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Development, Operation, and Results From the Texas Automated Buoy System

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The Texas Automated Buoy System (TABS) is a coastal network of moored buoys that report near–real-time observations about currents and winds along the Texas coast. Established in 1995, the primary mission of TABS is ocean observations in the service of oil spill preparedness and response. The state of Texas funded the system with the intent of improving the data available to oil spill trajectory modelers. In its 12 years of operation, TABS has proven its usefulness during realistic oil spill drills and actual spills. The original capabilities of TABS, i.e., measurement of surface currents and temperatures, have been extended to the marine surface layer, the entire water column, and the sea floor. In addition to observations, a modeling component has been integrated into the TABS program. The goal is to form the core of a complete ocean observing system for Texas waters. As the nation embarks on the development of an integrated ocean observing system, TABS will continue to be an active participant of the Gulf of Mexico Coastal Ocean Observing System (GCOOS) regional association and the primary source of near-surface current measurements in the northwestern Gulf of Mexico. This article describes the origin of TABS, the philosophy behind the operation and development of the system, the resulting modifications to improve the system, the expansion of the system to include new sensors, the development of TABS forecasting models and real-time analysis tools, and how TABS has met many of the societal goals envisioned for GCOOS.

Introduction

On 8 June 1990 the Norwegian supertanker *Mega Borg,* loaded with 41 million gallons of Angolan crude, exploded and caught fire while lightering its cargo about 60 nautical miles south of Galveston, Texas (Scholz and Michel, 1992). Four crewmen lost their lives, and the fire raged for days until it was extinguished. Eventually 5.1 million gallons of oil were released into the Gulf of Mexico. A climatology of ocean currents available at the time, together with wind data, suggested that the oil would be driven onshore by the winds and downcoast (toward the southwest) by the coastal current. Ultimate landfall was expected to occur around Corpus Christi. Counter to the usual June climatology (Cochrane and Kelly, 1986), the coastal currents were running up the Texas coast and the oil was carried northeast into Louisiana waters. Roughly 50% of the light crude oil burned and 25% evaporated. Responders used skimmers and booms and applied dispersants to recover and control the remaining oil. Fortunately the offshore nature of the spill and the limited fauna in the region limited the natural resource damage (Helton and Penn, 1999).

During the first few hours of an oil spill critical decisions regarding the logistics of protection and cleanup operations must be made by the spill-response management team. An effective response requires immediate information about wind and current velocity conditions to quickly evaluate the trajectory, fate, and potential impact of the spilled material; information that was not available in 1990. In 1991 the Texas legislature passed the Texas counterpart of the federal Oil Pollution Act of 1990, the Oil Spill Prevention and Response Act. This act designated the Texas General Land Office (GLO) as the lead state agency for preventing and responding to oil spills in the marine environment. In 1994 the GLO implemented plans for an operational system of instrumented buoys off the Texas coast, to be known as the Texas Automated Buoy System (TABS). The purpose of the buoy system was to protect Texas coastal waters by providing timely, accurate observations of winds and currents (Kelly et al., 1998; Guinasso et al., 2001; Martin et al., 2005) for use in spill response operations. The GLO funded, from its Coastal Protection Fee, the Geochemical and Environmental Research Group (GERG) at Texas A&M University to design, build, and operate a system of moored, telemetering current meter buoys using off-the-shelf technology. GERG, working with Woods Hole Group (WHG) of East Falmouth, MA, designed the buoys to measure current velocity at a fixed depth of about 6 feet below the surface using an electromagnetic current sensor and transmit the data to shore on a regular schedule via the existing offshore cellular telephone network. In early 1995, less than 9 mo after receiving the contract, GERG deployed the first five buoys using this technology. In March 1996 TABS experienced its first major test with the barge *Buffalo 292* oil spill (Lehr, 1997). In its first 10 yr of operation there have been 20 major spills in which National Oceanic and Atmospheric Administration (NOAA) personnel have worked with and consulted the TABS data (Martin et al., 2005).

The primary mission of TABS is to provide near–real-time data when a spill occurs. However, the GLO recognized from the inception of the project that three factors would form TABS into an effective public resource as well. Thus, the GLO supports research to improve the reliability, operational range, and versatility of the TABS buoys; it insists that all TABS data be immediately disseminated through a user-friendly Internet website; and it encourages other scientific research projects to build on the TABS resources. To that end, the buoys have been continuously improved since the original design to incorporate new technology, lessons learned in the field, and expanding mission goals. From its inception in 1995, when the concept of a user-friendly Internet was just beginning to emerge, the buoy observations have been made available to the GLO and the general public on the Internet. In 1998 a modeling component was added to the TABS program with the development and implementation of the Princeton Ocean Model (POM), adapted to perform simulations on the Texas shelf. In 2002 the Regional Ocean Modeling System (ROMS) was implemented for the Texas shelf, but with a grid that covered the entire Gulf of Mexico. In order to complement the numerical models, a statistically based methodology for achieving optimal nowcasts of the shelf-wide circulation was started in 2003. Also in 2003 real-time analysis of the daily observations was included, which provides the user with quality controlled oceanographic, meteorological, and engineering products. (see http://tabs.gerg.tamu.edu/Tglo/RTA//RTA_index.html)

Today the TABS buoy network consists of 10 actively monitored sites, eight along the coast and two on either side of the Flower Garden Banks National Marine Sanctuary. The eight coastal sites are funded by the GLO: one near Sabine Pass, two off Galveston, one midway between Freeport and Corpus Christi, two off Corpus Christi, and two off Brownsville. The state of Texas has funded TABS at a level of about $700,000 per year in fiscal years 2002–2007. The two Flower Garden Banks sites are funded separately (a yearly average of $350,000 from 2001 to 2006) by an oil industry consortium, but are operated as part of the TABS program. The GLO-supported inshore sites off of Galveston and Corpus Christi have been occupied continuously since 2 April 1995. Figure 1 shows the locations and Table 1 lists the coordinates of the 10 actively monitored sites, as well as the discontinued sites.

TABS was, to the best of our knowledge, the first offshore observing system in the Gulf of Mexico. The Texas Coastal Ocean Observing Network (TCOON; http://lighthouse.tamucc.edu/TCOON/HomePage) began earlier with three stations in 1991 and has expanded to more than 40 stations today, but it focuses on water level on the coast and inshore waters. The Physical Oceanographic Real-Time System (PORTS; http://tidesandcurrents.noaa.gov/ports.html) has been operational in Tampa Bay since 1990–1991 and in Galveston Bay/Houston Ship Channel since 1996–1997. The Wave-Current-Surge Information System for Coastal Louisiana (WAVCIS; http://wavcis.csi.lsu.edu/) is operated by the Coastal Studies Institute of Louisiana State University. It began with its first station (CSI 13) in 1998 (Zhang, 2003); today there are six operational stations in water depths ranging from 5 m to 21 m. The Coastal Ocean Monitoring and Prediction System (COMPS; http://comps.marine.usf.edu/), operated by the University of South Florida, was implemented in 1997 for the West Florida Shelf (Merz, 2001). It consists of a real-time array of both offshore buoy and coastal stations (Weisberg et al., 2002). A comprehensive list of all the observing systems that are part of the Gulf of Mexico Coastal Ocean Observing System (GCOOS) is provided at http://ocean.tamu.edu/GCOOS/System/insitu.htm.

The purpose of this article is to present an overview of the development, operation, and results of running the TABS operational coastal observing system on the Texas shelf for the past 12 yr. The paper is organized in six sections: Development, Field Operations, Data Management, Modeling, Achievements, and Conclusions. The Development and Field Operations sections provide a review of the development, capabilities, and operational experience of the TABS system. The section on Data Management describes the measures used to retrieve, store, and quality control the observations, the steps used for the real-time analysis of the quality controlled observations, and the steps taken to disseminate the data and the products. The section on Modeling discusses the development

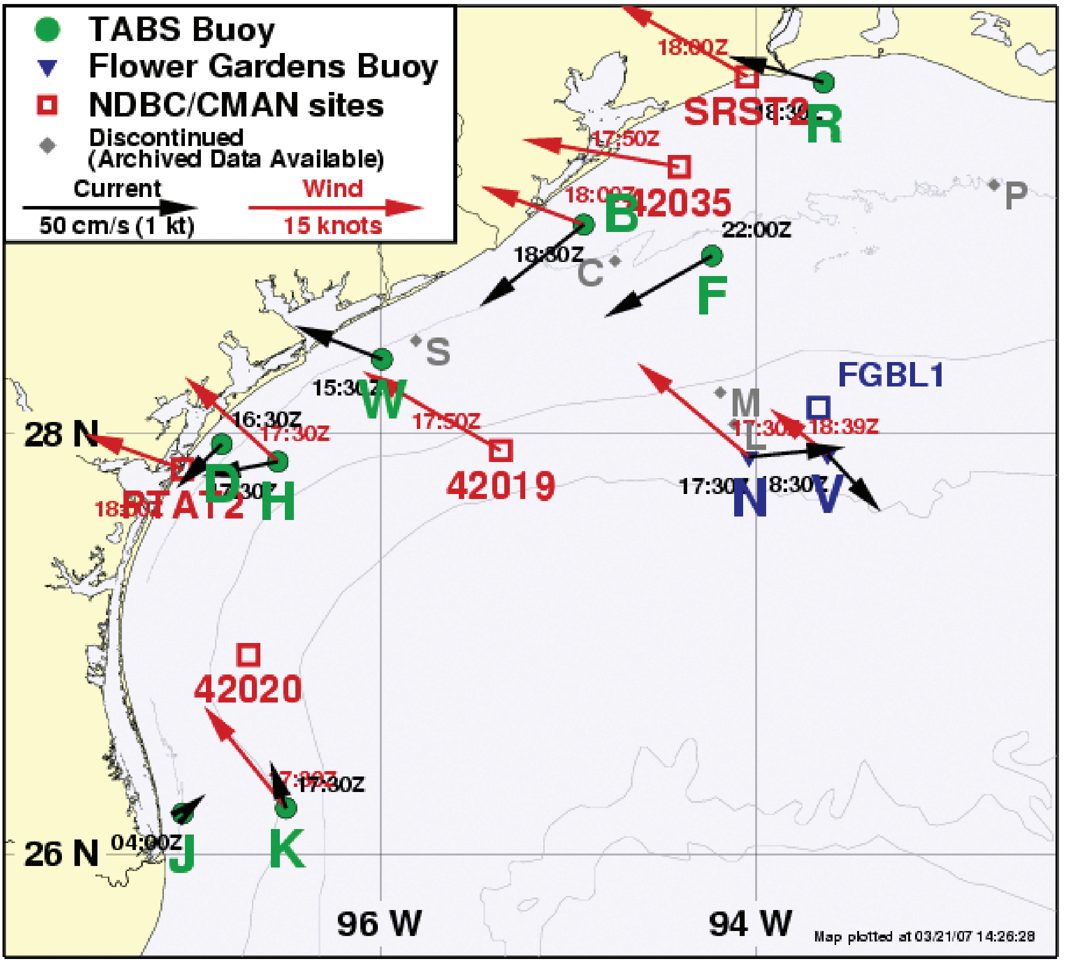

Fig. 1. Map displayed on the TABS Internet home page showing the location of the TABS buoys as well as the NOPP and LSU buoys, the NOAA CMAN weather stations, and the NOAA NDBC weather buoys that are linked to the TABS Internet home page. Bathymetry contours are shown for the 20-, 50-, 200-, 2,000-, and 3,500-m depths.

and implementation of the numerical and statistical models used to complement and enhance the buoy observations. The section on Achievements highlights a few of the more significant results of the TABS system, including how TABS has worked with NOAA during oil spills and how we have endeavored to meet the societal goals of the Integrated Ocean Observing System. Finally, the Conclusions section summarizes the article and outlines the future development of TABS.

Development

The mandate of the TABS system is to provide high-quality, near-surface current measurements. At its most basic level, each TABS buoy records vector-averaged currents at a fixed depth of 1.8 m below the surface, does so every 30 min, and transmits the current speed and direction to shore once every 2 hr. In order to accomplish this mission, the buoy consists of four principal subsystems: the oceanographic and meteorological sensors, the communications link, a solar-powered electrical system, and the buoy flotation structure (Chaplin and Kelly, 1995). Until recently the flotation structure for all TABS buoys was a spar design. A spar buoy provides a stable platform for making high-quality, low-noise current measurements because it does not respond to high-frequency waves like the more common discus buoy used by the National Data Buoy Center (NDBC). A spar buoy does not have the reserve buoyancy, power, and payload capacity that a discus buoy has, and this has placed acceptable constraints on the versatility and operational range of the buoys.

TABLE 1. Locations of TABS buoys.

Buoy	Depth	Latitude (N)	Longitude (W)	Date first deployed
A[a]	40 feet	29°31.950′	93°48.733′	21 June 1995
B	63 feet	28°58.1850′	94°54.966′	2 April 1995
C[a]	72 feet	28°48.549′	94°45.126′	2 April 1995
D	60 feet	27°55.93′	96°48.460′	31 May 1995
E[a]	126 feet	27°20.298′	97°06.000′	31 May 1995
F	79 feet	28°50.153′	94°14.131′	22 Feb. 1996
G[a]	41 feet	29°33.985′	93°28.096′	11 March 1997
H[b]	110 feet	27°52.406′	96°33.367′	4 June 1997
J	68 feet	26°11.300′	97°03.040′	13 May 1998
K	204 feet	26°13.010′	96°29.930′	13 May 1998
L[c]	270 feet	28°02.500′	94°07.000′	20 April 1998
M[c]	186 feet	28°11.500′	94°11.500′	20 April 1998
N[c]	345 feet	27°53.382′	94°02.222′	20 April 1998
P[d]	66 feet	29°10.000′	92°44.250′	15 Aug. 1999
R	32 feet	29°38.643′	93°38.386′	27 July 1998
S[a]	72 feet	28°26.206′	95°48.674′	19 Feb. 1999
W	73 feet	28°20.086′	96°01.328′	28 Nov. 2001
V[e]	90 feet	27°54.018′	93°37.260′	23 Jan. 2002

[a] These buoy locations have been discontinued. Data are available in the website archive.
[b] The buoy H site was reoccupied on 27 Aug. 2005, after being discontinued in 1998.
[c] These buoys were operated by a project funded by the NOPP, Office of Naval Research through Dynalysis of Princeton. Funding ended in CY1999 and operations ceased. N was resurrected as part of the FGBJIP in 2002.
[d] This buoy was operated by a project funded by the Minerals Management Service through Louisiana State University. Funding ended in CY1999 and operation has ceased.
[e] Buoys N and V are operated on behalf of a consortium of oil companies operating in the vicinity of the Flower Garden Banks National Marine Sanctuary.

TABS I.—The original spar buoys, designated as TABS I and first deployed in 1995, were designed for the near-shore coastal environment and were intended to obtain near-surface currents and water temperature. Urethane Technologies, Inc. of Denham Springs, LA, fabricated the buoy with a flotation package of closed-cell, cross-linked, polyethylene foam with a polyurethane fabric-reinforced skin. A Marsh McBirney, Inc. (MMI) electromagnetic two-axis 585-current sensor was used to measure water velocities. Woods Hole Group (WHG), in addition to assisting with the design, manufactured the original computer system that ran the buoy. The cellular telephone network operated by Petrocom for the offshore oil industry provided the means for the near–real-time observations. The buoy was equipped, as are all buoys, with an integral radar reflector in the upper mast and a Coast Guard–approved amber night flashing light. A schematic of the buoy in its present form is shown in Figure 2. The system and sampling information of the TABS I buoy is detailed in Table 2, which lists the measurements made by each buoy type, the sensors used, the elevation of the sensors, the sampling time, the averaging interval, and the telemetry acquisition frequency.

The design has been continuously improved since the original TABS I buoy went to sea. During the first 5 yr of the program, the design work was subcontracted to WHG, but beginning about 7 yr ago (2000) the design work was transferred in-house. From the beginning of the TABS program, all of the assembly, wiring, system upgrades, and maintenance on the buoys has been done at GERG's facilities at Texas A&M University. In 2001 the hull was redesigned to utilize structural aluminum alloys to make the buoy more robust and serviceable. The top endcap of the buoy was also redesigned to take advantage of the increased hull diameter and newer antenna designs, which enabled the antenna to be mounted inside the protective covers of the buoy. The new tops were equipped with 10,000-psi bulkhead connectors for all cables to provide hull integrity and increase survivability should the buoy become submerged during collision or storm. This modification was the result of lessons learned in the field when flooding of the mast occasionally occurred through the cable glands. After these changes, there have been no broken antennas on a TABS I buoy nor have any of the buoys flooded.

Major changes in the TABS I buoys were also made in the current sensor, the onboard computer system, and the communication link. After a few years of operations, many of the Marsh McBirney sensors developed saltwater leaks that affected data availability. These sensors have all been replaced with a single-point, vector-

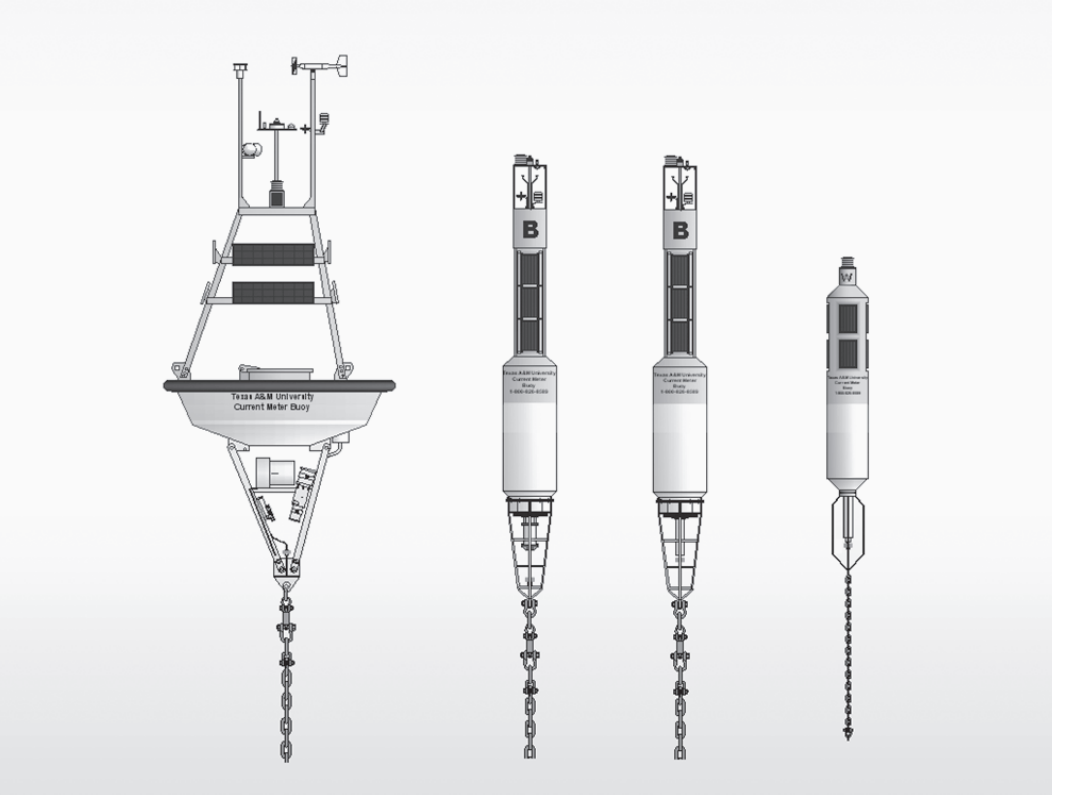

Fig. 2. Schematic of TABS I (far right), TABS II (middle two: leftmost with downward-looking RDI ADCP and Aanderaa DCS 4100R and rightmost with Aanderaa DCS 4100R only) and 3-m discus buoys (far left) fabricated at GERG. The older style Windsonic anemometers are depicted on the two TABS II buoys. Buoys are to scale.

averaging, acoustic Doppler sensor manufactured by Aanderaa Data Instruments AS of Norway, the Doppler Current Sensor (DCS) 3900R and DCS 4100R. This acoustic sensor is significantly less susceptible to fouling (see Fig. 3) than the MMI sensor and has proven to be very reliable in the field (Walpert et al., 2001). The 4100R is a new generation of the 3900R sensor, designed so that the electronics are housed outside the Durotong plastic material that encapsulates the Doppler ceramics. This change was made by the manufacturer in mid-2005 to address the problem of failure in the DCS tilt sensors. In conjunction with the change to the DCS current sensor, the system electronics for the TABS I were re-designed. The newly designed electronics made use of a single Remote System Manager (RSM)/daughterboard combination and eliminated three electronic boards from the system. The new system was also designed to allow the attachment of ancillary systems such as the Seabird MicroCat C/T sensors.

Digital satellite communications are now available at costs less than the original offshore cellular telephone service first used in the TABS I buoy. All TABS buoys now use the Qualcomm GSP-1620 Packet Data Modem, which uses the Globalstar satellite network as the primary communication link. The Globalstar Corporation provides the satellite data-link service, utilizing a constellation of 48 low-earth orbit satellites that can transfer data at a rate of 9,600 bps. This communications link is faster and more reliable than the cellular system used by the original TABS buoys. The average data transmission success rates have increased to more than 97%, whereas individual buoys have had long stretches, i.e., months, in which the transmission rate is 99.9%.

The power system for the TABS I buoy imposes constraints on the number and type of sensors and onboard systems that can be accommodated. The 6-inch interior hull diameter of the TABS I spar buoy provides a physical limitation to the size of the instrument compartment and the area available on the mast for solar panels. Consequently each TABS I buoy contains two 12V DC gel cell batteries, each with 144 watt hours capacity at full charge and six 10-watt multicrystalline silicon solar panels made by BP Solar. Even in winter the solar panels are capable of

TABLE 2. TABS buoy system and sampling parameters.

	Measurements	TABS I	TABS II[a]
Oceanographic	Current speed	Y	Y
	Current direction	Y	Y
	Seawater temperature	Y	Y
Meteorological[a]	Wind speed	N	Y
	Wind direction	N	Y
	Air temperature	N	Y
	Relative humidity	N	Y
	Air pressure	N	Y
Sensors			
Oceanographic	Currents: speed, direction, buoy orientation and tilt	Aanderaa DCS 3900R	Aanderaa DCS 4100R
	Seawater temperature[b]	Aanderaa DCS 3900R	Aanderaa DCS 4100R
	ADCP	–	Optional
	Acoustic modem	–	Optional
	Conductivity and temperature	–	Aanderaa
	Conductivity, turbidity, and transmissometer	–	Optional
Meteorological	Wind speed and direction	–	Gill Instruments Wind Observer II Ultrasonic Anemometer Model 1390
	Buoy tilt compensation for winds	–	Honeywell HMR 3300 Digital Compass or a Shaevitz AccuStar II Dual Axis Clinometer
	Buoy orientation for winds	–	Either a KVH C100 compass or a Honeywell HMR 3300 digital compass
	Air temperature	–	Either a Rotronics MP101A or an RM Young 41342VC in a radiation shield
	Relative humidity	–	Rotronics MP101A
	Air pressure	–	Vaisala PTB 100A
Site elevation		sea level	sea level
Sensor elevation			
Oceanographic	Currents	1.8 m below site elevation	1.8 m below site elevation
	Water temperature	1.8 m below site elevation	1.8 m below site elevation
	Temperature/conductivity	None	1.5 m below site elevation
Meteorological	Winds	–	3.4 m above site elevation
	Air temperature	–	3.4 m above site elevation
	Relative humidity	–	3.4 m above site elevation
	Air pressure	–	3.4 m above site elevation
GPS		None	Garmin

TABLE 2. Continued.

Measurements		TABS I	TABS II[a]
Main telemetry		Qualcom GSP-1620 Packet Data Modem utilizing the Globalstar LEO satellite communications network	Qualcom GSP-1620 Packet Data Modem utilizing the Globalstar LEO satellite communications network
Backup telemetry[c]		System ARGOS	System ARGOS
Acquisition frequency[d]			
	For all sensors	Every 2 hr beginning at 0000 GMT	Every 2 hr beginning at 0000 GMT
Sampling time			
	For all sensors	Every 30 min, starting on the hour and half-hour	Every 30 min, starting on the hour and half-hour
Averaging interval[d]			
Oceanographic	Currents[e]	5 min average of ping data taken once every second, tilt and buoy orientation simultaneously strobed at 1 Hz	5 min average of ping data taken once every second, tilt and buoy orientation simultaneously strobed at 1 Hz
	Seawater temperature	Instantaneous: taken at the end of the 5 min sampling period	Instantaneous: taken at the end of the 5 min sampling period
Meteorological	Winds[f]	–	10 min average of 25 ms sampled data, except for wind gusts which is the maximum speed recorded in the 10 min
	Air temperature	–	Instantaneous: taken at the end of the 10 min sampling period
	Relative humidity	–	Instantaneous: taken at the end of the 10 min sampling period
	Air pressure	–	Instantaneous: taken at the end of the 10 min sampling period

[a] Only the TABS II buoy is capable of carrying a meteorological package. Wind speed and direction, air temperature, and barometric pressure are always measured. The instruments on the met package are interchangeable; consequently a humidity sensor is optional.
[b] The Aanderaa current sensor provides an integral seawater temperature sensor.
[c] Current velocity and seawater temperature only, no net data.
[d] In the event of an incident we have the ability to increase the acquisition frequency and sampling time.
[e] Currents are tilt compensated and oriented to magnetic north onboard the buoys.
[f] Winds are tilt compensated and oriented to magnetic north onboard the buoy.

Fig. 3. Barnacle encrusted Aanderaa DCS 3900 sensor recovered from site R after a 6-mo deployment. The velocity data were acceptable in spite of this level of fouling.

fully recharging the batteries on a sunny day. At full charge the buoy can operate for 45 d in overcast skies when little if any charging occurs.

TABS II.—In 1997, after a year-and-a-half of successful field operations with the TABS I model, the GLO directed GERG to develop an improved and more capable TABS buoy. GERG worked with manufacturers to design and build a ''second-generation'' version of the spar buoy, known as TABS II. The TABS II was originally designed with four major enhancements: 1) operation in regions with poor or no cellular phone coverage using the Westinghouse HS1000 satellite telephone system (Globalstar was not available at the time and Geostationary Operational Environmental Satellite (GOES) did not provide two-way communications that was needed); 2) an increased size of the flotation package for deployment in water depths greater than 100 ft (30 m); 3) an ARGOS satellite data transmission system that is automatically activated if the primary communication link fails, and; 4) a Climatronics TAC Met meteorological package to measure wind speed and direction. Since the initial TABS II buoys were designed and successfully deployed, several modifications have been made to improve the reliability, robustness, and data quality of the TABS buoy (Magnell et al., 1998). The original TABS II design, which incorporated the MMI current sensor, was upgraded to the Aanderaa DCS 3900R and DCS 4100R in conjunction with the change made in the TABS I current sensor. The original meteorological package was redesigned to use a Gill acoustic wind velocity sensor and now includes sensors to measure air temperature, humidity, and barometric pressure. In 2001 the TABS II design was further modified to incorporate a downward-looking acoustic Doppler current profiler (ADCP) in addition to the surface measurement with the Aanderaa DCS velocity sensor.

Beginning in 2001 the original Westinghouse satellite telephone system was replaced with the Qualcomm satellite data modem (GSP-1620), which operates on the Globalstar satellite data network. The greatest drawback of the use of the Westinghouse system on a spar buoy was its tuned 37-inch antenna. The antenna was the greatest failure point of the buoy because of its inconsistent tuning response and its vulnerability and exposure to damage. The Qualcomm data modem made use of a much smaller antenna (4-inch diameter by 2.5-inch height), reported data at a higher rate, and required half the power and half the space of the Westinghouse system. New radio frequency cables from Times Microwave Systems were incorporated to improve the data transmission through the bulkhead fittings. These were eventually bypassed by locating the digital modem in a water-tight housing on the top of the buoy. The first system was deployed on buoy ''N'' and went in the water on 23 Jan. 2002. Since then the modem has been extremely reliable (working even when buoys are lying on a ship's aft deck while in transit to be deployed) and has been incorporated as the primary communications link on all TABS buoys.

All TABS buoys now have a redundant, independent, communications link based on the Service ARGOS satellite system. ARGOS provides both location information and data-collection service worldwide using three polar-orbiting satellites. The communication link for two of the ARGOS satellites is such that data can be sent by the buoy only while a satellite is passing overhead, whereas the third satellite, launched in Oct. 2006, has two-way capability. Each satellite makes six to eight passes per day. The times of the passes are predictable, but not evenly spaced. The data transfer rate is 4,800 bps, but the message length can only be 32 bytes. Consequently only the surface currents and battery voltage data can be included in the message. Although limited, this system is reliable, consumes little power, can be equipped with a short, easy to waterproof antenna (important for improving the robustness of the buoy to vandalism), and is economical. The computer software of all the TABS buoys recognizes when the primary communications system is not functioning and automatically switches to the ARGOS mode. Operation of the ARGOS backup system is enabled automatically once every 10 d.

In 2004 and 2005, GERG fabricated four new TABS II buoys based on the original TABS II hull design, but with an all new electronics and computer system of our own design in lieu of the original WHG design. The newest buoys have an integrated high-resolution temperature and conductivity cell and a GPS system as standard sensors. They also have the capability of accepting additional sensors such as ADCPs, turbidity sensors, transmissometers, and acoustic modems to retrieve data from bottom-mounted instrumentation such as wave gauges or upward-looking ADCPs. A schematic of the buoy in its present form is shown in Figure 2. The system and sampling information of the TABS II buoy are detailed in Table 2, which lists the measurements made by each buoy type, the sensors used, the elevation of the sensors, the sampling time, the averaging interval, and the telemetry acquisition frequency.

GERG considers software as one of the critical components of any observing system. The buoy controller software needs to be extremely robust and capable of diagnosing and repairing problems when possible and sending diagnostic information ashore when errors or faults are detected. Errors that cannot be corrected autonomously on the buoy have to be repairable from a shore base via telemetry. As part of the new TABS II buoys, GERG designed and developed a new buoy controller based on the Prometheus PC-104 computer system manufactured by Diamond Systems Corporation. The computer uses Tiny Linux as the operating system and system programs that are written in Perl and C. The Prometheus is a small footprint computer operating at 100 MHz with multitasking ability, powerful computational ability, large storage capacity, and relatively low power consumption. The computer is interfaced to three proprietary boards developed at GERG: an ADCP power supply board that provides a clean 54 volts for ADCP operation; a sensor interface board that enables two-way communication with all the digital sensors as well as control over analog sensors; and a 12-channel power switch board that turns power on and off to each individual sensor according to program requirements. This provides the operator with total control over each sensor schedule and provides the ability to remotely change the schedule or sampling regime whenever required. A Windows-based graphical user interface (GUI) that interfaces with the Linux-based software on the buoy makes it possible for technicians without a Unix background to effectively communicate, set up, make changes, and test the buoys either remotely via satellite, through the existing WIFI system, or through a hardwired monitor port.

Of the six buoys GERG fabricated using the PC-104–based controllers, only one has failed or reset in the field. The one failure occurred when a hard disk on board the buoy filled with image files due to a malfunctioning instrument. Part of the reason for the success of these buoys is that the software running on the PC-104 is robust and self-diagnosing. The buoy software was engineered in modular form to enable easy sensor or system updates to be uploaded via satellite, hardwire, or over the integrated WIFI system. The buoy software monitors its own operation and reports any problems in the form of diagnostic files that are transmitted with the data. The software monitors the system voltage, system current, charge and discharge rates of the batteries and is capable of running sensor diagnostics on individual sensors at any time they are required.

The power system for the TABS II buoy must meet greater demands than the TABS I buoy, primarily because of the increased number and type of sensors that are accommodated and the new PC-104 computer. The 22-inch interior diameter of the TABS II spar buoy provides a larger instrument compartment than a TABS I as well as greater buoyancy to carry more batteries and instruments. Consequently, each TABS II buoy contains sixteen 12V DC gel cell batteries, each with 144 watt hr capacity at full charge and nine 10-watt amorphous silicon solar panels capable of generating a conservative 200 watt hr per d in full sun. During normal operation the buoy uses approximately 140 watt hr in a 24-hr period. At an operating power of 5 watts, the PC-104 is the major power consumer. Efforts have been made to allow the computer to sleep when not needed. At full charge the buoy is capable of operating all sensors for at least 16 d in overcast skies when little if any charging occurs. The charge/discharge current and the overall system current of the buoy are continuously monitored and reported by the controller. Should it become necessary, individual sensors may be shut down to conserve power.

Three-meter discus buoy.—The reserve buoyancy of a TABS II buoy (Fig. 2) is approximately 750 pounds, whereas the reserve buoyancy of the newer 3-m discus is on the order of 7,300 pounds. This gives the 3-m buoy the capability to operate in much deeper depths and during higher sea states than the TABS II buoy. It also provides for the capability to support far greater power budgets that the TABS I and II designs. Beginning in 2002, NOAA funded research to build and deploy an in situ optical early warning system to detect harmful algal blooms on the Texas coast. This provided the impetus to design, fabricate, and outfit a 3-m discus buoy around a Flow-Cam cytometer, an instrument capable of imaging individual microscopic phytoplankton associated with harmful algal blooms (Campbell et al., 2007). The buoy was also equipped to operate a variety of subsurface and surface sensors that fulfilled the TABS mission as well as additional sensors, some of which required large power supplies and continuous operation, including nutrient analyzers, acoustic modems, and directional wave accelerometers. The PC-104 computer was first designed and built for the 3-m discus buoy and then adapted for the TABS II buoys, as we have discussed. The buoy was built, deployed, and, despite numerous technical challenges, showed that the concept of detecting harmful algal blooms is technically feasible. This led to the opportunity to design and fabricate 3-m discus buoys for the University of Southern Mississippi (USM). The first buoy was deployed in the Mississippi Sound in Nov. 2004 and survived a close pass by Hurricane Katrina.

Pilot studies.—In 2005, tests were conducted of an instrument package deployed on the bottom that showed it was feasible to a) use an upward-looking, bottom-mounted ADCP to measure near–real-time waves and currents and b) transfer that data to an overhead TABS II buoy with acoustic modems (Bender et al., 2006). More importantly, the test demonstrated that it is practical to use the TABS buoys as focal points for making sea floor in situ oceanographic measurements, particularly for light, nutrients, particles, and dissolved oxygen. The ongoing development of the 3-m discus buoys will enable additional ancillary sensors such as directional wave measurement, flow cytometry, and nutrient sensors. We have embarked on a program to fabricate and operate the fourth TABS buoy type, a 2.25-m discus hull design. This hull design will have significantly more reserve buoyancy, as well as additional sensors and capabilities including directional waves, but will be capable of deployment from smaller vessels.

Field Operations

Deployment of the first TABS I buoys began 2 April 1995 at Sites B and C, followed by deployments at Sites D and E on 31 May and Site A on 21 June. Since then, sites have been added, sites have been removed, and some sites have been relocated based on experience and operational requirements. As of Aug. 2007 there are 10 active locations: B, D, F, H, J, K, N, R, W, and V in water depths ranging from 10 m to 105 m and eight discontinued sites: A, C, E, G, L, M, P, and S. Sites R, D, F, and W are monitored with a TABS I buoy, and B, J, K, N, and V are monitored with TABS II buoys. The map (Fig. 1) and table of locations (Table 1) give the positions occupied by the TABS buoys since the inception of the project. The solid circles in Figure 1 show the present buoy locations; the small diamonds show the discontinued (archived) sites. When a TABS buoy is moved to a new location it is given a new designator letter, and when a buoy is removed from service its designator letter is retired. Thus, the data set associated with a letter is from a single location.

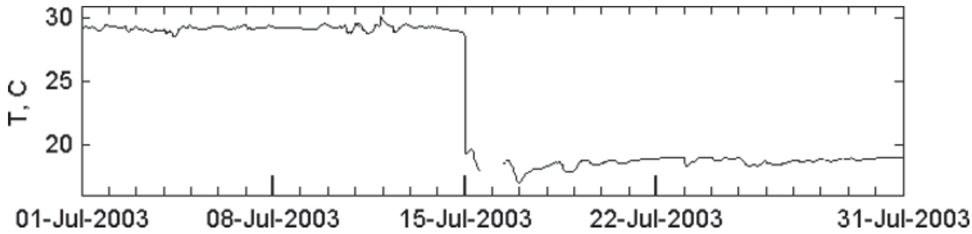

Fig. 4. Temperature recorded by buoy N during the passage of hurricane Claudette in July 2003. The buoy lost buoyancy on 15 July 2003 at 0000 UTC and descended to the bottom, where it continued to record data for 3 wk before the battery voltage dropped too low.

Each buoy is registered with the U.S. Coast Guard as a private aid-to-navigation. This protocol facilitates use of the archive database and simplifies changes to the U.S. Coast Guard Aids to Navigation database.

The TABS buoys are intended for oceanographic missions of long duration and must be able to reliably withstand storms, hurricanes, fishing pressure, ship collisions, vandalism, and long periods at sea. In order to accomplish this, the mean time between failure (MTBF) for the buoy and its components must be well understood. Improving the MTBF has been an ongoing process of evaluation and modification based on new technology and lessons learned. Many of the design changes implemented over the years were done to improve the ruggedness of the buoys following failure of a component or subsystem. For example, all hull penetrations are now made with 10,000-psi rated bulkhead connectors instead of cable glands. Long whip antennas are no longer used. When the Globalstar satellite system came online and replaced the Westinghouse Satellite telephones, it made it possible to extend the deployment period to 6–7 mo. As a result of these and many other changes, the MTBF of a buoy is 6 mo. The goal is to continually increase the MTBF. Experience with deployments at the inshore sites, particularly during the spring and summer months, continues to show that biofouling can become a problem, even for the Aanderaa sensor, after only 6 mo. Offshore buoy systems at sites such as K, N, and V do not suffer the same fouling problems, and the deployment duration is limited by mooring wear, which takes place over a 9–10-mo. period.

Storms and hurricanes continue to be one of the biggest challenges to improving the MTBF. In July 2003 Hurricane Claudette passed directly over two TABS II buoys deployed at the Flower Garden Banks, buoys N and V. High winds and waves pushed the buoys beneath the surface to a depth (estimated to be about 15 m) where the urethane foam flotation compressed and was unable to provide enough buoyancy to return to the surface. The buoys sank. Using side scan sonar the buoys were located on the bottom, and 6 mo later one of the buoys was grappled for and recovered. The instrument compartment had maintained its water-tight integrity, despite being in 100 m of water. Relying on internal batteries, the buoy recorded water temperature (Fig. 4) and velocity data for nearly 3 wk while lying on the bottom. A failure analysis was conducted after Claudette, and the mooring was found to be the principle cause of the failure. All TABS moorings were subsequently examined and redesigned to withstand a category three hurricane. In late Sept. 2005 the buoys deployed at sites N and V, with the redesigned moorings, were lost during the close passage of Hurricane Rita, a category four hurricane. On 24 Sept. the eye wall of Rita, with 120 mph winds, passed over the top of buoy R, a TABS I buoy. This buoy was probably forced to the bottom as well, but because the water depth was less than 15 m it resurfaced afterwards and continued to record water temperature and velocity, doing so until it was recovered 3 wk later. Based on these experiences, we have concluded that the TABS II buoy is unlikely to survive a strong category three hurricane when moored in waters approaching 100 m in depth. We have embarked on a program to replace the buoys at N and V with the fourth TABS buoy type, a 2.25-m discus hull design. This hull design has significantly more reserve buoyancy, as well as additional sensors and capabilities, and is capable of being deployed from smaller vessels.

Collision damage and vandalism continue to challenge our best efforts to improve the MTBF of the buoy. Although instances of vandalism and unintended collisions continue, there has been a noticeable reduction in recent years. We attribute the decrease to increased awareness by the commercial and charter fishing industry over 12 years to the presence and importance of the TABS buoys. In one instance a buoy that had sustained repeated collision damage was repositioned 7 nautical miles away from its original site, and that solved the problem. Some charter fishing fleets in south Texas waters use the TABS data to organize their fishing trips and then, while they are offshore, keep a watch on the buoys. GERG occasionally receives calls from these charter captains when they notice a buoy is off location or the data is not up to date. There was an instance in 2004 where a buoy had been dragged off location and two GERG-sponsored service cruises were unable to find the missing buoy. GERG subsequently received a phone call from a charter captain who had discovered it off location and called to report its position. The buoy was then recovered.

The quickest, and most reliable, way to service a TABS buoy is to replace the buoy with a newly serviced one. The recovered buoy is then brought back to Texas A&M University for examination, service, and repair. Disassembly of a TABS buoy while at sea to replace system components can be problematic because of salt air, spray, and heavy weather. The GLO has provided funding to maintain several spare TABS I buoys and TABS II buoys, which permits GERG to accomplish most service visits by replacing the buoy.

A significant motivation for extending the service cycle of a buoy is the growing cost of ship time. During the past several years the pool of ships with the requisite size, speed, lifting capability, and affordable daily rate structure needed for the TABS program has shrunk. Given the shrinking pool of dedicated ships, finding the means to service our buoys has become a challenge. During the last 3 yr, we have used a variety of vessels for TABS buoy operations. Vessels of the size and capabilities of Texas A&M's 182-foot *R/V Gyre* and University of Texas Marine Science Institute's 103-foot *R/V Longhorn* are necessary for launch and recovery of TABS buoys. Unfortunately the *Gyre* was retired on 31 Aug. 2005 and the *Longhorn* followed suit a year later. At present, there are no dedicated, university-owned, research vessels operating out of Texas ports. The nearest University-National Oceanographic Laboratory System (UNOLS) research vessel, the Louisiana Universities Marine Consortium (LUMCON) *R/V Pelican*, is home ported in Cocodrie, LA, nearly 400 nautical miles from our southernmost buoys. In the past year we have begun to successfully use vessels of opportunity that we outfit with our own portable winch, power pack, and A-frame. We send an additional person to sea to operate the winch and budget the cost for shipping the deck machinery to and from the mobilization site and the services of a welder and crane operator. In the past we chartered a boat and crew to retrieve the TABS II buoy at site J, the southernmost location. This was a job they had never done before and one that had none of our personnel onboard. The buoy was successfully recovered but was badly damaged in the process. The possibility of having to use boats and crews that are unfamiliar with the deployment and retrieval of TABS buoys places even more emphasis on designing and building a rugged buoy.

Data Management

Our land-based buoy data systems have three basic components: communication, data analysis, and data dissemination, which we discuss below.

Communication.—Primary communication with the TABS buoys is via the Globalstar satellite data network at 9600 baud. The buoys initiate the communications link once every 2 hr by placing a call to the standard dialup modem at GERG. The duration of the call is on the order of a minute or less, during which current speed and direction, water temperature, meteorological data, and engineering data are transmitted as hexadecimal strings. Full column ADCP profiles can be included as well; the call duration with 30 ADCP bins is typically 90 sec or less. The frequency of calls on all buoys was increased during 2005 from every 3 hr to every 2 hr. This provides the GLO and other users with data closer to real time. The advantage of Globalstar compared to GOES is the ability to conduct two-way communications. Because the link is two-way, the buoys can be instructed to transmit data more frequently in the event of an oil spill or other emergency. No information is lost if the call is not successful in making a connection or it is dropped prematurely before all the data is transmitted; first, because the computer on the buoy has an independent internal data archive that permanently stores all the data, and, second, because the most recent data are stored in an onboard buffer for later retrieval. Memory pointers keep track of what data have been successfully transmitted so no data are lost if telemetry is lost.

The buoy's onboard communication buffer is sized to hold 6 hr of data, which is uploaded every 2 hr when primary communications are active. Once the data are received at GERG, an automated data collection algorithm checks for data loss. Any gaps in the telemetered data can then be filled at the next successful transmission. If the communication buffer on board the buoy fills up, then this is assumed to be an indication that the primary communication link is down. The secondary communication link, System

ARGOS, is then initiated. The message size of System ARGOS is limited to 32 bytes, so we assure that the most recent data in the communication buffer have priority over older data. Each message, or burst, contains four sets of half-hourly currents and battery voltages. During a satellite overpass, up to seven bursts can be uploaded depending on the duration of the pass (a function of the elevation and azimuth) and the quality of the transmission link. The interval between satellite passes varies. Because the buffer is a last-in-first-out type, some older data may be pushed out of the buffer before they can be transmitted. However, a given satellite pass will always provide the most recent buoy observations, plus several hours of past observations. Because the interval between passes will range from about 2–4 h, some data gaps do occur. In the event that both primary and secondary communication fails, the computer on the buoy has an independent internal data archive that always stores all the data. The data can either be accessed remotely via Globalstar's two-way link, if primary communications are subsequently restored, or the data can be downloaded when the buoy is serviced.

Data analysis.—Once the TABS data are received in College Station, the analysis of the data proceeds in two steps: Level I quality control and Level II quality control. Level I quality control is automated and begins when the raw data from the TABS buoys are received at GERG. The raw data are transferred to a Linux server where the hexadecimal data are converted to engineering units. The second step then removes obviously flawed data. Graphical displays are generated every hour showing time series plots of the currents, water temperature, buoy tilt, and various engineering parameters that indicate the operating status of the buoy. An example of the plot displaying currents and water temperature is shown in Figure 5. Time series plots of the meteorological data, winds, air temperature, and atmospheric pressure are made available for the TABS II buoys. Once a day, the quality of the Level I data is reviewed by an experienced oceanographer, who can then make further corrections to the data when needed. The final quality-controlled Level I data are then inserted into a database for retrieval by users.

Level II quality control occurs each morning when the Real Time Analysis algorithm automatically performs an analysis of the previous 30 d of Level I data. The first step is an additional quality control of the Level I oceanographic, meteorological, and engineering data. Data are flagged for duplicate values, missing values, duplicate time stamps, bad time stamps, out-of-chronological sequence data, and statistical outliers such as spikes or unreasonable physical values. Current meter velocities that are identically zero for both components are flagged. Current speeds that exceed 150 cm s^{-1} or change by more than 35 cm s^{-1} in one time step (30 min) are flagged. The second step replaces the flagged data using a combination of linear interpolation for small gaps and a spectral preserving algorithm specifically designed at GERG for gaps up to 3 d. Linear interpolation is only used if there are less than three consecutive flagged records, i.e., no more than 90 min. Gaps and flagged data that are longer than 90 min, but less than 3 d are filled using a combination of the Lomb-Scargle periodogram [Lomb (1976) and Scargle (1982) independently developed a robust method for analyzing the spectral properties of an irregularly spaced data] to find frequencies of the significant peaks and a least-squares fit to the data on either side of the gap. The third step prepares a variety of products to present the Level II data on the Web at http://tabs.gerg.tamu.edu/tglo/RTA/RTA_index.html. These graphical products provide the user multiple views of the quality-controlled oceanographic, meteorological, and engineering data. Once a day, the quality of the Level II data is reviewed by an experienced oceanographer and an email report issued to interested parties. The Level II data are then made available, through the aforementioned website, for retrieval by users.

The Level II oceanographic data for each buoy is presented as a variety of products, including vector stick plots of the currents, current roses, scatter plots with the principle component analysis over plotted, the tidal analysis, comparisons to numerical model results, the probability of a flow reversal, the water temperature, and the successful quality controlled data return. In every case, interpolated data is denoted in red, and actual, quality-controlled data is in blue or in some cases (scatter plot) black. Several of the products are illustrated here. The current vectors and current roses are provided in 1-, 2-, 4-, 7-, 14-, and 30-d time slices to accommodate the needs of oil spill managers. An example of a 30-d current stick plot is shown in Figure 6. The vector velocities are filtered through a 3-hr filter and then through a 40-hr filter to show the long-term currents that control transport. Figure 7 is an example of the tidal analysis product. The 3-hr filtered current stick plot is shown in the top panel, the synthesized tidal velocity record in the middle panel, and, in the bottom panel, the detided velocity record. Finally, at the very

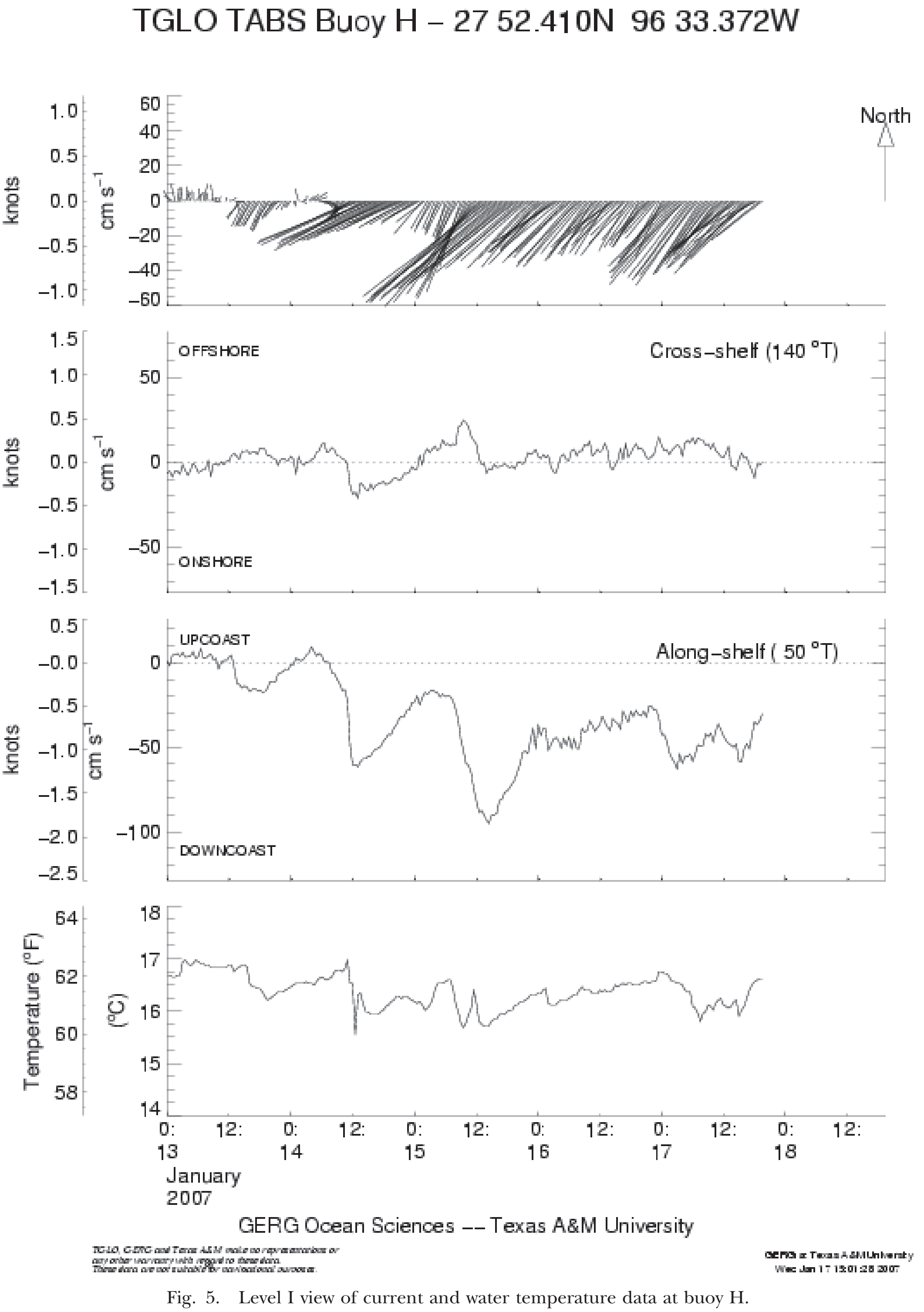

Fig. 5. Level I view of current and water temperature data at buoy H.

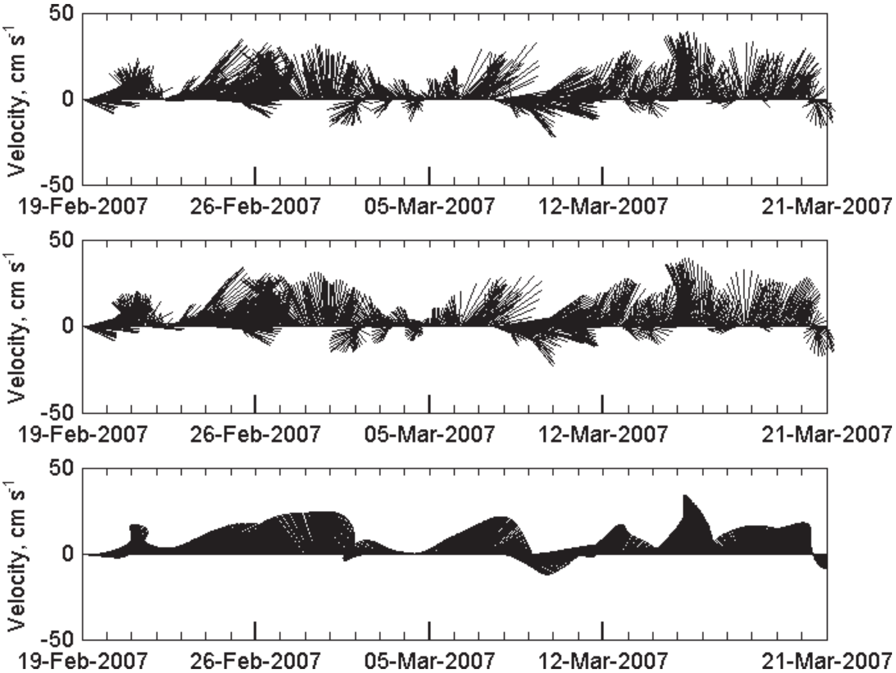

Fig. 6. An example of the RTA product showing the 30-d stick plot of currents at buoy V. The unfiltered data (top), the 3-hr filtered data (middle), and the 40-hr filtered data (bottom). Only 0.14% of the vectors have been interpolated (not shown).

bottom of the page, a table of the applicable tidal constituents used to create the tidal record is shown. The diurnal and semidiurnal tidal constituents have been determined from the historical record for each buoy. The nature of the flow on the Texas continental shelf tends to vary between inertial (circular) and alongcoast (rectilinear). The alongcoast variability product presents one means of visually presenting this variability state. It is derived by using a 12-hr sliding window to create a time series of the ratio of the principal component analysis major to minor ellipse axes. This ratio is mapped to a scale that indicates alongcoast flow when the ratio is much greater than one and is inertial as the ratio approaches one. Figure 8 shows an example.

For those buoys equipped with a meteorological station, the Level II wind data is presented as vector stick plots, time series of the speed of the wind and the gust, scatter plot, and wind rose. In addition, the air temperature, the barometric pressure, and the relative humidity are plotted. The processed winds are presented as 1-, 2-, 4-, 7-, 14-, and 30-d wind stick plots and wind roses, similar to that of the currents. The winds are sampled at 0.25 Hz over a 10-min time period. The time series of the 10-min averaged wind speed, as well as the wind gust, which is the maximum speed recorded in the 10 min, is presented. See Figure 9 for a typical example.

The Level II engineering data are shown in five different products. They are signal strength and ping count from the Aanderaa DCS sensor, battery voltage, buoy tilt, and data return. One of the products, the battery voltage for each buoy is shown as Figure 10. The unfiltered voltage is shown in the top panel and the 11-hr filtered voltage in the middle panel. The diurnal variation in the voltage is a reflection of the amount of solar radiation to which the solar panels are exposed. Based on a model of the expected clear sky solar insolation for the latitude of each buoy, the bottom panel shows the daily variations in the insolation. By midsummer the insolation will be 500 W m^{-2}. Here we see no charging due to extensive cloud cover during the last part of Jan. and the early part of Feb.

Data dissemination.—The Level I quality controlled data are inserted into an archival database designed to facilitate the extraction of user-specified subsets. The database is built on *mysql*, an open source Linux structured query language database, and on simple flat ascii files. The data have proven useful for model initialization,

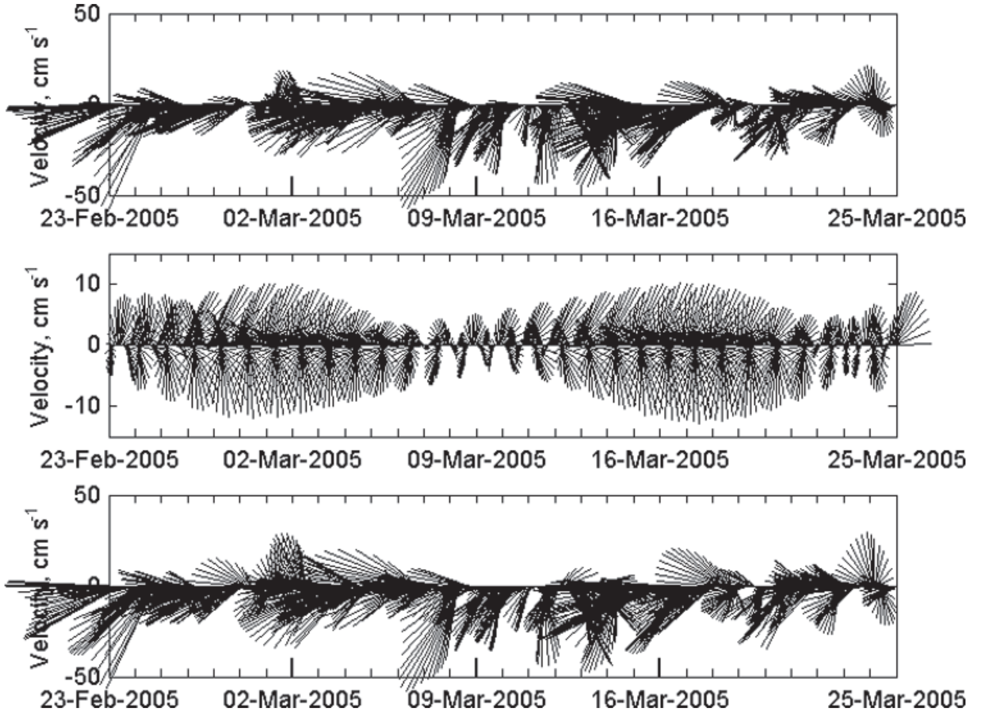

Fig. 7. An example of the RTA product showing the tidal velocities at buoy F. The 3-hr filtered data (top), the tidal currents (note the change in vertical scale) (middle), and the detided currents (bottom). The tides are small everywhere in the Gulf of Mexico; just 8.4% of the variance is described by the tides at buoy F. Only 0.35% of the vectors have been interpolated (not shown).

model skill assessment, research, and operational planning purposes. The GLO has direct access to this database via FTP over the Internet. The public has access through the World Wide Web (WWW) at http://tabs-os.gerg.tamu.edu/tglo/index.php. A quality controlled data set of all data collected during the TABS program is available on a DODS server at http://tabs.gerg.tamu.edu/DODSdata/. Additionally, TABS meteorological data from sites B, J, K, N, and V are branded as NDBC sites 42043, 42044, 42045, 42046, and 42047 and formatted for ingest into the National Data Buoy Center. Efforts are presently underway to format the TABS current observations for NDBC ingest.

The TABS web page provides the user with access to a variety of oceanographic and meteorological data products. Using their browser, the user is able to view either the latest data or access the database and view archived data. The user can also download the data for later use. This web presentation has been an integral part of the TABS system since 1996 (Lee et al., 1996). Users can select a TABS buoy location from the map or from text links for those without a graphical web browser. For each TABS station the user can choose to view either a graph of the past 4 d of data or the data in tabular format. The graph consists of a ''stick plot'' of the currents, cross shelf, and along shelf components of the current and water temperature (see Fig. 5). Data are presented in both English and metric units. Graphs can be downloaded as either a GIF image or a postscript file.

Several additional features of the TABS website assist in the utilization of the TABS data. A summary plot provides a stick plot for each buoy using a common time axis. A status table lists buoy latitude, longitude, lease block, and water depth. The status table also indicates which of the buoys have successfully transmitted their data during the past 12 hr and contains other information regarding the operational status of each buoy. Each buoy page also contains a link that allows the user to search the TABS database and retrieve data from a buoy for a user-selectable time period. The user can access up to 2 mo of data at a time. The results of each database search can be viewed in both graphical and tabular format.

In the summer of 2003 a major power failure caused a disk hardware failure on the primary server that runs and maintains the TABS website and data system. Since that time the TABS

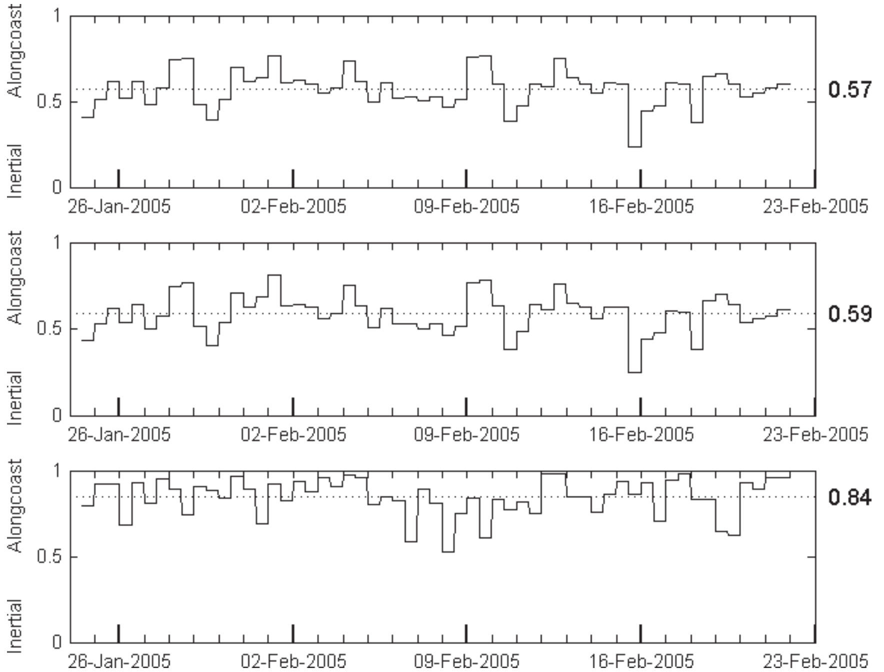

Fig. 8. An example of the RTA product showing the along-coast variability at buoy J. This figure is meant to convey how much of the currents are along-coast versus inertial, where a value of one denotes alongcoast and a value of zero inertial. It is derived from the ratio of the principle component analysis (PCA) major to minor ellipse ratio. It is blocky by nature because it evaluates a 12-hr block of currents. The unfiltered data (top), the 3-hr filtered data (middle), and the 40-hr filtered data where the mean is annotated (bottom). The longer period flows become more and more alongcoast.

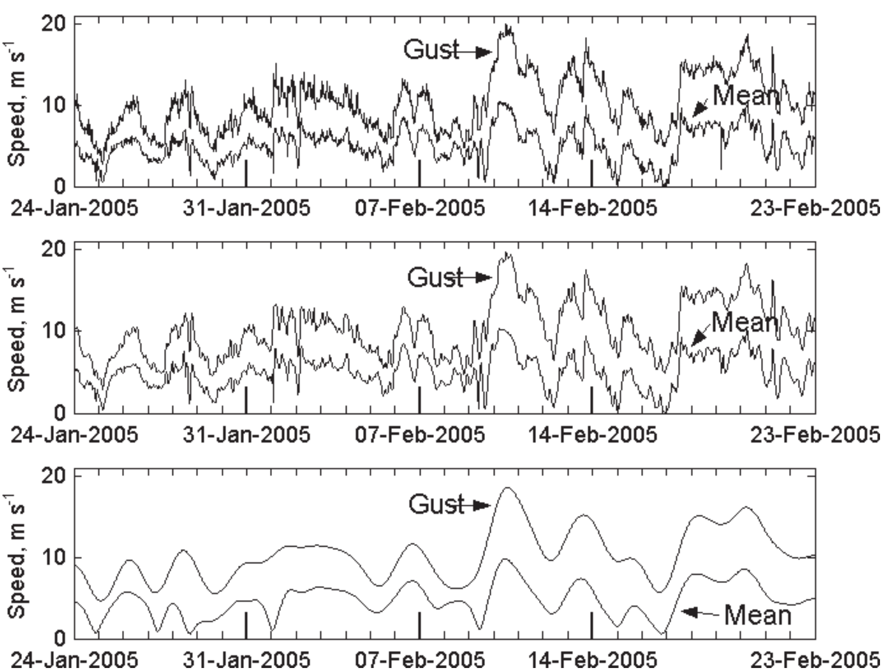

Fig. 9. An example of the RTA product showing the wind gust and mean wind speed at buoy V. The unfiltered data (top), the 3-hr filtered data (middle), and the 40-hr filtered data (bottom).

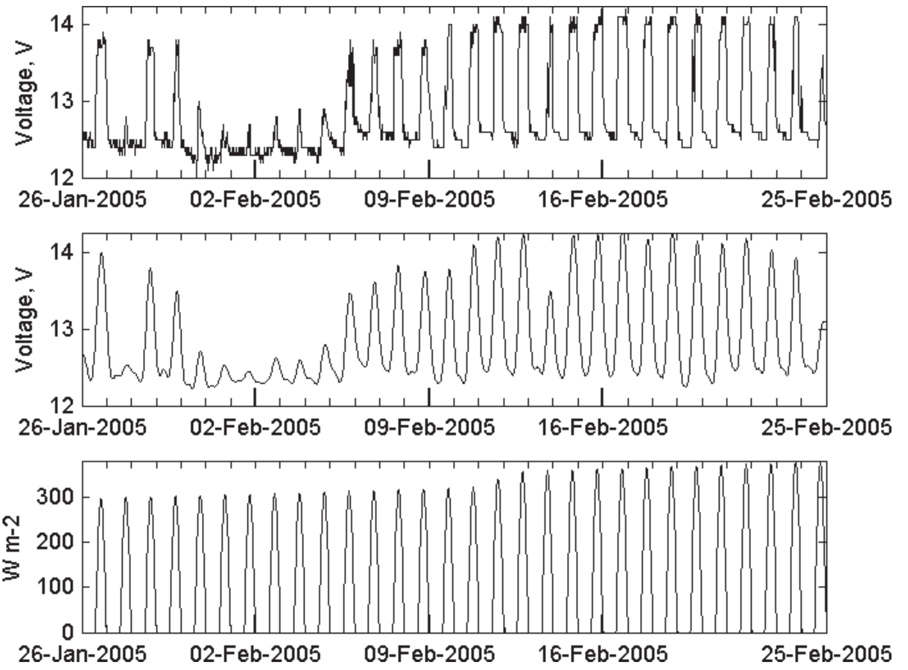

Fig. 10. An example of the RTA product showing battery voltage and clear sky insolation for buoy F. The unfiltered battery voltage (top) and the 11-hr filtered data (middle). Note the distinctive diurnal solar charging cycle. The bottom panel shows the estimated solar insolation for buoy F's latitude. The effect of cloud cover is seen at the beginning of Feb.

website, data, and software have been mirrored hourly onto two other machines to ensure reliability in the case of a hardware or power failure. One of these is a Redundant Array of Inexpensive Disks (RAID) server located at GERG, but in a different building, and the other is a machine located in the Department of Oceanography on the Texas A&M main campus. Both of these machines are backed up nightly and the backups are stored at off-site locations. Both servers at GERG are connected to switches served by redundant fiber optic links to the Texas A&M University high-speed backbone. The GERG facility is a node on the University's Gigapop internet network. An internet ring controller connects GERG to a loop of controllers through redundant fiber optic paths in such a manner that cutting one fiber optic link will not interrupt internet service. Both GERG servers, separate data communication systems, and all networking equipment are supported by uninterruptible power systems. The TABS website can be supported even with power failures of up to a 5-hr duration.

The TABS website also provides access to data from the National Data Buoy Center's buoy and coastal (CMAN) meteorological data. These data are obtained directly from NDBC each hour. We include four offshore buoys and two CMAN stations, e.g., 42035 located southeast of Galveston; 42019 and 42020, which are east and southeast of Port Aransas, respectively; 42038, which is east of the Flower Garden Banks; SRST2 near Sabine; and PTAT2 near Port Aransas. These data are updated hourly and presented in both graphical and tabular formats.

The website also contains a number of links to additional real-time oceanographic and meteorological data. Links to National Weather Service coastal and offshore weather forecasts for the Gulf of Mexico are provided on the main TABS web page. Links have been added to model results of currents as well as ETA-32 gridded wind forecasts. There are links to the GCOOS, Houston/Galveston PORTS website, TCOON, National Data Buoy Center, Galveston Bay and Corpus Christi Bay Animated Hydrodynamic and Oil Spill Model output, Satellite Sea Surface Temperature Images from NOAA and Johns Hopkins University, Tampa Bay PORTS, and other relevant sites.

A ''Notice to Mariners'' is included on the TABS web page to request users avoid contact with the buoys and report problems if they notice the buoys off location or if they see damage. Access to the notice is available on all data pages as well as the main page.

Analysis of the TABS web server access logs shows that utilization of the TABS website has been increasing since its inception. Peak usage of the TABS website generally occurs in mid-Oct. and then tails off rather sharply. We see this as a reflection of the end of the recreational boating season and a decrease of usage by boaters. The three largest groups of TABS users come from the .com, .edu, and .net Internet domains. The first represents commercial entities primarily from within the United States, the second represents educational institutions in the United States, and the last are network service providers. However, since some of the major Internet service providers are in the .com domain, i.e., AOL, it would appear that the majority of the use of the TABS site is coming from the general public.

Noteworthy groups that access the TABS site include users from the Texas State government, specifically the Texas General Land Office, and users from the U.S. government, including users from NOAA, Minerals Management Service (MMS), United States Coast Guard (USCG), and NASA. Usage by the offshore industry includes most of the major oil companies. In addition we have seen usage from 69 foreign countries to date.

Modeling

In 1998 a modeling component was added to the TABS program with the development and implementation of the POM adapted to perform simulations on the Texas shelf. In 2002 the modeling was extended with the implementation of the ROMS. It has always been recognized that there is a need to estimate the circulation field between the sparsely located TABS buoys. Whereas the half-hourly temporal coverage of the TABS current meters is exceptional, the geographic coverage, as seen in Figure 1, is too sparse to capture the expected spatial modes of circulation on this shelf. On the basis of hydrographic data primarily collected by the Texas–Louisiana Shelf Circulation and Transport Processes Study, Li et al. (1996) examined the energetic scales of spatial variability across the Texas–Louisiana continental shelf. They found that the cross-shelf scales over the western half of the shelf are shorter (~15 km) than those in the eastern and central shelf (~20 km), whereas the along-shelf scales (~35 km) are essentially the same everywhere on the shelf. The difference in the cross-shelf scales was attributed to the shelf width. These scales are considerably smaller that the average 120 km along-shelf separation between TABS buoys and 70 km across-shelf separation. The minimum along-shelf separation between buoys is 40 km, and the minimum cross-shelf separation is 55 km. In order to estimate the circulation field between the sparsely located TABS buoys, two numerical and one statistical model have been developed and are described below, as are the winds used to drive the two forecast models.

Princeton Ocean Model.—The original shelf circulation model, developed and maintained by Joseph Yip from 1998–2002, consists of a three-dimensional version of the POM adapted to perform simulations on the Texas shelf on a domain extending from 25°N on the Mexican coast to 85°W at the coastline of Florida. The operational POM model is a simplified barotropic version that performs a 24-hr surface current prediction once per day. A data–model comparison—performed from April through Dec. 1999 of nine near-shore TABS buoys—indicated modest skill of the model in predicting the wind-driven circulation.

Regional Ocean Modeling System.—Limitations in the original POM shelf circulation model led to the development of a second-generation shelf circulation model using the ROMS. The development was started in 2002 and continues today. The ROMS-based circulation model was designed to provide greater maintainability and extensibility than was available with the POM model, as well as to enable greater flexibility and ease of managing and transforming the simulation model input and output fields. Both the computational kernel and the data handling infrastructure were completely revised for these purposes.

ROMS is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. (See Ezer et al. 2002 and the references therein for background information on both POM and ROMS.) Computationally, ROMS uses advanced numerical algorithms and software technology to facilitate efficient simulations on single and parallel computer architectures. Scientifically, it contains a variety of modular features including high-order advection schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; biological modules; radiation boundary conditions; and data assimilation. These scientific and computational features provide for both an easily maintained present operational system and a flexible upgrade path for the research and development of future, improved versions of the system. The higher-order advection scheme and the boundary layer schemes, in terms of mixing, are used; data assimilation is not.

Significant differences between the first and second generation systems include:

- The expansion of the computational domain from the original POM grid extending from the shoreline to the continental shelf to a ROMS grid across the entire Gulf of Mexico. The grid on the shelf is on the order of a few kilometers
- Four 48-hr predictive simulations per day as opposed to one 24-hr simulation per day with the original system
- The use of a computer cluster to perform parallel simulations of larger domains at higher resolutions in about the same amount of time as the POM simulations

YBR statistical nowcast model.—Efforts to develop and refine a statistical circulation model to complement the numerical models are underway. The objective of this endeavor is to demonstrate an effective methodology for achieving optimal nowcasts of shelf-wide circulation by using dominant empirical modal patterns of existing well-resolved near-surface Surface Current and Lagrangian Drift Program-I (SCULP-I) surface drifter data fitted to the sparse TABS current data. This concept was first explored by Yip and Reid (2002) for application to the Texas–Louisiana shelf and was presented at the Oceans 2002 Conference on Marine Frontiers shortly after the young lead author lost his battle with cancer. Because that paper was well received, we have worked with Professor Reid to present a materially expanded version of that study as an appropriate recognition of Yip's contributions to the description, data analysis, and dynamics of the Texas–Louisiana shelf circulation. In the YBR model (Yip and Reid 2002), empirical orthogonal function (EOF) modes are first determined from daily average velocity fields derived from the SCULP-I surface drifter data. Ohlmann and Niiler (2005) present a comprehensive analysis of the drifter measurements made with the near surface floats of the SCULP. The SCULP-I subset of the drifter data are clearly very relevant to the needs of the TABS program, having been deployed in the northern Gulf of Mexico during a 1-yr period. First the drifters characterize the upper meter of the water column, comparable to the depth measured by the TABS buoys. Second, the domain of the data covers the entire Texas shelf, from the Sabine River to Brownsville. These data include the two major forcing mechanisms on the Texas shelf, the wind-driven flow in the upper layer, and the longer term flow driven by weather systems and freshwater input from rivers, particularly the Mississippi. Both the TABS current data and the SCULP-I drifter data include tidal and inertial oscillation signals, but these are suppressed by employing daily average currents. Furthermore, DiMarco and Reid (1998) have shown that the tidal signal is weak on the Texas–Louisiana shelf. The drifter velocity data were binned into a boundary-fitted grid covering the Texas–Louisiana shelf. The bins were comparable in size to the energetic spatial scales of spatial variability identified by Li et al.(1996). A nowcast of the shelf-wide circulation is made each day (http://tabs.gerg.tamu.edu/Tglo/RTA//RTA_index.html) by using the real-time TABS current data to find the amplitudes of the dominant empirical modes, modes first found by analyzing the drifter data for EOF spatial patterns. In this manner the circulation field between the sparsely located TABS buoys is estimated using a method quite different from that of a numerical circulation model.

Winds.—The readily available meteorological observations and near–real-time forecasts are collected, archived, and disseminated for use in forcing the POM and ROMS numerical models and to the GLO and others for use in spill-response planning. Data are captured from the National Weather Service, the National Data Buoy Center, and numerical weather model output from the National Centers for Environmental Prediction (NCEP).

The Gulf of Mexico NDBC buoy observations and coastal marine meteorological observations from Gulf-coast first-order airports are extracted from the Global Telecommunications System (GTS) in near–real-time using UNIDATA's Local Data Manager (LDM) software. Access to the GTS stream is provided by the Texas A&M University Department of Atmospheric Sciences. A software program named ZEPHYR converts the data from meteorological codes into convenient tabular listings. These data are used in displays of current conditions, for model-data comparisons, and in the production of gridded wind fields based on observations. This collection system is quite robust and has run with little to no maintenance for about a decade.

Maintaining a system to collect NCEP model output on a continuous basis has been more challenging due to increases in weather model resolution, forecast time horizons, and file sizes and changes in grid-point locations, host servers, model output file names, and parameter placements within files. Some of the maintenance issues have relatively simple solutions, such as faster network connections and more disk space. Changes in grid resolution and grid point locations cause a cascade of work that extends beyond the collection systems into the POM and ROMS models themselves.

The POM and ROMS modeling systems are driven by the NCEP NAM forecast model wind fields. NCEP's NAM model was formerly (and perhaps still better known) as the ETA model. We will continue to use ETA here. The ETA model is run at NCEP four times per day. Each new run is downloaded as it becomes available. The forecast fields represent conditions at 3-hr intervals out to an 80-hr time horizon but we presently only use fields out to 48 hr. The 17 files, collected four times per day, total 5.8 GB/day. The Gulf of Mexico surface wind fields are extracted and made available to the modelers. ETA wind fields and surface currents from POM and ROMS are automatically posted graphically to our website and numerically in another directory for use by NOAA HAZAT teams for their use.

An interoperable TABS/modeling system.—The goal of the Integrated Ocean Observing System (IOOS) Data Management and Communications Plan is to develop machine-to-machine interoperable systems, with provisions for data discovery, access, metadata, transport, and archive. In order to achieve an interoperable system for the TABS observations and modeling forecasts, funding was first obtained from the National Ocean Partnership Program (NOPP). The task continues with funding from the Southeastern Universities Research Association (SURA). The SURA Coastal Ocean and Observing and Prediction (SCOOP) program is an Office of Naval Research and NOAA–funded study designed to implement the Data Management and Communications Plan.

As part of this work the ROMS program was converted to accept input in netCDF format with internal arrays named and organized according to standard formats (COARDS/CF). The output routines were also modified to conform to this interchange format. With properly constructed URLs, NetCDF files can be moved across the network using OPeNDAP-enabled software as easily as local files can be accessed. In theory we could recompile ROMS with OPeNDAP-enabled netCDF libraries, and at run time ROMS could access files directly from the NCEP NOMAD servers. However, NOMADS is not yet sufficiently reliable for our operational system, and issues of network latency could be a serious problem not best solved in model code. We will be working on catalog metadata that will support online browsing. This will be particularly useful for establishing and maintaining geographic information systems (GIS) that we are also developing as part of SCOOP. The GIS system will enable TGLO to rapidly zoom to problem sites and overlay model, wind, observations, and other relevant parameters to give a comprehensive view of environmental conditions.

POM and ROMS output and the NOAA/ERD LAS server.—TABS and the Texas General Land Office enjoy an informal, but strong relationship with NOAA's Office of Response and Restoration Emergency Response Division (ERD) (formerly Hazardous Materials Response Division or HAZMAT). As a public service we continue to integrate the General NOAA Oil Modeling Environment (GNOME) model into the TABS and TABS modeling system. We have installed a copy of the NOAA PMEL Live Access Server (LAS) for use by NOAA ERD to rapidly acquire and subset the POM and ROMS model output and ETA wind fields. Alternate methods of having hot-start data sets for GNOME are being developed by this group so that GNOME will be ready to go in a moment's notice in the event of a spill.

Achievements

The primary mission of TABS—to provide near real-time data when a spill occurs—has been met many times. The three-fold collateral goals envisioned by the GLO to form TABS into an effective public resource have been successfully met as well. The reliability, operational range, and versatility of the TABS buoys have been continually improved, as discussed in the sections on Development and Field Operations, all the TABS data have been disseminated through a user-friendly Internet website as discussed in the section on Data Management, and other scientific research projects have been built on the TABS resources such as modeling and real-time analysis. In this section we elaborate further on some of those achievements.

Oil spill response.—Fortunately there have been no catastrophic oil spills rivaling that of the 1990 *MegaBorg* explosion, but during the major spills that have occurred, and the numerous realistic drills that have been conducted, TABS has fulfilled its primary mission by providing near–real-time data. In its first 10 yr of operation there were 20 major spills in which NOAA personnel worked with the GLO and consulted the TABS data (Martin et al., 2005). There were many less-serious spills in which the TABS data were consulted, but such queries were not recorded in the NOAA database. We look at two oil spills, the *Buffalo Marine Barge 292* oil spill of 1996 and the more recent *DBL-152* oil spill of 2005–2006, as examples of the informal relationship that has developed over the years between the GLO and NOAA. During the *Buffalo Marine Barge 292* oil spill the NOAA HAZMAT modeling team and the GLO's trajectory modeling team used TABS data and computer simulations to forecast the movement of the oil to an unprecedented level of accuracy (Lehr et al., 1997; Martin et al., 1997; Martin et al., 2005). The trajectory modelers did not have to begin their work with only educated guesses about the offshore currents. The currents were known within minutes of the spill and were continuously tracked for 24 d. Midway through the spill TABS data showed the direction of the coastal current switching from upcoast to downcoast. The benefit to cleanup and protection operations allowed Incident Command to stand-down an alert to the Sabine Pass area and refocus efforts down coast a full day earlier than would have been possible before TABS. It also saved an estimated $225,000 in costs for an unnecessary deployment to protect an area no longer at risk.

In Dec. 2005 a TABS II buoy with a surface current meter and a downward-looking ADCP was deployed about 30 miles south of Sabine, TX, to assist with tracking subsurface oil from the *DBL-152* oil spill (Michel, 2006). Shortly before midnight on 10 Nov. 2005 the Integrated Tank Barge DBL-152 was in tow from Houston, TX, to Tampa, FL, when it struck a submerged oil platform that had been damaged by Hurricane Rita. The tug and barge were approximately 55 km south of Cameron, LA, when the collision occurred. Eventually 2.7 million gallons of heavy refined oil were released. Because of the oil's density, it sank to the bottom where it was periodically resuspended by storm events. A TABS II buoy with a downward-looking ADCP was deployed at the spill site to provide data on bottom currents critical to predicting where the oil would be transported.

An example of the spill response community's acceptance of the TABS concept is the joint industry project funded by 16 offshore operators to maintain two TABS II buoys at the Flower Garden Banks National Marine Sanctuary. These buoys (see N and V in Fig. 1) provide current and wind observations to the operators in the vicinity of the Sanctuary in the event they need data to respond to a spill in this ecologically sensitive area.

Collateral uses.—The reliability, operational range, and versatility of the TABS buoys have improved to the point that the buoys have been successfully used in locations remote from the Texas shelf and for missions beyond that of oil spill response. In 2001 two TABS buoys were deployed off the Mississippi delta as part of the Northern Gulf of Mexico Littoral Initiative program sponsored by the Naval Oceanographic Office (NAVO). In 2001, a TABS I buoy equipped with an Aanderaa DCS 3900R velocity sensor and a TABS II buoy with an ADCP sensor and meteorological station were loaned, with the permission of the GLO, to the U.S. Navy to provide meteorological and oceanographic data during the recovery operations of the Ehime Maru (Bender et al., 2002a). These buoys were deployed just offshore of the Honolulu International Airport and operated from 18 July 2002 to 26 Nov. 2002 when the recovery operations were completed. Based in part on the success of this program, a TABS II buoy was purchased by NAVO in 2002 for use at a nationally-important location. This buoy was equipped with an Iridium satellite communications system, instead of the standard Globalstar, and a downward-looking RDI ADCP. GERG-TAMU personnel trained NAVO personnel in the operation and maintenance of the TABS buoy and assisted them in creating their own ground station in Stennis, MS, to handle data from this buoy.

Gulf of Mexico Coastal Ocean Observing System.—TABS is a charter member of the GCOOS. GCOOS will augment and integrate a sustained observing system for the Gulf of Mexico as part of the IOOS (Ocean.US, 2006). GCOOS aims to provide ocean observations and products needed by users in the region to meet the seven societal goals of IOOS:

- Detecting and predicting climate variability and consequences
- Preserving and restoring healthy marine ecosystems
- Ensuring human health
- Managing resources
- Facilitating safe and efficient marine transportation
- Enhancing national security
- Predicting and mitigating coastal hazards.

Since its inception in 1995, TABS has contributed to most of these IOOS goals. The primary purpose of TABS is to ensure a reliable source of accurate, up-to-date information on ocean currents along the Texas coast. The TABS current measurements enable rapid assessment of the fate of oil spills, facilitating efficient remedial efforts to preserve healthy marine ecosystems. Surface current measurements and modeling provide the basis to predict dispersion of waterborne contaminants. The TABS oceanographic data provide a regional ecological climatology for sea surface temperature for use in assessing ecosystem health. TABS, through its collection of sustained time series of long duration, provide in situ measurements that aid in the detection and prediction of climatic change. Today, more than 1.5 million half-hourly current and temperature measurements have been collected in near real-time. At sites B and D 12 yr of measurements of sea surface temperature and currents are available. The present-day TABS system has improved the spatial resolution of measurements in Texas offshore waters by providing 10 observation sites. TABS has played a significant role in maritime operations by providing near–real-time surface current measurements that improve the effectiveness of search, rescue, and emergency response capabilities. The U.S. Coast Guard uses TABS data following accidents when oil rig workers are missing or a helicopter disappears during an overwater flight to an offshore platform. Private mariners also use TABS data to help them safely navigate coastal waters.

Climatology: General.—One of the collateral goals of TABS is to provide the foundation for scientific research projects. This goal continues to be successfully met in a number of ways. We have many indications from our colleagues that these data are being used in teaching and research. Early on in the program Crout (1997) and Kelly et al. (1999) used the TABS database features to facilitate studies comparing currents calculated from satellite altimetry with those observed by the TABS buoys. Using the first 7 yr of TABS data, Bender et al. (2002b) showed that there is insufficient information to conclusively establish if there is a statistically discernible link between surface currents and the El Nino Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO).

We have used the database of currents to construct an oceanographic climatology and the monthly historical record for each of the TABS buoys. The climatology page, http://tabs.gerg.tamu.edu/tglo/Climatology/Climate_index.html, shows a shelf-wide view of the monthly averaged currents and the individual current roses for each buoy site. The historical record, accessible through http://tabs.gerg.tamu.edu/tglo/Hindcast/B/2006/Dec/Oceanographic_CurrentStick.html, shows the current stick plot, scatter plot, current rose, and water temperature for each buoy for every month since the buoy was first deployed. The historical data for each month can also be downloaded. If the buoy recorded meteorological data, those products are available as well.

Climatology: Seasonal surface currents.—In coastal regions wind stress is a predominant source of momentum. Cochrane and Kelly (1986) and Nowlin et al. (1998) showed that there is a high correlation between the along-coast wind stress and the along-coast currents on the Texas shelf. Cho et al. (1998) confirmed that the main circulation over the LATEX shelf is wind driven. The direction of the winds in the Gulf of Mexico is determined by the seasonal position of the high-pressure systems (Zavala-Hidalgo, 2003). In the fall and winter high-pressure systems move from the northwest continental United States into the Gulf generating northeasterly winds in the western gulf, whereas in the summer the Bermuda high and the warming of the continental United States generate southeasterly winds. During the nonsummer months the northeasterly winds drive a strong downcoast flow along the inner shelf, while during the summer the weaker southeasterly winds drive a weaker upcoast flow. Hereafter we define downcoast (upcoast) as proceeding in the counterclockwise (clockwise) direction from the Atchafalaya River to Mexico (Mexico to the Atchafalaya), i.e., cyclonically (anticyclonically) along the curved coastline.

As a result of the 1.5 million half-hourly measurements of velocity data, we have a statistically reliable description of the mean seasonal surface currents on the shelf. Figure 11 shows the mean surface currents for the winter months, from Sept. through May, based on all half-hourly measurements available from 1995 to 2005 for the 10 TABS buoys depicted. A mean downcoast flow is clearly evident, driven by the predominant easterly winds. The concave shape of the coast causes the alongshore wind stress to decrease from its maximum in the vicinity of buoy R to its minimum in the vicinity of buoys J and K, where the mean currents are weakest. During the summer the winds are southerly and the conditions seen in the winter are reversed. Figure 12 shows the mean surface currents for the summer months, i.e., June, July, and Aug. These mean currents are based on half-hourly surface current measurements recorded for all the monthly data available from 1995 to 2005 for the 10 TABS buoys depicted. A mean upcoast flow is clearly evident.

Hurricane conditions.—Since June 1995 when the first TABS buoys were deployed there have been eight tropical storms and three hurricanes (Brett, Claudette, and Rita) that have crossed the

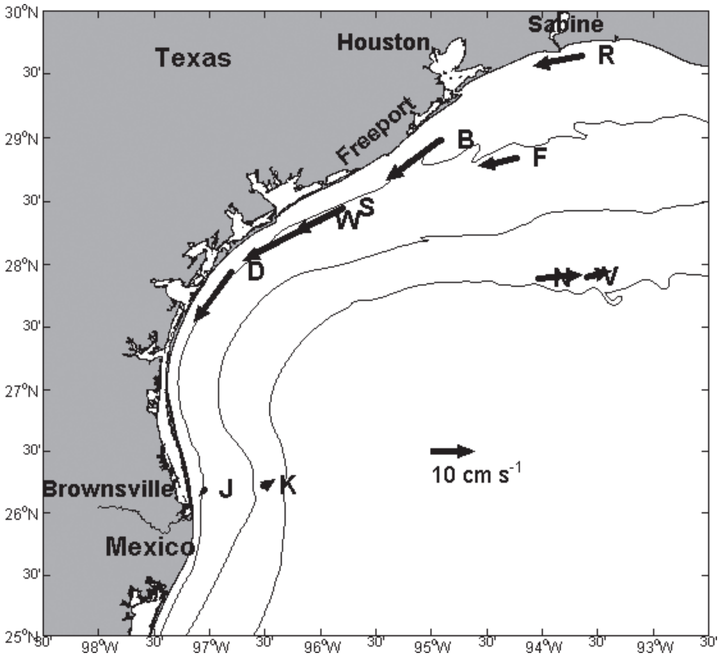

Fig. 11. Mean surface currents for the winter (Sept. through May) on the Texas continental shelf. Bathymetry contours are shown for the 20, 50, and 200 m depths.

Texas shelf. Hurricanes Brett and Katrina have been the only major (>category three) landfalling storms; Claudette was a category one storm. Brett was the first major hurricane to strike the Texas coast since Hurricane Gerry in Oct. 1989. The track of Brett took it to the north of buoy J before making landfall at 0000 UTC on 23 Aug. 1999. Before 21 Aug., the surface

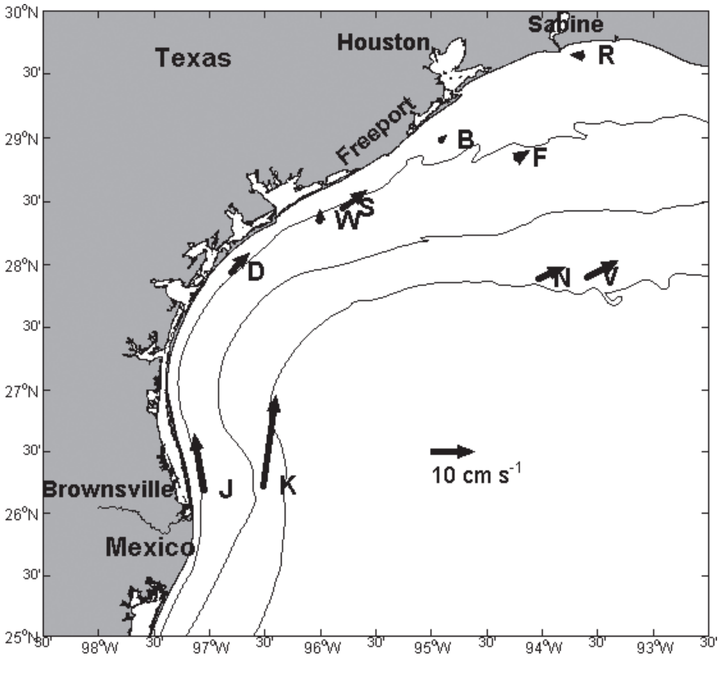

Fig. 12. Mean surface currents for the summer (June, July, and Aug.) on the Texas continental shelf. Bathymetry contours are shown for the 20, 50, and 200 m depths.

currents recorded by buoy J were inertially dominated. As the storm approached from the southeast a strong downcoast (where downcoast has been previously defined as toward Mexico) current was established in response to the downcoast wind stress. The current speed eventually peaked at 110 cm s^{-1} as the eye wall made its closest approach to the buoy around 1600 UTC on 22 Aug. After the storm went ashore over the central portion of Padre Island the currents at buoy J reversed to 50 cm s^{-1} upcoast and remained that way for 3 wk. The surface water temperature decreased by 2 C as a result of the hurricane. Nearly 4 yr later Hurricane Claudette became a category one hurricane just as it made landfall on 15 July 2003. It remained a tropical storm for 24 hr after making landfall. The track of Claudette took it over buoys N and V and slightly to the north of buoy W. Buoys N and V recorded peak wind gusts of 56 and 46 knots, respectively. As the storm approached buoy W from the east, a strengthening downcoast current was recorded by the buoy. A sustained downcoast current of 115 cm s^{-1} was recorded for 5 hr as the eye wall made its closest approach to the buoy and then went ashore. Even after the storm went ashore over Matagorda Island at 1530 UTC the currents remained downcoast for nearly 3 d before reversing to upcoast. The surface water temperature decreased by 1.5 C as a result of the hurricane. Hurricane Rita was an intense hurricane that reached category five strength over the central Gulf of Mexico before weakening and coming ashore near the Texas/Louisiana border as a category three storm. As it made landfall on 24 Sept. 2005, the eyewall of hurricane Rita passed directly over the top of buoy R. Before 23 Sept. the currents were weak and inertially dominated (see Fig. 13), but as the storm approached from the southeast a strong downcoast current was established in response to the downcoast wind stress. The current speed eventually peaked at nearly 160 cm s^{-1} as the eye wall passed over the buoy. As the storm went ashore the winds decreased and the currents quickly relaxed, but showed no signs of significant inertial oscillations that might be expected given the large and sudden increase in the wind speed. While this seems somewhat surprising, Rita was fast moving, and the step change in wind speed lasted for less than one inertial period. At buoy F, sustained offshore currents of at least 90 cm s^{-1} were recorded for more than 20 hr until 1400 UTC on 24 Sept. The surface water temperature at buoy R decreased by 3 C and by 2 C at buoy F as a result of the hurricane. In each hurricane, Brett, Claudette, and Rita, the cyclonic winds coupled with the curved coastlines to cause a nearly identical near-shore current response, a strong downcoast current as the hurricane makes its approach to the Texas coastline. Up to the point of landfall this pattern is identical, but after landfall the current pattern is noticeably different.

Conclusions

In April 1995, Texas funded the deployment and operation of a coastal network of near real-time current meters known as TABS. The founding mission of TABS was to improve the data available to oil spill trajectory modelers. Nearly 12 yr later, TABS remains the only system in the country with the primary mission of ocean observations in the service of oil spill preparedness and response. This mission, coupled with stable GLO funding, has enabled us to improve the technology and operational range of the TABS buoys, readily disseminate the results through the web, and fulfill important societal and science goals.

Today TABS forms the core of a regional ocean observing system for Texas waters that can benefit a great number of research projects and operational programs for industry, academia, and government. As the nation embarks on the development of an IOOS, TABS will continue to be an active participant of the GCOOS regional association and the primary source of near-surface current measurements in the northwestern Gulf of Mexico. The lessons learned during 12 yr of operations serve as a valuable roadmap for the operators of new ocean observing systems.

The underlying theme behind the lessons learned can be reduced to a few concepts: attention to detail; a highly competent and dedicated staff; stable, long-term funding; and the flexibility to meet ever new challenges. For example, the availability of ships with the requisite size, speed, lifting capability, and affordable daily structure needed for the TABS program has shrunk during the past several years. We no longer have the luxury of relying on nearby UNOLS research vessels. This has created new challenges for servicing the TABS buoys that we have met by chartering vessels and outfitting the boat with winch, power pack, and A-frame; an endeavor that has been successful. Changes in technology are relentless, and most provide an opportunity to improve the capability of the buoys. Other than the basic shape of the hulls, there is little of the TABS buoys today that originally went to sea in 1995. Failures are always disappointing, and we have had our fair share,

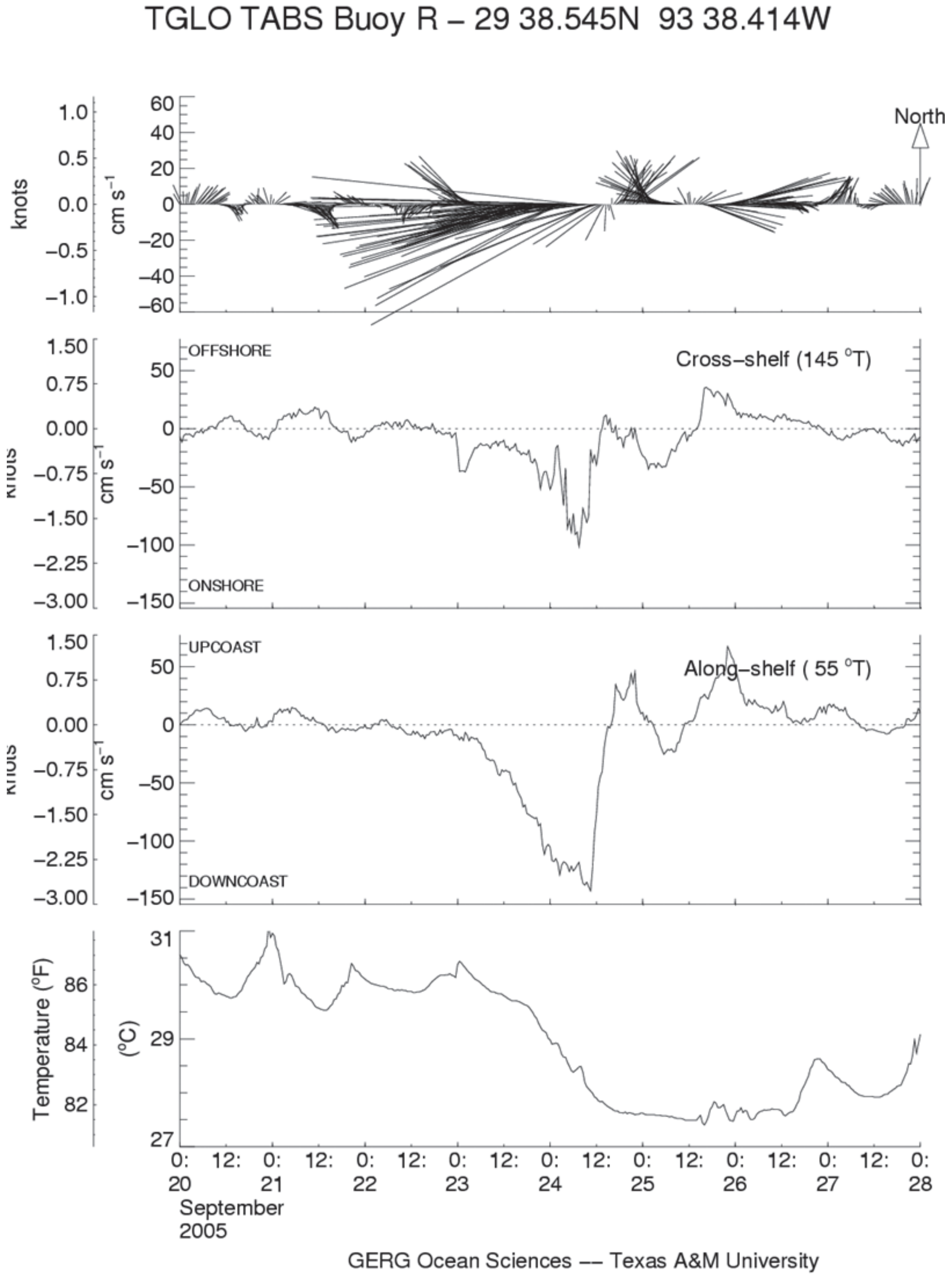

Fig. 13. Surface currents and water temperature at buoy R during the passage of Hurricane Rita. Beginning at 1800 in the evening of 22 Sept. 2005 CDT, the temperature begins to drop and the currents increase as the eye of the hurricane approaches.

but they generally provide the opportunity to reexamine the design and make constructive improvements. Finally, we believe that a primary lesson of TABS is that an academic institution, coupled with a stable source of funding, is fully capable of running an operational coastal observing system for the long haul.

It is our intention that TABS continue to provide operational ocean measurements off the Texas coast. We intend to continue to improve the reliability of the TABS buoys through testing, field experience, and design modifications and to share that knowledge with the ocean observing community. We are actively working to extend the capabilities of TABS from its original, and ongoing, mission of surface current and temperature measurement to measurements of the water column, the sea floor, and the marine surface layer. These additions will help increase the density of offshore meteorological observations and provide the vertical resolution of currents needed for data assimilation into TABS forecast modeling efforts.

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