how the information could have enabled scientists to better predict where the oil would go.

Lagrangian coherent structures might help explain why the surface oil disappeared more rapidly than anyone expected—much faster, for example, than the oil from the *Exxon Valdez* spill in 1989 in Prince William Sound in Alaska. (The fate of the subsurface oil has been more controversial, and much of it may still remain at the bottom of the Gulf.) The warm Gulf of Mexico, it turned out, is home to hordes of microorganisms that feed on hydrocarbons that naturally seep into the Gulf waters. Giv-

IN BRIEF

Invisible dividing lines often form in the flow of fluids, including winds and oceanic currents.

Such "transport barriers," so-called Lagrangian coherent structures, make these chaotic phenomena more predictable.

Understanding these structures could aid in search operations at sea and improve cleanup after an oil spill. It could also help in any problem involving turbulent fluid motion, such as modeling blood flow or weather.

en a much more abundant supply of hydrocarbons than usual, these microorganisms flourished. Microbiologist Dave Valentine and mathematician Igor Mezic, both at the University of California, Santa Barbara, showed that the bacteria tended to congregate in coherent regions defined by transport barriers. Clearly, the long-term stability of those regions helped the oil degrade. Valentine notes that it would have been a different story if the blowout had happened off the coast of Brazil, another region where vast deepwater oil reserves have been discovered. There the currents lead out to sea, where a captive supply of bacteria does not exist to chow down on the hydrocarbons.

Transport barriers may also explain why the oil from Deepwater Horizon avoided flowing into the Loop Current, a persistent jet that leads through the Florida Straits and into the Atlantic, where it could have polluted beaches along the East Coast. As late as July 2, the National Oceanic and Atmospheric Administration was predicting a 61 to 80 percent chance some oil would make it to the Loop Current. The prediction was based on 15 years of historical ocean current data from the Gulf of Mexico.

In 2010 we apparently got lucky. First, unusually strong winds from the Southwest pushed the oil slick to the north, away from the Loop Current. In addition, a giant eddy, called Eddy Franklin, detached from the Loop Current and pushed it farther south than usual, forming a barrier between the oil and the current. It remains to be seen whether any of these phenomena could have been anticipated. Haller, however, with oceanographer Maria Olascoaga of the University of Miami, has shown that other seemingly capricious changes in the oil slick were predictable. On May 17, for instance, a giant "tiger tail" (named after its shape) of oil suddenly traveled more than 160 kilometers southeast in one day. According to their computer analysis, the tiger tail traveled along an attracting Lagrangian coherent structure, and the impending instability was presaged seven days earlier by the formation of a strong attracting "core" on that structure. Likewise, an abrupt westward retreat of the oil slick's leading edge on June 16 was anticipated nine days earlier by the formation of an exceptionally strong repelling core to the east of the slick. Had surveillance been in place that could identify transport barriers, cleanup boats could have been sent to the right locations.

Beyond the study of oceanic currents, applications of the transport barrier concept have proliferated in recent years. For example, Shane Ross of Virginia Polytechnic Institute has studied the effect of transport barriers in the atmosphere on airborne pathogens. He and plant biologist David Schmale, also at Virginia Tech, used a small drone airplane to collect air samples at an altitude between tens and hundreds of meters above Blacksburg. When an attracting structure passed by or when two repelling structures passed in rapid succession, the researchers detected a spike in the number of spores of a fungus called *Fusarium*. Ross hypothesizes that in the first case the spores had been pulled toward the coherent structures, whereas in the second they had become trapped between the two repelling barriers, like cattle herded into a small region by prods. Some of the spores were of a species that does not usually occur in Virginia, which suggests that the structures remained intact long enough for the spores to be transported several hundred kilometers.

Shadden is now studying the role of Lagrangian coherent structures in blood flow. For example, he has used these structures to reveal the boundaries between blood ejected on one heartbeat and blood ejected on the next. He showed that most of the blood in a normal ventricle remains there for at most two heartbeats. But in six patients with enlarged hearts, regions of blood recirculated for much longer—"a widely recognized risk factor for thrombosis," he wrote in a draft of his study.

More than a decade after Haller named them, Lagrangian coherent structures are still far from being a mainstream tool in oceanography or atmospheric science. One objection raised about their usefulness is that if there are errors in the measurement of the flow field, they will surely propagate and produce errors in the predictions of the transport barrier as well. But the Monterey Bay experiment found that the location of the transport barriers was relatively insensitive to measurement errors.

Another objection is that to compute the structures, you need to know the entire flow field, meaning the velocity of water flowing at each point. But if you know that, you can forecast the oil slick using existing computer models. So what are calculations of Lagrangian coherent structures good for?

As it turns out, forecasting is not the only game in town. "Hindcasting" may turn out to be important in finding the source of "mystery oil spills" that wash ashore from unknown sources—often from sunken ships. For example, the *SS Jacob Luckenbach,* which sank off San Francisco in 1953, polluted the California coast every year beginning around 1991, but the source of the spill was not discovered until 2002. Plane crashes and shipwrecks have also produced "debris spills" and "body spills." Because conventional ocean models cannot be reversed in time, rescuers cannot extrapolate backward from the observed debris field to find the source. Oceanographer C. J. Beegle-Krause and mathematician Thomas Peacock of the Massachusetts Institute of Technology are now working on using Lagrangian coherent structures to forecast where shipwreck survivors will drift in the currents, which would help narrow down the search area. In such situations, as Peacock notes, "even a few minutes might be a matter of life and death."

Finally, Lagrangian coherent structures provide more than mere forecasts or hindcasts; they provide understanding. Knowing about the structures enables scientists to better interpret the predictions of computer models. If a model predicts that a filament of oil will move toward Pensacola and we can see a structure pushing it or pulling it that way, we can be reasonably confident in the prediction. If there is no corresponding structure, we might treat the model with more skepticism.

Mathematicians are now broadening their research into different types of organized structures in turbulent fluids, such as eddies and jets. With deeper understanding, we may be able to answer questions about chaotic phenomena that now elude us. SA

MORE TO EXPLORE

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See videos of fluid barriers at **ScientificAmerican.com/jul2013/chaos**