Eos, Vol. 84, No. 14, 8 April 2003

The Seas of Titan

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Oceanography may no longer be only an Earth science. Evidence continues to mount that Saturn's giant moon, Titan, may have seas of liquid hydrocarbons that exhibit many phenomena familiar to terrestrial oceanographers, but with an other-worldly flavor (Figure 1). In less than two years, the Cassini-Huygens mission, a massive joint undertaking of NASA, the European Space Agency, and the Italian Space Agency, will arrive at Saturn and begin exploring the strange world of Titan. Our goal here is to introduce Titan to the oceanographic community, to outline the data to come, and prompt new modeling efforts. We pay particular attention to phenomena observable from Cassini, although we note that many terrestrial phenomena—only now beginning to be surveyed on Earth via moored instrument networks, submersibles, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs), etc.—may have analogues on Titan. We anticipate that Earth will have much to tell us about oceans on Titan, and vice-versa.

Titan, the second-largest moon in the solar system (2575 km radius), falls between Mars and Mercury in size [*Lorenz and Mitton*, 2002]. Its dense atmosphere, like that of Earth, has molecular nitrogen as its dominant constituent; but unlike the present-day Earth, it is chemically much more reducing. Methane, at a few percent, is the next-most abundant constituent and acts as a condensable greenhouse gas that participates in a hydrological cycle forming clouds and precipitation, just as water vapor does on Earth.

Titan is cold. Nearly ten times further from the Sun than the Earth, its surface temperature is 94 K (-179°C), warmed by the strong greenhouse of its thick atmosphere, but cooled by the "nuclear winter" anti-greenhouse blocking effect of the organic smog formed like ozone on Earth by the action of ultraviolet light. Because of its opacity of 2–3 at visible (red) wavelengths, this smog hid the surface from the cameras of Voyager 1 during its close flyby of Titan in 1980. The smog becomes progressively less opaque at longer wavelengths, so that it has been possible to produce crude maps of Titan's surface at near-infrared wavelengths using the Hubble Space Telescope (Figure 2) and ground-based observatories in the last decade. These maps show large dark regions that may be seas of liquid methane and ethane.

Titan's size and mass indicate a composition of roughly half ice and half rock, with the latter probably forming a central core. Thus, the bulk of Titan's solid surface, both bedrock and any "sand," should be predominantly water ice in composition, with some amount of organic (i.e., carbon-bearing, but a-biogenic) material.

Background: Liquid Hydrocarbons on Titan

Since the discovery of a methane-bearing atmosphere in 1944, scientists have considered the possibility of surface liquids on Titan. This notion, supported by the fact that methane in Titan's atmosphere would be destroyed in 106–107 years by photolysis, suggests that, unless we are viewing an anomalous period in Titan's history, the atmospheric inventory of methane must be buffered by a surface reservoir. Like water on Earth, methane is a condensible greenhouse gas, and surface-atmosphere equilibrium is a strong control on climate.

Results from the Voyager spacecraft [*Flasar*, 1983] showed that, although the surface temperature was close to the triple point of methane, the lowest parts of the atmosphere could not be saturated with methane and, thus, oceans of pure methane were unlikely. (Although it may be noted that the terrestrial atmosphere has a relative humidity well under 100% on a global average, despite the fact that oceans cover nearly 70% of its surface.). One solution (literally) to the paradox was suggested by *Lunine et al.* [1983], who noted that the dominant photochemical product, ethane, is an involatile liquid at Titan surface conditions and fully miscible with methane, and thus, that the relative humidity of methane would be lowered in a mixed ethane/methane ocean.

Photochemical models would predict the accumulation of several hundred meters global depth of ethane over the age of the solar system, and would be mixed with a comparable amount of methane and nitrogen. Over time, the methane would be irreversibly converted in the atmosphere into ethane, leading to a secular decrease in depth, unless volatiles were added to the ocean-atmosphere system; e.g., by volcanism. A mixed solid-liquid surface would imply global equivalent ocean depths comparable with typical icy satellite topography of 1–2 km.

Maps of Titan (*Smith et al.*, [1996]; e.g., see Figure 2) reveal that there is no global ocean present, as considered in early papers, but do allow for basins of liquid—perhaps in impact craters—up to around 500 km across. Indeed, these dark regions are literally pitch-black, which would be expected for bodies of liquid hydrocarbons.

The dynamics of liquid basins on Titan were first considered by *Sagan and Dermott* [1982], who noted that tidal dissipation in Titan seas might be significant (although, see *Lorenz and Lunine* [1997] for a review). *Sears* [1995] used a numerical model to study tides.

Driven by solar heating a thousand times less than on Earth, winds on Titan may be relatively weak, yet provide an important oceanic forcing mechanism. Wind-generated waves on Titan were considered in a short but pioneering paper by *Srokosz et al.* [1992], who pointed out that, due to low gravity, fully-developed waves on Titan would be large and have slow phase speeds compared with Earth. For example, for a 1 ms^{-1} wind, surface gravity waves on Titan would have heights of 0.2 m (compared with 0.025 m on Earth) and have much longer period (5.7 s versus 0.8 s) and wavelength (7 m versus 1 m). The wavelength regimes for capillary and gravity waves in Titan seas are similar to those for Earth, a fact of some importance for radar observations. *Ori et al.* [1998] outlined some general considerations on river and ocean dynamics with particular reference to the formation of ripples and other bedforms.

Ghafoor et al. [2000] have applied and adjusted empirical terrestrial wave-growth models to determine likely wave heights on Titan as functions of fetch and wind speed. They note that, due to the stronger ocean-atmosphere coupling (the ratio of densities of air and liquid are approximately 100 for Titan and 1000 for Earth), waves of a given height are produced by wind speeds three times less on Titan than

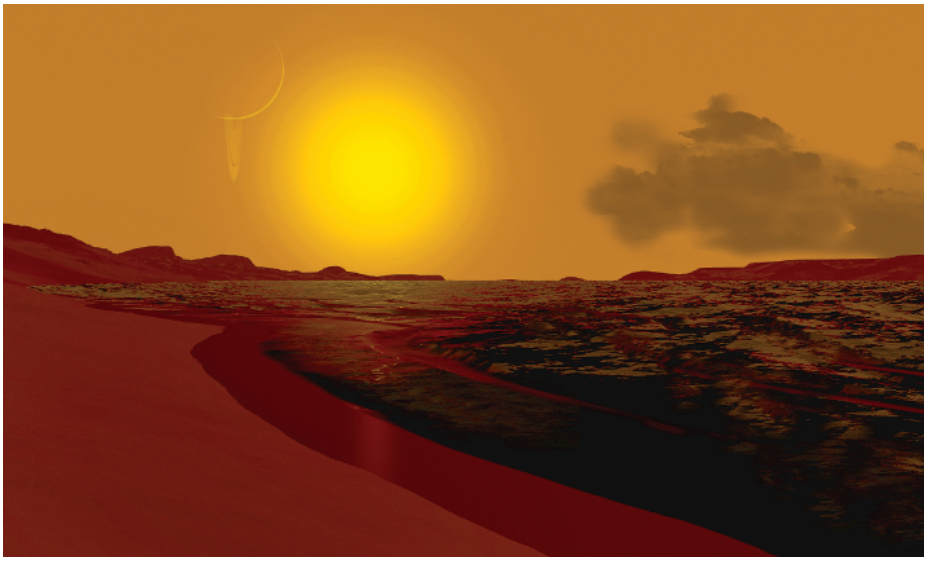

Fig. 1. Artist's impression of Titan's beachfront vista; by Mark Robertson-Tessi of the Arizona Space Grant program, in collaboration with Ralph Lorenz. (See http://www.lpl.arizona.edu/~rlorenz/titanart/titan1.html). The thick haze in the atmosphere blurs, but does not completely obscure, the view of the Sun and Saturn.

on Earth. They estimate that a 1-ms^{-1} wind would become fully developed to a significant wave height of 0.2 m on Titan after a fetch of about 20 km, well below the likely size of liquid basins.

Recent work [*Tokano et al.*, 2002] indicates that Saturn's gravitational tide on Titan may generate (predictable) winds in the lower atmosphere on the order of 0.5 ms^{-1}. These tidal winds (Figure 2) are powered not by solar heat, but by work done to circularize Titan's orbit.

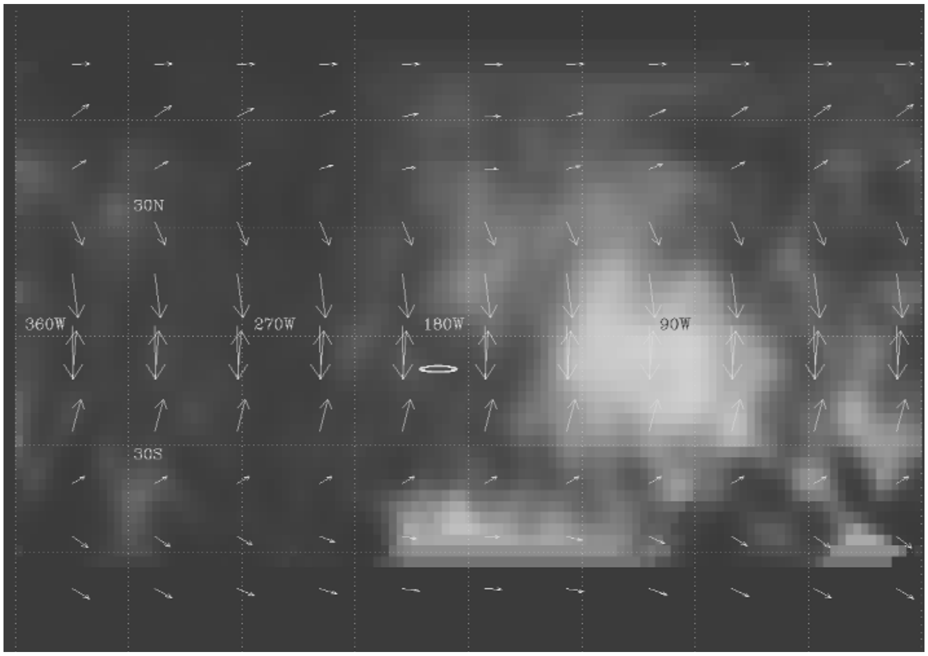

Fig. 2. A map of the near-surface winds due to Saturn's gravitational tide, averaged over one 16-day orbit (the vectors typically rotate throughout one orbit cycle), from Tokano and Neubauer *[2002] overlain on a map of Titan made from Hubble Space Telescope images* [Smith et al., *1996]. The darkest regions are likely to be hydrocarbon seas. The maximum vector length is about 0.5 m/s; a remarkable feature is the convergence near the equator as the air "chases" the moving tidal bulge. The horizontal ellipse is the landing area of the Huygens probe.*

Hydrocarbons: The New Sea Water

Table 1 summarizes the various physical properties pertinent to Titan's oceanography. The overriding difference between Titan and Earth is that the gravity on Titan is seven times lower, much like that of our moon. Titan's fluids are rather more volatile than water (as indeed they must be in order to be liquid at these low temperatures), and the latent heat of vaporization is considerably less than that of water. In thermodynamic terms, hydrocarbon seas on Titan are closer to their boiling point than are oceans on Earth. It may be that wave action, and river flow, are made erosive by cavitation. If there are interconnected seas with length scales comparable with the planetary radius, the atmospheric tide may itself force sea level elevation changes—again, of several meters—through the "inverted barometer" effect.

Waves and Beaches

The gentle winds on Titan suggest that waves impacting beaches should be less energetic than those on Earth, both in energy density (due to lower gravity, lower wind speeds, and lower fluid density), and in frequency of occurrence, due to lower phase speed (longer wave periods). The weakness of wave action may be compensated by a propensity for erosion-enhancing cavitation or enhanced by the resistance of the land surface. If the shoreline is solid water ice, it will be hard as rock; but a more organic-rich composition may be susceptible to erosion.

A shallow slope dissipates more wave energy because the wave travels in contact with the bed longer and less energy is reflected back to sea. Tidal flats with little wave erosion may be a common feature; indeed, the tidal range over a 500-km sea may be as much as 2 m. On the other hand, perhaps the steep walls of impact craters may make cliffs a more typical shoreline landform. Breaking waves on shoaling beaches could lead to the formation of long-shore currents and associated rip currents.

Currents and Circulation

The modest but persistent winds on Titan could lead to weak, three-dimensional basin-scale circulation. In analogy with the Great Lakes or enclosed seas on Earth, wind forcing in combination with bottom friction and the Coriolis effect (f), also could give rise to intensified quasi-geostrophic coastal currents around the perimeter of larger basins on Titan. For both Earth and Titan, the Rossby number, Ro=U/fL (the ratio of nonlinear to Coriolis effects for currents of speed U and horizontal scales of order L), is of order 0.1 in offshore regions, and of order unity in flow-enhanced "boundary" regions (Table 1). On Titan, the external deformation radius, $r_o = (gH)^{0.5}/f$, characterizing the e-folding lateral scale for motions in a non-stratified (barotropic) sea, is less than 0.06 times the value on Earth for the same depth, H. Thus, for a 1-km-deep, mid-latitude ocean: r_o~1000 km on Earth, but only ~60 km on Titan. Corresponding estimates for the internal deformation radius—r_i~NH/f—representing the e-folding scale for currents in a baroclinic (stratified) sea, are strongly dependent on the buoyancy frequency, N. Because we expect little vertical stratification in Titan's seas, N and $r_i^{\sim 0}$.

Fig. 3. In January 2005, the ESA Huygens probe will parachute through Titan's atmosphere. It may splash down into and bob around in an ethane sea or lake, recording wave dynamics and chemical composition for several minutes. Artist's impression; by kind permission of James Garry (see www.fastlight.demon.co.uk).

Titan's axis is tilted by 26° to the Sun, leading, as on Earth, to seasons and reduced average insolation at high latitudes, where temperatures appear 3–4 K cooler than the equator. It will be interesting to see to what extent, if any, Titan's liquids participate in the (apparently weak; see *Lorenz et al.*, [2001]) meridional transfer of heat. On Earth, the oceans are responsible for some 30–50% of the zonally integrated, poleward heat transport needed to maintain global thermal equilibrium.

Liquid hydrocarbons, with a higher—and always positive—coefficient of expansion than water, may be expected to have a profoundly different 'thermally driven' circulation, if it has one at all. Lack of a density maximum—probable wind-mixing, sea floor tidal dissipation, and the deposition of heavier organics from above—are all likely to make flow stagnation or strong stratification unlikely.

Cassini-Huygens and Future Missions

The Cassini orbiter will arrive at Saturn in June 2004 and begin a 4-year tour (in Earth years), orbiting and making a detailed study of Saturn, its rings, magnetosphere, and satellites. Key among these is Titan, whose gravity is used to adjust Cassini's orbit around Saturn. Cassini will make 44 close flybys of Titan, each of which is being choreographed in detail to maximize the scientific return. Cassini will observe Titan with an optical camera, a mapping spectrometer, a radar, and other instruments. The first close Titan flyby occurs in October 2004. On the third, in January 2005, the 300-kg ESA Huygens probe will parachute through Titan's atmosphere. During the 135-min descent, the probe will profile the atmosphere, sampling its gas and aerosol to determine chemical composition. In addition, a camera will image the surface at ever-improving resolution until the probe hits the surface. At that point, the probe may fail, although there is a good chance it may continue to transmit. This is particularly so if the probe should splash down into a liquid. The splashdown loads are modest (12g or so) at the 5 m/s impact speed, and the probe should float for some time. The probe is equipped with instruments to measure the liquid's composition, and a small sonar to provide a lower limit on "oceanic" depth. Tilt sensors and accelerometers will allow the probe to function as a buoy and characterize any wave motions (see Figure 3). After some time, the probe's batteries may fail or the radio link will degrade, and the mission will be over.

Remote sensing, however, will continue on subsequent flybys. Radar imaging will cover about 20% of Titan's surface at resolutions of around 400 m; optical imaging will cover most of the surface (except the extreme north in polar night); although the achievable resolution will depend on the haze opacity. As well as mapping shoreline morphology, optical and microwave sunglints and microwave radiometry and scatterometry will help characterize the sea state at different times and locations.

Cassini (http://saturn.jpl.nasa.gov) will doubtless whet our appetite for more data; the mission may be extended beyond 2008. But outer solar system exploration is slow: Cassini was proposed some 20 years ago. It is, thus, not too early to begin contemplating future missions.

Although the key scientific questions will need Cassini's findings to be refined, it is clear that close access to many locations on Titan's heterogeneous surface will be needed; the view from orbit will not be enough. Astrobiology and research into the origin of life may make chemical analysis of surface organic deposits a priority. Site selection and characterization support for this, and intrinsic scientific and popular interest will make high-resolution, optical imaging a key payload element. This would allow detailed geomorphological analyses of fluvial and littoral features, and provide insight into meteorological and oceanographic processes. Sub-surface radar sounding may be another technique with interdisciplinary applications: to search for near-surface crustal melt (i.e., water), and to profile the depth of hydrocarbon lakes and seas.

It remains to be seen what kind of platform might carry such instrumentation. The variety of likely sites makes one or two mobile platforms more flexible and attractive than a fleet of landers, and the unknown and probably difficult trafficability of Titan's land surface advocates an airborne platform. Such a vehicle—likely an airship, but conceivably a heavier-than-air aircraft—could exploit Titan's unique low-gravity, thick-atmosphere environment to travel with only modest energy consumption.

The Future of the "New Playground"

Many aspects of Earth sciences are heavily parameterized. With oceans of data, it may be enough to predict phenomena of interest with purely empirical models, without necessarily understanding the underlying processes completely. Titan will give us a chance to explore these processes more fully, in that Titan provides a laboratory with an entirely different set of conditions and parameters.

Table 1. Parameters of Titan and Earth Surface Environments

		Titan	Earth
Planetary Radius	(km)	2575	6370
Surface Gravity	(ms^{-2})	1.35	9.81
Rotation Period	(s)	1.4x10^{6}	8.6x10^{4}
Atmosphere			
Composition		~95% N_2, ~5% CH_4	79% N_2, 20% O_2
Surface Temperature	(K)	94	288
Surface Pressure	(mbar)	1440	1013
Surface Density	(kgm^{-3})	5.3	1.25
Speed of Sound	(ms^{-1})	~200	~330
Scale Height	(km)	20	8
Typical Wind Speed	(ms^{-1})	<0.5	~10
Ocean			
Composition*		CH_4 (C_2H_6)	H_2O
Density	(kgm^{-3})	450 (650)	1000
Cubic Expansivity	(K^{-1})	1.3x10^{-3}(1.0x10^{-3})	2x10^{-4}
Viscosity	(Pa-s)	2x10^{-4} (1.2x10^{-3})	10^{-3}
Surface Tension	(Nm^{-1})	1.8x10^{-2} (1.8x10^{-2})	7.3x10^{-2}
Speed of Sound	(ms^{-1})	1500 (2000)	~1500
Specific Heat Capacity	(J kg^{-1}K^{-1})	~2000	4200
Latent Heat of Vaporization	(J kg^{-1})	~5x10^{5}	2.9x10^{6}
Boiling Point at Surface Pressure	(K)	115 (190)	373
Rossby Number Ro, Open Sea		0.1	0.1
Rossby Number Ro, Boundary		1.0	1.0
External Deformation Radius r_o	(km)	60	1000
Internal Deformation Radius r_i	(km)	- (?)	10

* strictly, the oceans are likely to be a ternary mixture of liquid ethane, methane and nitrogen, with the latter only a modest constituent (<10%). Propane and argon may be present at a level of a few percent or less, and dissolved traces of many other compounds may exist, together with insoluble suspended matter.

Note: Dynamical numbers are new: Thermodynamic and other data from R. D. Lorenz, *Exploring The Surface of Titan*, Ph.D. Thesis, University of Kent at Canterbury, 1994 ; see also *Ori et al.,* 1998; *Srokosz et al.*, 1992 and *Ghafoor et al.*, 2000.

Titan promises to be a new playground for oceanographers. While Cassini data will doubtless stimulate a new array of investigations, we have already begun exploring some avenues theoretically; in particular, wind-driven wave growth in hydrocarbon seas, and the wind- and tidally-forced circulation in large lakes on this slowly-rotating moon.

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Author Information

Ralph D. Lorenz, University of Arizona, Tucson; Erin Kraal and Erik Asphaug, University of California, Santa Cruz; and Richard E. Thomson, Institute of Ocean Sciences, Sydney, British Columbia

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Bill Would Extend Efforts Against Harmful Algal Blooms and Hypoxia

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Legislation to deal with the problems of harmful algal blooms and hypoxia in U.S. waters needs to recognize the growing national scope and economic effects of these phenomena, improve monitoring capabilities, and target remedies for them. It should also emphasize research and management in the Great Lakes and other fresh water bodies, as well as in U.S. coastal waters.

This, according to a panel of scientists who testified at a 13 March hearing of the Science Subcommittee on Environment, Technology, and Standards of the U.S. House of Representatives.

Those testifying said the two phenomena are causing enormous, negative ecological and economic impacts.

Donald Scavia, senior scientist with the National Ocean Service of the National Oceanic and Atmospheric Administration, said, "Harmful algal blooms and hypoxia are now among the most pressing environmental issues facing coastal states."

Scavia said that a recent national assessment of eutrophication by his agency indicates that the hypoxia problem is not limited to areas off the coasts of Louisiana and Texas. He said, "At some time each year, over half of our nation's estuaries experience natural-caused and/or human-induced hypoxic conditions. Thirty percent [of them] experience anoxia (e.g., areas in which oxygen is absent), resulting in fish kills and other resource impacts."

The issues of harmful algal blooms and hypoxia are linked, because excess nutrient loads can lead to algae overgrowth in many coastal ecosystems; and hypoxia, or oxygen depletion, often occurs when harmful algal blooms die off and decompose.

The hearing was held in conjunction with efforts to re-authorize the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998. In the Senate, Olympia Snowe (R-Maine) and John Breaux (D-Louisiana) have already introduced a bill, S.247. In the House, Representative Vernon Ehlers (R-Michigan), chair of the subcommittee which held the hearing, is expected to introduce legislation soon that incorporates the 13 March testimony and builds on the Senate bill.

The 1998 legislation established several task forces and programs that have helped to increase scientific understanding of harmful algal blooms and hypoxia. The task forces produced several reports, including an integrated assessment of causes and consequences of the annual spring-summer hypoxic conditions in the northern Gulf of Mexico—mapped by NOAA since 1985. In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force issued an ambitious action plan to reduce, mitigate, and control Gulf hypoxia and the annual hypoxic "dead zone" around the mouth of the Mississippi River, by reducing nitrogen loads into the Gulf by at least 30%.

Ecological and Economic Costs

At the 13 March hearing, Donald Anderson, a senior scientist with the Woods Hole Oceanographic Institution, and director of the U.S. National Office for Marine Biotoxins and Harmful Algal Blooms, said algal blooms are a much larger problem than was thought a decade ago. "Virtually every coastal state is now threatened by harmful or toxic algal species, whereas 30 years ago, the problem was much more scattered and sporadic," he said.

Anderson said the increased scope of the problem likely is due to a combination of favorable nutrient environments caused by pollution or other anthropogenic influences, better detection methods, dispersal of blooms by natural currents, and the flushing of ship ballast water in coastal areas.

He said that the blooms can kill or harm marine organisms, and can even be harmful to humans; and that the economic cost is $50–100 million annually from losses of commercial shellfish and fish.

Anderson said that a reauthorization bill needs to address public health, as well as prevention, control, and mitigation issues. He stated it should also recognize the impact of algal blooms on fresh water, including the Great Lakes. "We must add fresh water [harmful algal bloom] research to the national agenda; not replace marine programs with new initiatives focused on fresh water," he said.

Wayne Carmichael, professor of aquatic biology and toxicology at Wright State University in Dayton, Ohio, said research indicates that the major reason for the current increases in harmful blooms in the Great Lakes is the invasion of zebra mussels, which have the ability to contribute to processes that alter the phytoplankton community there. He said high anthropogenic phosphorus loading—which had led to algal blooms in the 1960s and 1970s—was largely curtailed by the early 1980s, but that "nuisance" blooms have re-occurred since zebra mussels invaded in the late 1980s.

At the hearing, Charles Groat, director of the U.S. Geological Survey, emphasized the need for an improved monitoring system to better model the susceptibility of water systems to nutrients. "Along with data and information from research and monitoring, models and other analytical tools provide the scientific information needed for sound resource management decisions," he said. "The major challenge faced by researchers developing and implementing modeling tools is the lack of suitable monitoring data that provide the basis for understanding the natural and human-induced changes in flow and chemical loads to coastal and receiving waters."

Groat said there is far less data about water-quality loading available now than a decade ago. The 2001 hypoxia action plan for the Gulf of Mexico relied on data from the period 1980–1996, but Groat said the water-quality load monitoring network for the Mississippi River that is required for the assessment of downstream accumulation and its effects on receiving waters—including the Gulf of Mexico—has been significantly reduced over the past decade. Due to financial cutbacks, USGS has recently been able to take sufficient measurements at only about 20% of the 133 stations in the Mississippi Basin.

—RANDY SHOWSTACK, Staff Writer