ELSEVIER

Energy Policy 35 (2007) 966–983

ENERGY POLICY

www.elsevier.com/locate/enpol

The impact of weather and ocean forecasting on hydrocarbon production and pollution management in the Gulf of Mexico

Mark J. Kaiser*, Allan G. Pulsipher

Center for Energy Studies, Louisiana State University, Energy Coast & Environment Building, Nicholson Extension Drive, Baton Rouge, LA 70803, USA

Available online 29 March 2006

Abstract

Over the past 2 years, the vulnerability of offshore production in the Gulf of Mexico (GOM) has been brought to light by extensive damage to oil and gas facilities and pipelines resulting from Hurricanes Ivan, Katrina, and Rita. The occurrences of extreme weather regularly force operators to shut-down production, cease drilling and construction activities, and evacuate personnel. Loop currents and eddies can also impact offshore operations and delay installation and drilling activities and reduce the effectiveness of oil spill response strategies. The purpose of this paper is to describe how weather and ocean forecasting impact production activities and pollution management in the GOM. Physical outcome and decision models in support of production and development activities and oil spill response management are presented, and the expected economic benefits that may result from the implementation of an integrated ocean observation network in the region are summarized. Improved ocean observation systems are expected to reduce the uncertainty of forecasting and to enhance the value of ocean/weather information throughout the Gulf region. The source of benefits and the size of activity from which improved ocean observation benefits may be derived are estimated for energy development and production activities and oil spill response management.

Keywords: Benefit analysis; Hydrocarbon development activities; Ocean observation systems

1. Introduction

The Outer Continental Shelf (OCS)[1] of the Gulf of Mexico (GOM) is the most extensively developed and mature offshore petroleum province in the world. More than 40,000 wells have been drilled in the OCS since offshore production began in 1947, and there are currently over 4000 active structures in water depths ranging up to 7000 ft. About 27% of the United States domestic oil supply and 17% gas supply comes from the OCS, and in 2005, prior to the arrival of Hurricane Katrina, OCS lands averaged daily production of about 1.5 million barrels (MMbbl) of oil and 10.0 billion cubic feet (Bcf) of natural gas (Energy Information Administration, 2005).

Weather plays a major factor in human activities offshore, and extreme weather in particular, can have an enormous impact on the cost of doing business. Storms and hurricanes regularly challenge and endanger the Gulf Coast community and energy infrastructure throughout the region. Tropical storms cause damage to physical, economic, biological, and social systems, but the severest effects tend to be highly localized. Every year about 10 storms form over the tropical portions of the Atlantic Ocean, the Caribbean Sea, and the GOM, and about half of these storms will grow into 75 mph hurricanes. Of these 5 hurricanes, 2–3 are likely to strike the coast of the United States (Table 1, Fig. 1). The most active time for hurricane development is mid-August through mid-October (Fig. 2). Likely prevailing storm tracks vary by month (Fig. 3).

Over the past 2 years, the vulnerability of offshore production in the GOM has been brought to light by extensive damage to oil and gas facilities and pipelines resulting from Hurricanes Ivan, Katrina, and Rita. The 2005 hurricane season was the worst in the history of

*Corresponding author. Tel.: +1 225 578 4554; fax: +1 225 578 4541.
E-mail address: mkaiser@lsu.edu (M.J. Kaiser).

[1]The OCS of each coastal state generally begins 3 nautical miles from shore for all but two states—Texas and Florida—which are 3 marine leagues (9 nautical miles), and extends at least 200 miles through the Exclusive Economic Zone.

0301-4215/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2006.01.026

offshore production in the GOM and is the most destructive and costliest natural disaster in the history of the United States (Blake et al., 2005). In 2004, Hurricane Ivan destroyed seven platforms and caused significant damage to 24 other structures and 17 large diameter pipelines (Wright, 2004). In 2005, Hurricanes Katrina and Rita destroyed 109 older, end-of-life facilities representing about 1.7% of GOM oil production and 0.9% of natural gas production. Another 53 structures suffered significant damage (Fig. 4). Five drilling rigs were also destroyed and 19 rigs sustained severe damage (Fig. 5). Insured losses to the offshore energy industry in 2005 are estimated to range from $35 to 60 billion (Lyle, 2005; Paganie and Buschee, 2005); for the 2004 hurricane season, insured losses have been estimated at $23 billion (Dwyer et al., 2005). Hurricane Andrew (1992) by comparison caused losses of $22 billion (Daniels, 1994).

When a hurricane enters the GOM, oil production and transportation pipelines shut-down, crews are evacuated,

Table 1
Extreme weather events in the Gulf of Mexico (2000–2005)

Hurricane	Year	Magnitude[a]
Katrina	2005	5
Rita	2005	5
Wilma	2005	3
Charley	2004	4
Frances	2004	2
Ivan	2004	3
Jeanne	2004	3
Larry	2003	0
Henri	2003	0
Grace	2003	0
Erika	2003	1
Claudette	2003	4
Bill	2003	0
Lili	2002	4
Isidore	2002	3
Hanna	2002	0
Fay	2002	0
Edouard	2002	0
Bertha	2002	0
Gabrielle	2001	1
Barry	2001	0
Allison	2001	0
Keith	2000	4
Gordon	2000	1

Source: National Climatic Data Center.
[a]The Saffir–Simpson hurricane scale is based on estimated maximum sustained surface winds. A tropical storm is denoted by a magnitude of 0.

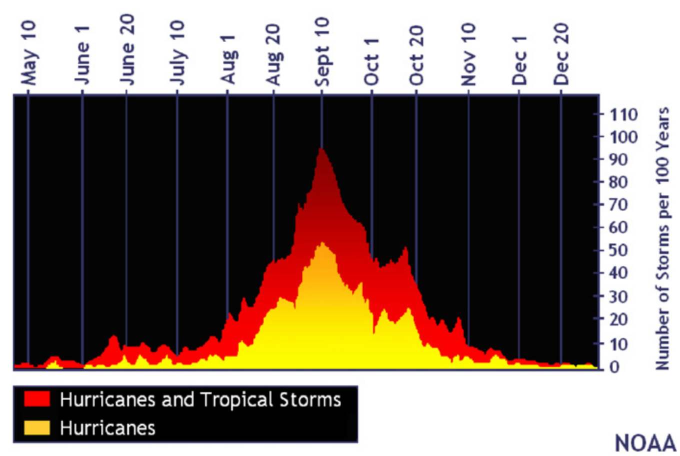

Fig. 2. Number of hurricanes and tropical storms per 100 Years. *Source*: NOAA.

Fig. 1. Continental United States landfalling hurricanes, 1950–2004. *Source*: NOAA.

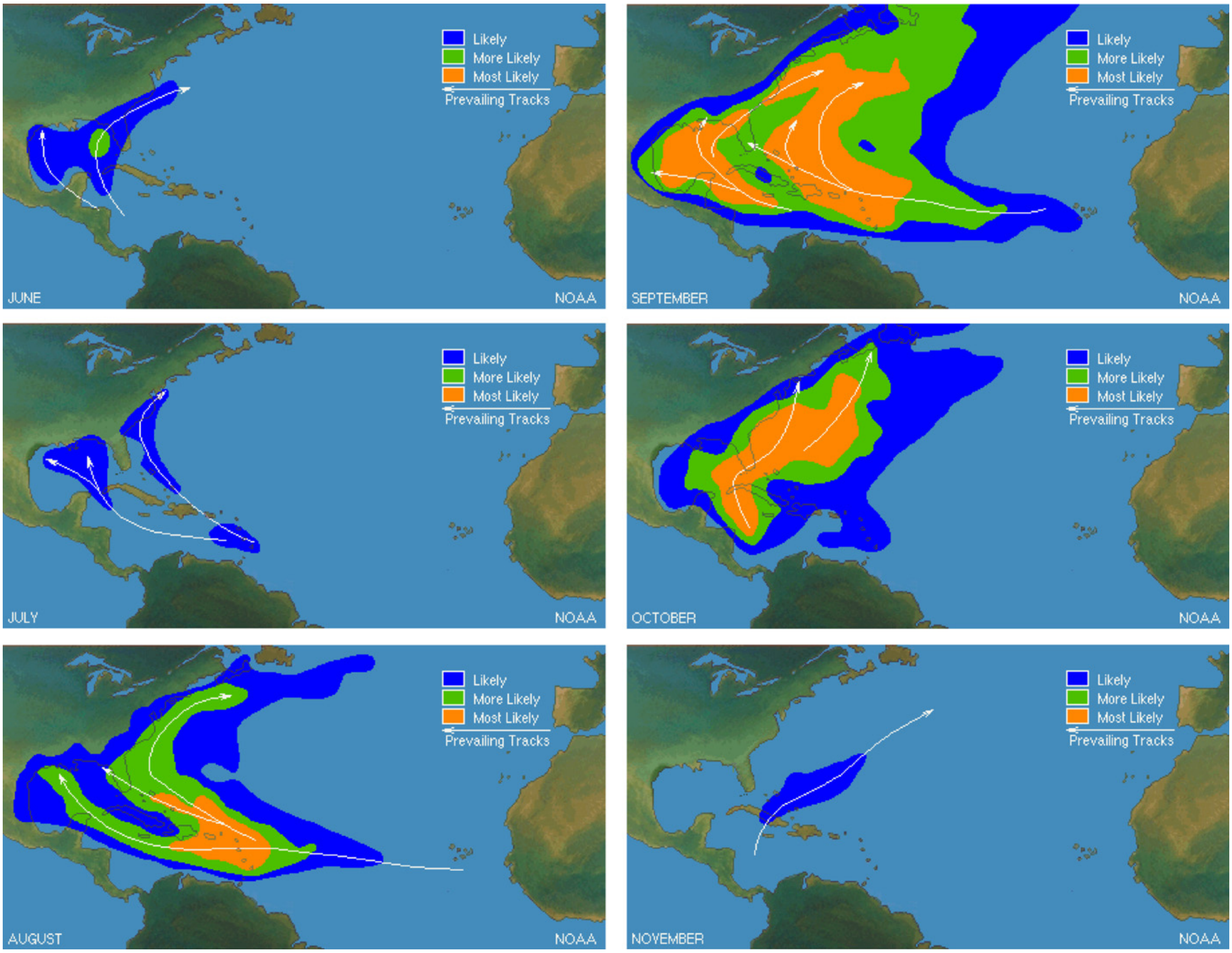

Fig. 3. Likely prevailing hurricane tracks in the Gulf of Mexico during the hurricane season. *Source*: NOAA.

and refineries along the Gulf Coast close. Drilling rigs pull pipe and anchor down, and supply vessels, commercial ships, and barges may be moved into one of Louisiana's many bayous where they have more protection from the storm. Ocean-going vessels transiting into or out of the GOM near the time of the event use hurricane forecasts to plot course to avoid the storm. If the path of the storm appears to threaten Louisiana, the Louisiana Offshore Oil Port (LOOP), the biggest and only deepwater oil port in the country (Fig. 6), closes to shipping and flows through on-shore pipelines are halted.[2] Crude oil from the Gulf to the Midwest via the Capline pipeline, and the petroleum product conduits the Colonial, Plantation, and Dixie pipelines also shut-down ahead of the storm. The Plantation and Colonial pipelines are major suppliers of gasoline, diesel, and jet fuel to the Northeast, MidAtlantic, and Southeast regions; the Dixie pipeline transports propane throughout the region. If the path of the storm approaches Texas, ports from Houston to Corpus Christi Close and the Seaway and Sun crude pipelines, which run from the Texas Gulf Coast to Cushing, Oklahoma, shut-down. The Centennial, Explorer, Longhorn, and TEPPCO pipelines which serve the Midwest, West Texas, and Northeast regions also shut-down. Storm surges resulting from the hurricane may damage onshore gas processing plants, destroying key components and leaving significant amounts of debris in the facilities.

Hurricanes are not the only extreme weather event that impacts offshore oil and gas production activities. As operators have pushed into deeper waters in the GOM, the impact of loop currents on operations have become increasingly problematic. The Loop Current is an offshoot of the Gulf stream, a major North Atlantic Ocean boundary current located off the east coast of the United States. The Loop Current is formed when the Gulf Stream

[2]LOOP facilities are located south of New Orleans in Lafourche Parish in southeast Louisiana and in adjacent offshore waters west of the Mississippi River Delta. The LOOP pipeline traverses the major wetland habitats in the Louisiana coastal area. The 159 km pipelines crosses the near-offshore GOM near Fourchon through beach/barrier headland, estuary, and bottom land hardwood and bald cypress/water-tupelo swamp forests within the estuary.

enters the GOM through the Yucatan Straits and "loops" through the basin in a clockwise direction before exiting through the Straits of Florida (Table 2, Fig. 7). When the loop exits through the Florida Straits, it often becomes pinched and sheds some of its flow into a separate eddy of warm water which migrates backward, southwest across the GOM, bringing strong Loop Current forces into active exploration and production areas (DeLuca, 2004). Eddy currents spin off like cyclones and travel freely across the Gulf until dissipating in the Western GOM in an area called the Eddy Graveyard. Some oceanographers refer to the Loop Current as the equivalent of a hurricane beneath the water, and its impact on deepwater installations is increasing as operators have moved into deeper and more eddy prone areas.

Fig. 4. Mars tension leg platform before and after Hurricane Katrina. *Source*: Shell.

The Loop Current is a persistent feature in the GOM characterized by strong surface current velocities and variable path and intensity profiles. Loop Currents may attain speeds as high as 4 knots (5 mph) at the surface—the equivalent of a 60 mph gale-force wind—extend to depths of 1000 ft and measure 250 miles in diameter. The warm-core eddies that break away from the northern extremity of the Loop Current are characterized by intense current velocities which can cause serious impact to offshore operations and have been known to slow drilling rigs enroute to a drill site. Typically, two to three eddies form each year. Currents influence rig selection, riser design, operational planning, and the design and installation of production systems, moorings, subsea components and pipelines. Of particular importance is fatigue associated with dynamic response to current loading. For effective planning and decision-making, operators require reliable ocean current forecasts. A number of initiatives are underway by the academic, government and commercial scientific community to develop and verify current models around the world. The CASE (Climatology and Simulation of Eddies) joint industry project, Oceanweather's WANE (West Africa Normals and Extremes) joint venture between Fugro and the Nansen Environmental and Remote Sensing Center at the University of Bergen, and the US Navy are all working on advanced ocean current modeling programs (Szabo et al., 2003).

The National Oceanographic Partnership Program (NOPP) formulated a plan for an Integrated, Sustained Ocean Observing System (ISOOS) in a 1999 report to Congress (NOPP, 1999), intending to move the United States from what is now a largely ad hoc and fragmented approach to ocean observation to a coordinated and sustained activity similar to the existing national weather information system (Adams et al., 2000; NOPP and

Fig. 5. The Ocean Warwick jack-up rig rests by the shore in Dauphin Island, Alabama, on August 30, 2005, after Hurricane Katrina passed through the area. *Source*: Diamond Offshore Drilling, Inc.

Fig. 6. The Louisiana Offshore Oil Port (LOOP) marine terminal, Fourchon booster station, and Clovelly dome storage terminal. *Source*: LOOP.

Table 2
Eddy events in the Gulf of Mexico (1999–2005)

Eddy	Year	Size
Vortex	2005	Large
U2	2005	Small
Ulysses	2004	Huge
Titantic	2003	Huge
Sargassum	2003	Huge
Rebel	2002	Small
QE-2	2002	Small
Quick	2002	Huge
Pelagic	2002	Huge
Odessa	2001	Medium
Nansen	2001	Medium
Millenium	2001	Huge
Lazy	2000	Small
Kinetic	2000	Small
Juggernaut	1999	Huge
Indigo	1999	Small
Haskell	1999	Small
Gyre	1999	Small

Source: Horizon Marine, Inc.

ORAP, 1999; Ocean, 2002). Implementation of ISOOS will require investments in infrastructure and ongoing support for new and existing observation systems in the open and coastal ocean. The importance of a national network of ocean observation systems has recently been reiterated by the US Commission on Ocean Policy (2004).

The purpose of this paper is to describe the manner in which weather and ocean data is used in planning and decision-making activities in offshore energy development and oil spill response management, and to identify and quantify the expected economic benefits of improved weather/ocean forecasting on these activities. The outline of the paper is as follows. In Section 2, background information on coastal and ocean observation systems are summarized, and in Section 3, the economic valuation methodology is presented. In Sections 4–7, the decision, physical outcome, and potential benefits of improved observation systems to energy exploration, development, and production activities are described. In Section 8, the decision, physical outcome and economic outcome models related to oil spill response management are discussed. In Section 9, conclusions complete the paper.

2. Gulf of Mexico coastal and ocean observation systems

Four basic elements are common to all ocean observation systems: data collection; data transmission; data processing; and data presentation. The data collection system depends on the purpose of the station and local conditions. Each station has sensors to measure environmental parameters, a data collection computer for

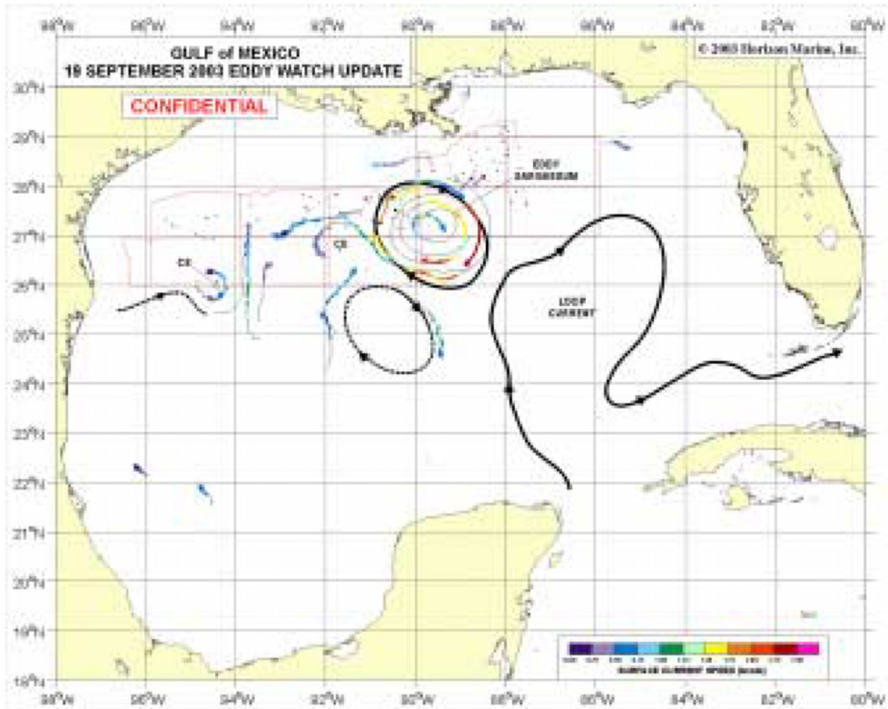

Fig. 7. Typical loop current pattern and Eddy Sargassum (September 2003). *Source*: Horizon Marine, Inc.

controlling the sensors and storing the data on-site, one or more telemetry devices for transmitting data from the station, and solar panels and batteries to power the system. The sensors used to measure environmental parameters include acoustic transducers for measuring water elevations, anemometers for wind speed and direction, Acoustic Doppler Current Profiling (ADCP) instruments, and multi-parameter water-quality probes. Each sensor is interfaced to the data collection computer via serial communication ports or analog-to-digital conversion hardware.

Ocean observation systems are maintained by many different agencies, universities and industries. The management and organizational structure is particularly complex with various organizations, funding sources, and mandates evolving over the years. The systems are diverse in terms of their capability and coverage (Fig. 8) but they also share many common features. Typical near-time or real-time oceanographic and meteorological measurements include winds, waves, current, water density, nutrients, water quality, and biological indices. The observation system may be attached to an oil/gas platform (Fig. 9), satellite structure (Fig. 10), or a floating buoy (Fig. 11). Weather and ocean data in the GOM are also collected by commercial ships, aircraft, and satellite observation. For a description of the capabilities of each system, the NOAA website (www.csc.noaa.gov) maintains up-to-date links. The reports (Michaud et al., 1994; Blaha et al., 2000; Cole et al., 2003; Kelly et al., 1998; Martin et al., 1997; Vincent et al., 2000) and references contained therein provide useful summaries of individual systems and further direction in the literature.

3. Valuation strategy

The state of knowledge of ocean data is incomplete and uncertain, and so improved and integrated ocean/weather observation systems are expected to enhance the value of the information and create additional network externalities (NOPP and ORAP, 1999). Weather information is valuable, and to the extent that improved ocean observation systems can improve the data on which weather/ocean forecasts is based, is potentially very beneficial to energy production activities and pollution management in the GOM.

The potential impact of savings that may be incurred from improved ocean observation systems was introduced by Kite-Powell and Colgan in a study focused on the Gulf of Maine (Kite-Powell et al., 2001). Kite-Powell and Colgan performed order-of-magnitude assessments for general categories of benefits using the following approach:

Step 1. Value activity A that uses and/or is impacted by ocean forecasts, $V(A)$.

Step 2. Assume that the benefit of improved ocean observation systems is expressed by a small factor, $\varepsilon(A)>0$.

Step 3. Compute the value of improved observation systems in region R as the summation of the identified activities, $V(R)=\sum_A \varepsilon(A)V(A)$.

The valuation strategy is based on estimating $V(A)$ from public sources of information and hypothesizing the value of $\varepsilon(A)$ for each activity identified. Ideally, it would be desirable to derive the value of $\varepsilon(A)$ from fundamental data or to ascertain the cost to achieve a desired level of $\varepsilon(A)$, but establishing such relationships are currently beyond the

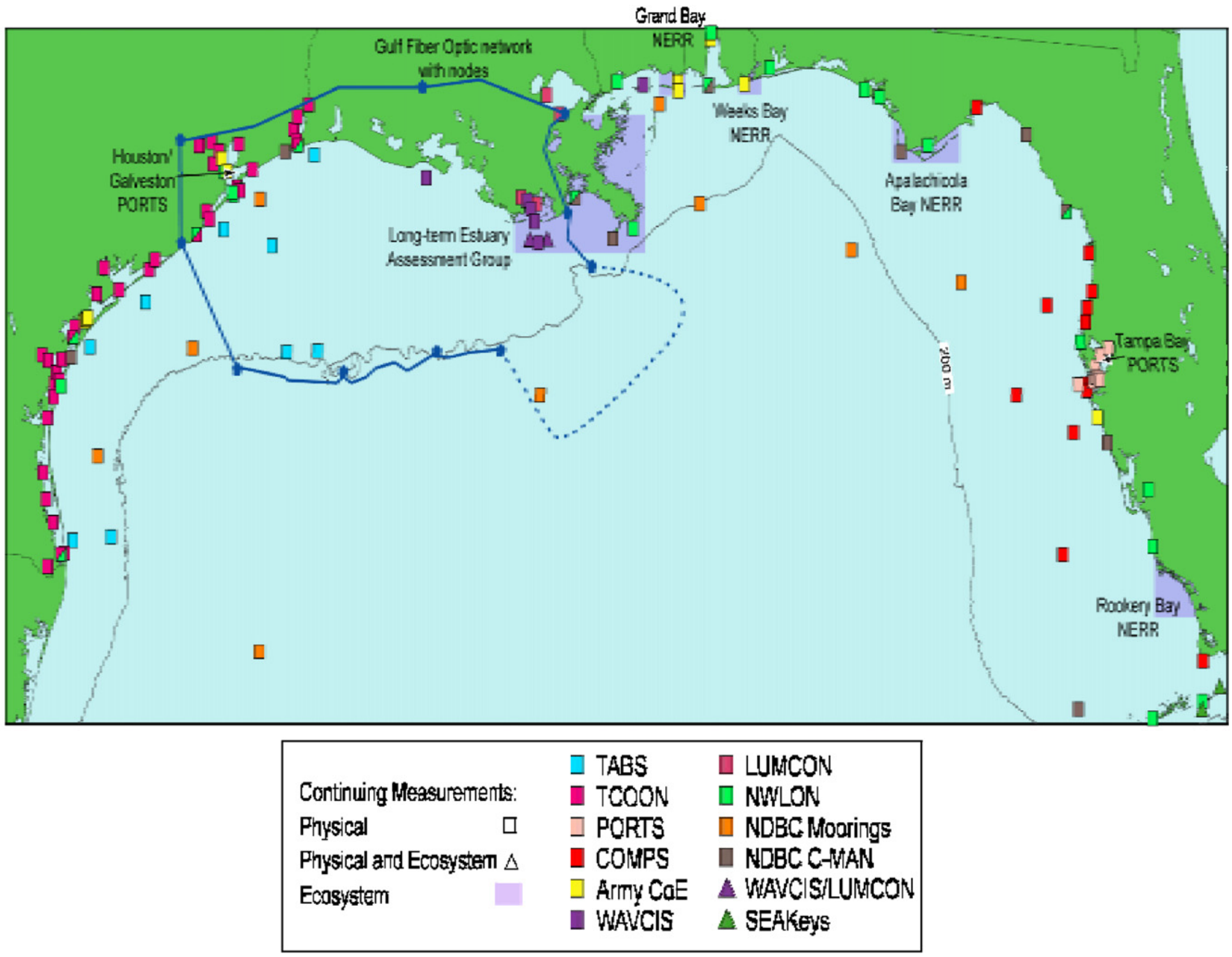

Fig. 8. Gulf of Mexico observing sites. *Source*: Texas General Land Office.

state of knowledge of observation systems. No direct link between $\varepsilon(A)$ and $V(A)$ can thus be "derived" and it remains difficult to justify the value of $\varepsilon(A)$ on a fundamental level. The default condition is to assume the factor $\varepsilon(A)$ "small" (e.g., 1%, 1 day, etc.), and this is considered a reasonable and conservative estimate of the expected benefits to be incurred.

The standard economic approach to valuing information requires: a description of the information being valued and of the uncertainty in the phenomena it describes; a model of how this information is used to make decisions; a model of how these decisions affect physical outcomes; and a model of how physical outcomes can be translated into economic outcomes. User sector representatives were identified to define the base case and improved information scenarios, and then information was obtained regarding the natural variation of the phenomena being described, including critical variables to nowcast/forecast, the forecast horizon, spatial and temporal resolution. A decision model is sketched describing how users incorporate information into their choices and decisions. The physical outcome describes how outcomes result from the decision parameters and the variation in the natural phenomena. Finally, a first-order economic outcome model describes how the physical outcomes translate into economic changes.

4. Offshore energy development stages

Offshore energy development projects generally follow a four-stage sequence of activity: from exploration to development to production, and eventually, decommissioning. In the exploration stage, areas that are considered to have prospects of containing oil and gas reserves are drilled with exploratory wells and stratigraphic test wells. In the development stage, the mineral deposit is prepared for commercial production. This includes the acquisition, construction, and installation of facilities to extract, treat, gather, and store the oil and gas. In contrast to a single exploratory well for which drilling can last anywhere from 2 weeks to 3 months, drilling the wells off a platform can last many months and extend over several years. Development activities typically include drilling and equipping development wells and service wells, and the construction

Fig. 9. Ocean observation system attached to an oil/gas structure. *Source*: LUMCON.

and installation of production facilities. The ongoing operation of the facility is considered the production phase. In production, the oil and gas is gathered, lifted to the surface, treated, processed, and possibly, stored. When the useful life of a production platform is reached, the equipment and structure is removed and the well casing severed and closed below the seabed.

5. Drilling activities

5.1. Decision model

Offshore drilling may be subject to significant delays caused by the weather. Waves are one of the most obvious environmental concerns for offshore operations and constitute the primary cause of downtime and reduced operating efficiency. Weather downtime can impact drilling operations in various ways; e.g., weather too severe for operations involving supply boats may lead to delay if stock levels on the rig decline to a critical level; weather may impact anchoring up and moving time; weather may be too severe for drilling to occur; weather may result in damaged or destroyed rigs or lost drill strings and risers. If operating limits are exceeded because wave heights, ocean currents, or eddies are too strong, drilling operations will be temporarily abandoned and resumed when conditions fall within the operating capabilities of the equipment. In deepwater, floating rigs are able to maintain position over the tops of wells through a dynamic positioning system that compensates for wind, waves, and currents to keep the vessel stationary relative to the seabed.

Safe working conditions for many offshore operations may be approximately specified by the critical values of wind speed, wave height, and current profile (Table 3). The GOM is a fairly benign operating environment for most of the year, but downtime due to weather can be an important factor in determining the total drilling costs, and in the deepwater, usually plays a more significant role because of the high dayrate of the drilling rig. Empirical evidence suggests that 1–3% of drilling cost is due to waiting on weather (Jenkins, 1975), although this is subject to significant variation depending on the time of year of drilling activity and the water depth of the operation.

Drilling activities generally follow three stages:

1. *Start limits*. Weather must be below these limits before an operation will start (or restart after abandonment).
2. *Suspend limits*. Work will be paused if the environment exceeds these limits. Work recommences as soon as weather conditions drop back below the threshold.
3. *Abandon limits*. Task will be abandoned if these limits are exceeded. Work will not be restarted until weather conditions fall below the start limits.

The occurrence of a hurricane warning or alarm is enough to disrupt drilling operations and a significant amount of operating time can be lost to "false alarms" (Barrilleaux et al., 2001; Corona et al., 1996; Rowe et al., 2001). In deepwater operations, loop currents and the eddies may damage drilling strings/risers and impact the drilling schedule (Epps, 1997). In drilling operations, eddies may induce vortex-induced vibrations that reduce the fatigue life of equipment. The operational limit for diver operations is half a knot or less, while deployment of tubulars and risers can usually be safely performed in currents up to 1.5 knots.

5.2. Physical outcome

The impact of severe weather on drilling depends on the choice of rig the operator has chosen for the operation. Many different rigs can be used to drill an offshore well and rig selection depends upon factors such as the type of well being drilled, water depth and environmental criteria, the type and density of the seabed, expected drilling depth, load capacity, frequency of moves, ability to operate without support and rig availability.

If weather and environmental conditions are expected to be a problem, then sophisticated all-weather semis can be used to hedge against weather downtime. The increase in availability is achieved through the higher capital cost of the equipment, which in turn is passed to the operator in

Fig. 10. Ocean observation systems as independent satellite structures. *Source*: Tampa Bay PORTS—University of South Florida.

higher dayrates. Jack-ups are cheaper but are more prone to weather delay. The choice is up to the operator: the trade-off is between drilling availability and dayrate.

The cost of deepwater drilling can represent a significant portion of the total field development costs, perhaps as much as 20–40% of total costs, and so operators pay close attention to the environment to minimize the magnitude of the risk. Because of the potentially catastrophic effect a powerful eddy can have on a drilling riser, it is common to monitor the approach of an eddy and pull the riser or circulate the stroke pipe before the eddy actually reaches the platform. In April 2003, for example, strong eddy currents and tropical storm Bill and Hurricane Claudette impacted several deepwater operations; e.g., Shell's Nakika was delayed 1 week; Total's Matterhorn TLP was delayed 6 weeks; Heerema's Balder experienced several delays in BP's Mardi Gras pipeline installation (DeLuca, 2004).

"Eddy Watch" and "Eddy Net" are monitoring systems operated by Horizon Marine (www.horizonmarine.com) that provides real-time ocean current maps. The data is gathered through 45 drifting buoys equipped with Argos GPS satellite transmitters that float in the currents and track movements. The buoy data is combined with infrared satellite imagery, altimetry and remote sensing to compile the Eddy Watch report. Eddy Net is a real-time, rig-mounted ADCP system in 1700–2600 ft water depth installed at 6 sites in the GOM (Fig. 12) with plans for 20 sites total. Operators also directly monitor currents through their own site surveys of current meters installed on boats, rigs, and platforms; e.g., Shell uses the ADAM system (ADCP Data Acquisition Manager). ChevronTexaco, BP, and Marathon use ADCP on various active production facilities and drilling rigs.

5.3. Economic outcome model

The *Joint Association Survey on Drilling Costs* estimated that the total cost of drilling in the GOM in 2000 was $4.6 billion (2000 Joint Association Survey on Drilling Costs, 2001), and over the past few years, the total annual

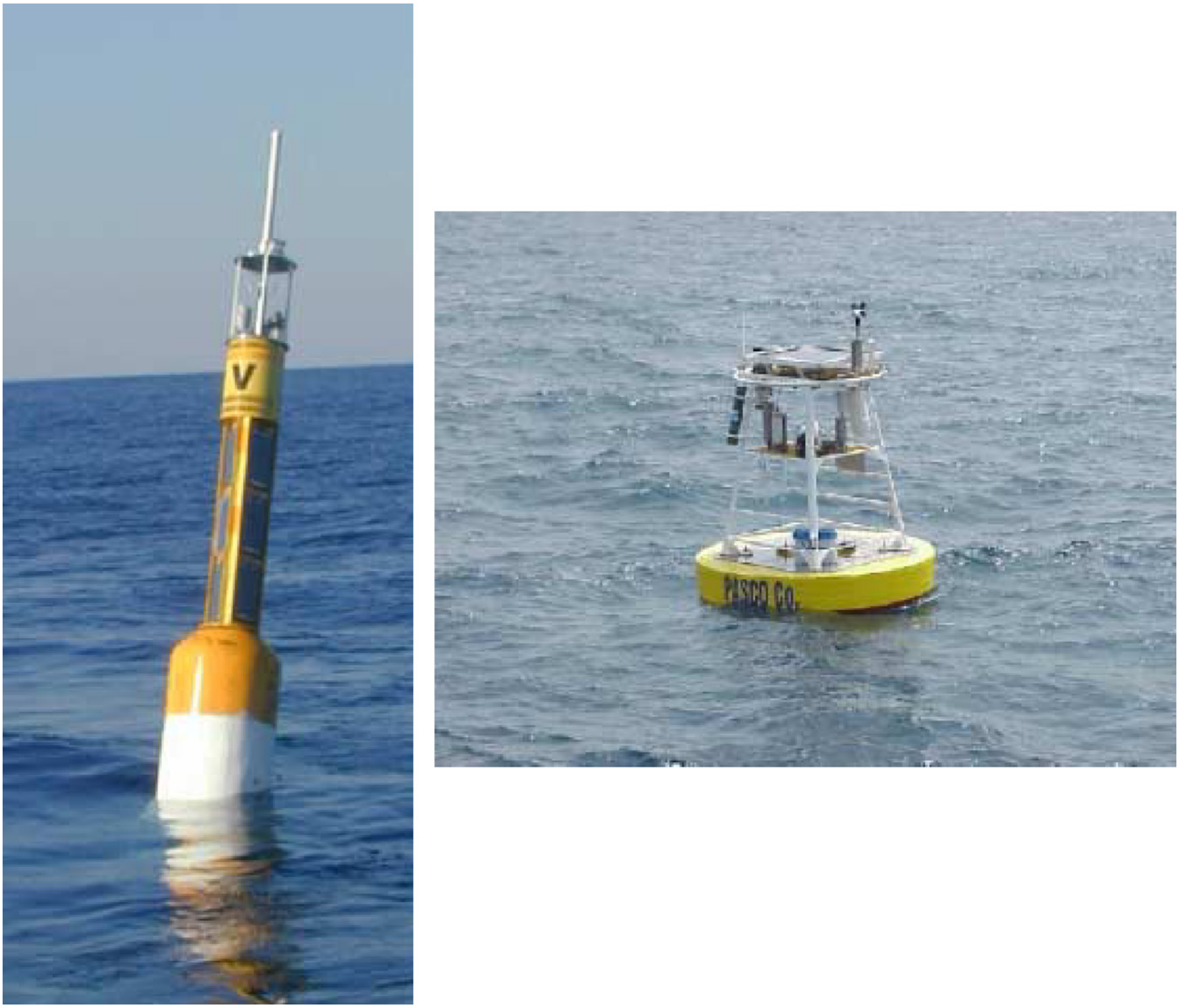

Fig. 11. Floating ocean observation systems. *Source*: TABS I Buoy (Texas A&M) and Pasco Buoy (University of South Florida).

Table 3
Limiting conditions for offshore weather-sensitive activities in the GOM

Activity	Limiting conditions
Evacuation by crew boat	WH[a] < 5 ft, daylight
Evacuation by helicopter (fixed structure)	WS[b] < 40 mph, daylight
Deepwater drilling	WS < 80 mph, WH < 8 ft, CV[c] < 2 knots
Tubular and riser deployment	WS < 80 mph, WH < 8 ft, CV < 1.5 knots
Lifting and coupling	WH < 5 ft
Evacuation by helicopter (floating structure)	WS < 50 mph, WH < 5 ft, daylight
Diving operations	CV < 0.5 knots
Boom containment	WH < 1 ft

[a]WH = Wave height.
[b]WS = Wind speed.
[c]CV = Current velocity.

offshore drilling cost ranged between $3–5 billion. If we assume 1–3% of the total drilling cost is due to waiting on weather and that improved ocean observation systems can mitigate 1% of these costs, the expected annual savings due to improved ocean observation data is estimated to lie between $300,000 and $1.5 million (M).

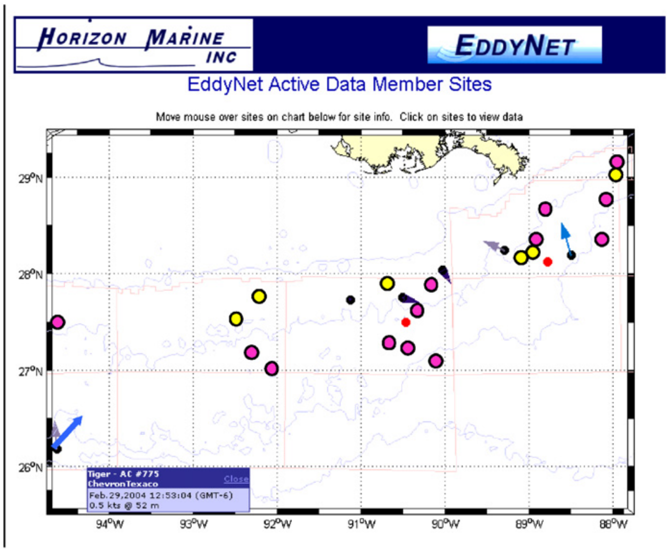

Fig. 12. EddyNet data collection sites. *Source*: Horizon Marine, Inc.

6. Development activities

6.1. Decision model

One of the primary goals in any construction project is predictability, but because of the nature and location of offshore operations, construction activities are is more uncertain and unpredictable than onshore. There are numerous independent uncontrollable variables in the offshore environment—adverse sea conditions and weather, availability and performance of equipment, defects in plans and specifications, and work conditions—that result in delay, and often, significant financial repercussions. Delay is a common risk in offshore construction and the parties of the contract apportion risks for delays that may be encountered. In the case of weather risk, construction contractors will frequently quote a lump sum (base) bid that includes weather downtime, except downtime due to named tropical storms, for work during the prime season (May 15–October 15).

There are a wide variety of construction vessels used in the GOM such as crane vessels, drill ships, dive support vessels, survey vessels, cable lay vessels, pipelay vessels, multi-purpose support vessels, dredging vessels, and trawling vessels. The vessels come in a variety of shapes and sizes, from rectangular barges to jack-ups and semisubmersibles. Contractors plan their operations using ocean/weather forecast to avoid adverse weather and operating conditions.

Offshore construction vessels differ from merchant ships because they do not trade cargo between ports and their most critical operations and loading conditions occur while working on the high seas. Construction vessels also differ from passenger ships since they are much stronger and the design standards have to satisfy a multitude of strict safety regulations.

There are guidelines for marine operations such as barge transportation, platform mating and lift-off. In barge transportation, for example, weather forecasts are normally provided at 12 h intervals and contain forecasts for the next 24 and 48 h, with the weather outlook for the coming 3-to-5 day period. Tows are designed to withstand a 10-year return period for extreme environmental conditions for the most exposed part of the route for the month or months during which the transportation takes place. For long duration tows passing through areas having different characteristic seastates, the worst seastate for the route is identified and used in the design of the cargo, grillage, and sea fastenings (Guidelines for Marine Operations. Marine Casualty Response: Salvage Engineering, 1986). In installation operations, time-sensitive equipment such as remote operated vehicles and heavy lift vessels may not be able to operate in high current.

6.2. Physical outcome

During construction activities, a moving vessel is installing (or removing) something relative to a fixed seabed, which leads to the requirement that vessel motions be minimized as much as possible to maximize the operational window. There are typically two options by which projects are installed and completed offshore: floatover, in which the unit is lowered into place from its transportation vessel; or heavy lift, in which the unit is lifted into place with large vessel-mounted cranes. The transportation and installation limitations of the construction approaches dictate the size, weight and weight distribution of the modules. The heavy-lift method of installation is able to complete installations in challenging sea-states but the use of such equipment is also more costly. Lay barges are designed to operate at different wave heights, allowing the operator to choose the barge to the sea conditions in the area. The prime risk factor is the weather, and specifically, wave heights. A barge that can operate in 6-foot wave height cost about \$250,000/day in 2004, while the cost for a 15-foot wave height lay barge cost about \$500,000/day. The application of reliable ocean forecasting in pipe laying is obvious. If pipeline installation is finished late, or delayed by unexpected ocean conditions, the direct cost of delay expressed in terms of the dayrates and the opportunity cost of nonproductive structures and wells is likely to be substantial.

6.3. Economic outcome model

Order-of-magnitude savings for construction and transportation activities in the GOM are estimated as follows. Assume three hurricane events per season and weather forecast model improvements that provides a 10% or more accurate prediction of the storm path and arrival time saving 3–5 total work days.

(1) Operator savings—construction

Assumptions

- Activity: 50 installed structures/yr, 50 removed structures/yr.

- Construction activity level at time of hurricane passage: 50% total structures.
- Number of structures in hurricane path: 50% total structures.
- Derrick barge cost: $100,000/day.

Expected savings:

(50 + 50)(0.50)(0.50)(0.10)($100,000/day)(3–5 days) = $0.75–1.25 M/yr.

(2) Operator savings—supply vessel

Assumptions

- Number of active supply vessels: 500/day.
- Number of supply vessels in hurricane path: 50% total structures.
- Supply vessel cost: $20,000/day.

Expected savings:

(500)(0.50)(0.10)($20,000/day) (3–5 days) = $1.5–2.5 M/yr.

7. Production activities

7.1. Decision model

Extreme weather events are unique and what is considered to be severe weather varies with each platform and drill site. Companies develop emergency procedures for each type of rig and manned platform they operate. Shut-down and evacuation procedures vary from company-to-company and depend upon the rig type and design, the location of the operation, and the behavior of the weather. There is no standardized shut-down or evacuation procedure, although there are many common features.

The decision to shut-down and evacuate, and the actions taken by the crew, help ensure that no employees are injured, environmental impact is minimized, damage to the operation or rig is contained, and drilling/production can be resumed as soon as possible after the event passes. The drilling superintendent and marine superintendent establish in writing specific procedures for the operation, evacuation, and securing of their particular rig or platform in adverse weather. The location and design of the rig determine the actions to be taken. Submersible, jack-up and semisubmersible rigs are usually not moved far from location. On submersible rigs, the rig is typically moved away from the wellhead to prevent damage, and on jack-up rigs, the hull is jacked up to avoid high seas. On semisubmersible rigs, the drill string hangs off in the wellhead and the anchors are slackened to reduce tension. Drill ships and drilling barges follow most of the same procedures but are moved out of the storm's path and into inland waters (Wind, Waves and Weather, 2004).

The occurrence of an extreme weather event requires operators to decide what facilities to shut-down and when personnel should be evacuated. Current GOM operating philosophy requires the evacuation of all personnel before the latest safe departure time and the shutdown of most, if not all, production activity. Shutting down production has an immediate negative economic impact on the operator, but because of the extreme risk involved, a "conservative" approach is normally taken in planning activity. Evacuation and shutdown action plans typically follow a well-defined sequence of activities:

1. Regional tropical cyclone climatology is reviewed for area of operation.
2. National Hurricane Center analysis/forecast charts are obtained, including surface, upper level, and sea state (wind/wave) charts.
3. Tropical waves, disturbances, and tropical cyclones are located and plotted.
4. The closest point of approach[3] and time to tropical cyclone is calculated.
5. Decisions on the course of action to follow on the latest safe departure time are made and executed.
6. Actions are reviewed when new meteorological analysis and forecast information becomes available.

Approximately 5–7 days before the expected arrival of the hurricane, the evacuation and shutdown action plan is initiated. Storm path, speed, and intensity forecast information from the National Hurricane Center is usually supplemented by in-house/consulting meteorologist and/or local weather service provider.[4] Team leaders, operational managers, and meteorologist meet twice a day to plan and schedule evacuation activities with primary consideration given to the latest safe departure time for personnel.[5]

Operators are responsible for the safety of all personnel on their structures, and 2–5 days prior to the arrival of the storm, all nonessential personnel are evacuated during daylight hours. Essential personnel are the last to go and are transported to shore after wells are closed and topside equipment secured 1–2 days before the storm is expected to hit. In the 1960s operators considered 3 days the minimum time window to evacuate personnel and shut-down operations, while today with better and more reliable

[3]The 1–2–3 Rule of Thumb is the most important aid in assessing "track error," the distance between the predicted position of a storm's center and its actual position. The 1–2–3 Rules of Thumb is derived from the latest 10-year average track error associated with hurricanes in the North Atlantic:

- 1—100 mile error radius for 24-h forecast
- 2—200 mile error radius for 48-h forecast
- 3—300 mile error radius for 72-h forecast

[4]The size of the private/commercial meteorological sector is estimated to employ approximately 4000 people in the GOM with $400–700 M in annual gross receipts (Outer Continental Shelf Oil and Gas Leasing Program, 2001). Most of the firms are sole proprietorships.

[5]It is possible for crews on manned platforms to bunker down and weather out most hurricanes in the GOM, but for safety and family concerns, all personnel are usually evacuated. The safety record associated with offshore production has been exceptional over the past two decades. The last major event occurred with Hurricane Juan in 1985, where several rigs and boats capsized and in total nine lives were lost offshore.

weather forecasting, 1–2 days is considered a safe window. Shut-down can be performed automatically, in fact nearly instantaneously, using automatic control systems on wells where it is deployed for manned platforms, shut-down is performed in stages according to facility requirements.

Severe weather procedures vary according to the type of rig and location relative to the storm path. Highlights of typical activities follow (Wind, Waves and Weather, 2004).

Submersible and jack-up rigs:

- On submersible rigs, the rigs move away from the wellhead a sufficient distance to prevent wellhead damage and increase ballast so that high seas will not move the rig off location.
- On jack-up rigs, the hull is jacked up to avoid high seas.
- Drill pipe in the derrick on both submersible and jack-up rigs are removed.

Semisubmersible rigs:

- Suspend drilling and hang off the drill string in the wellhead before the arrival of extreme weather.
- If waves are expected to be large and the weather extremely severe, pull the upper package and dump mud and bulk material.
- Lay down and secure the cranes, deballast the rig, and apply thrusters to relieve tension on the windward anchors.

Companies transport crews offshore in helicopters, crew boats, and workboats according to their operational guidelines. The major environmental parameters in emergency evacuation are the wind speed and wave height, and safe working conditions for many offshore operations may be approximately specified by critical values of these parameters (recall Table 3). The limiting conditions for the operation of helicopters are usually defined in terms of wind speed (typically 40–50 mph), and visual flight rules specify that the operating minimum for single-engine helicopters is a 3-mile visibility with a 500-ft ceiling. The minimum operating conditions for multiengine helicopters is a 2-mile visibility with a 300-ft ceiling. Wave height must fall below a given threshold (typically 5–8 ft) to ensure safe transfer operations with the crew or workboat. Evacuations are performed in the daytime and the method of evacuation depends on the sea state, distance to shore, climatic conditions, and availability of transportation equipment. Thunderstorm activity will restrict helicopter usage. The number of personnel involved in an evacuation depends on the type of structure: a small drilling rig may have a crew less than 10 while a large production platform could have over 100. There are currently about 810 manned platforms and about 25,000 personnel working offshore on any given day in the GOM.

Some of the large operators in the GOM own a fleet of helicopters and will maintain annual contracts with service boats moored at various offshore production sites. Smaller operators reserve space on crew boats and helicopters[6] subject to availability. There is usually sufficient capacity to ensure crews are transported in a safe and timely manner. For the planners and managers of evacuation activities, however, work conditions remain stressful and difficult when hurricanes threaten until all personnel arrive safely on-shore.

7.2. Physical outcome

Immediately following a storm, the Minerals Management Service (MMS) will issue a Notice to Lessees requiring operators to conduct a Level X ($X = \text{I, II, III}$) survey for a Y-mile corridor around the storm path. The values of X and Y depend upon the severity of the storm and the reports of damage by operators. The complexity of the inspection increases with the level specified (Level I surveys are a visual inspection from the topside while a Level III survey involves diver inspection) and distance between the structure and the eye (center) of the storm.

Recovery operations follow a standardized sequence of activities:

1. Inspection. Assess the damage.
2. Clean-up. Remove debris and make the platform habitable.
3. Repair. Repair structural damage and replace equipment.
4. Start-up. Resume operations.

Each hurricane is unique, and the response of structures, pipelines, and drilling rigs in the path of the storm is also unique. Damage can occur in many forms and failures are often due to a combination of conditions. Examples of major damage include bent structural supports such as braces and jacket legs, collapsed rig derricks, damaged production vessels and piping, overturned helidecks and collapsed living quarters. The integrity of the structure does not have to be compriseded for the MMS to consider the damage major. Less significant damage typically include shifted equipment or water damage.

Platform damage can be grouped into two broad categories:

- Failure of primary structural components, such as main braces, jacket legs, deck legs, and piles.
- Displacement of deck equipment, such as drilling rigs, production equipment, and quarters modules.

[6]Typical dayrates for a 34 ft crew boat is $600–800/day, while for a 190 ft crew boat, $2000–4000/day. Typical helicopter rates are $1000–1500/h. A crew boat can transport up to 90–130 people; a helicopter up to 25 depending on its size. Unscheduled, weather-related evacuations have been estimated to add approximately $10,000 per production facility and $50,000 per drilling rig over and above normal transportation cost (Epps, 1997).

Engineers attempt to determine the cause of failure of each incident, but responses are complicated by the fact that the individual impacts must be recreated from imperfect (usually, unobservable) information such as wind speed and wave height at each location:

- Wave inundation of the deck[7] is usually the primary cause of damage to structure integrity, because waves on deck significantly increases the horizontal load and overturning moment of the structure.
- Displacement of deck equipment and collapsed rigs may be due to a combination of wind and wave inundation and poor maintenance. For older structures, if cathodic protection systems are not maintained, cracks in joints will make the structure more susceptible to fatigue failure.

Pipeline damage is grouped into two categories:

- Physical impact, such as the failure of the host facility or an anchor drag.
- Storm-induced loading, such as bottom current loading or foundation failure. Structures and pipelines located near the mouth of the Mississippi River are susceptible to seafloor failures because of soil instability.

Rig damage is complicated by the fact that if moorings fail, then semisubmersible drilling units will break free and drift throughout the Gulf possibly in high-density infrastructure regions. Over the past 15 years, mooring failures have occurred during Andrew (1992, two rigs), Lili (2002, one rig), Ivan (2004, five rigs), Katrina (2005, five rigs), and Rita (2005, four rigs). Mooring designs are currently a top concern among engineers and regulators since no one wants semis floating around during a storm or at the bottom of the sea (Abraham, 2005).

Starting up production and re-pressurizing wells after shutdown can be problematic and may take anywhere from a few days to several weeks, depending upon inspection requirements and equipment availability. Engineers inspect pipes, pumps, and process facilities before the wells are reopened. Wells that have been shut off can suffer from temporary shifts in the underground pressure, reducing initial output for weeks or months. In other fields, shutting down can help rebuild pressure and enhance production rates.

The success of start-up operations depend in large measure on the damage caused by the storm, the characteristics of the geologic formation, and the complexity of the wellbores. Since most GOM crude oil is light and in primary production, start up activities are mostly performed without consequence, and assuming no storm damage, fixed structures may come back on-line within 48–72 h of evacuation. Individual wells may be off production for several weeks or even months. For severe storms like Katrina and Rita, production may be offline for many months and structures permanently abandoned. Floating production systems, which operate in the deep waters of the GOM where hydrates[8] may form, may take up to 1 week to resume production if no damage was incurred.

7.3. Economic outcome model

A company will typically include anywhere from 3 to 5 days of weather-related production losses each year in their business plans to account for the uncertainty of weather. Operators incur the cost associated with deferred production, evacuation cost, damage assessment, and facility repair, if any, prior to the resumption of production. Most of these costs, with the exception of deferred production and human life consequences, cannot be mitigated or reduced, since offshore production facilities cannot be moved out of the path of the storm or otherwise avoid the storm's impact.

Operators design their structures to satisfy API RP 2A guidelines (API RP 2A, 2000) and federal regulations, and the MMS will generally accept the risk of losing a structure where there is no threat to life or the environment. Owners may be willing to accept the risk on less important structures (such as caissons and well protectors), but monetary considerations usually dictate increased capacity for structures with a high production rate, facilities which serve as a transportation or processing hub, and deepwater structures. From an economic perspective, for a given probability of an extreme weather event, the investment required to avoid damage must exceed some fraction of the cost to repair the damage. A trade-off thus exists which attempts to balance the potential costs of damage and disruption due to a catastrophic weather event against the benefits of a more robust (but expensive) design.

If production facilities are severely damaged or destroyed and there is a sufficient amount of reserves remaining in the field, then an economic assessment will determine if wells will be re-drilled and a new facility installed. The evaluation decision is usually straightforward since both reserves and cost are known with a reasonably high degree of certainty.

The direct cost involved with a hurricane event includes shut-down cost, C_1; evacuation cost, C_2; downtime cost, C_3; damage assessment cost, C_4; repair and replacement cost, C_5; and start-up cost, C_6. Improved ocean observation systems are expected to allow some of these costs to be reduced, delayed, or possibly avoided—in particular C_2 and C_3—although it is clear that no observation system can mitigate the damage of the event unless boats and drilling

[7]The maximum lateral force of a wave is concentrated at its crest, so the lowest deck of a platform is designed to sit above the wave crest elevation for 1-in-100 year waves.

[8]Hydrates are ice-like particles which block production tubing and pipeline. Most deepwater developments use insulation to preserve production thermal energy, which is critical during emergency shut-ins when no operational hydrate prevention measures are possible.

vessels are moved out of the track of the storm that otherwise would not have been moved because of the improved information. Shut-down and start-up cost (C_1, C_6), damage assessment (C_4), and facility repair (C_5) depend on the track and strength of the storm and the amount of damage inflicted and are not influenced by improved ocean observation systems except in the development design stage.[9]

Hurricane motion is controlled by the state of the surrounding atmosphere, and forecasts based upon more accurate and timely measurements of that state are themselves more accurate. If the forecast associated with a hurricane event can be improved, then production can stay on-line a greater period of time without sacrificing safety or environmental considerations, and in the best case, perhaps not shut-down at all. Order-of magnitude estimates for evacuation and lost production savings are provided as follows.

(1) Operator savings—evacuation
Assumptions
- Manned platforms in hurricane path: 750
- Rigs in hurricane path: 100
- Evacuation cost: $10,000/platform, $50,000/rig
- Weather forecasting model improvement: 10–20% more accurate prediction on hurricane path/zone to avoid evacuation

Expected savings:
(750)(0.10–0.20)($10,000/platform) +
(100)(0.10–0.20)($50,000/rig) = $1.25–2.5 M/yr

(2) Operator savings—lost production
Assumptions
- Number of hurricanes per season: 3
- One-half of GOM production shut-in per event: 1.5 MMBOE/day
- Net income margin per BOE: $5/BOE
- Weather forecasting model improvement: 0.5–1 day continued production

Expected savings:
(3)(1.5 MMBOE/day)($5/BOE)(0.5–1)
= $11.3−22.5 M/yr.

8. Oil spill management and response

8.1. Decision model

The risk of oil spills arise from activities associated with the exploration, development, production, and transportation of offshore oil and gas resources, as well as from the transport of oil across the ocean to port facilities (National Research Council, 1998, 2002). During the 1970s and early 1980s, most of the crude oil and products moved by water was associated with inland barges or coastwise movement between US production/processing and consumption regions. By the mid-1980s, waterborne commerce of foreign imports of crude oil and petroleum production exceeded coastwise transportation, and today, is dominated by foreign imports. The US currently imports 60% of its crude oil consumption.

Oil spills in coastal waters are especially damaging and clean-up can be very expensive. The Oil Pollution Act of 1990 (Ketkar, 2002) requires that response activities deal with the legal constraints and interest of various political entities as it attempts to minimize ecological damage. Better knowledge of wind and water currents will assist in the management and clean-up of oil spills.

Four factors generally influence oil spill response: the type of oil (e.g., heavy crude, distillate fuel, etc.); the amount of oil spilled; the spill conditions, which are described by sea temperature, ocean current, wind and weather conditions; and proximity to ecologically sensitive areas. Once notice has been received that a spill has occurred all of these factors are assessed to determine the spill response.

Information to support operational decisions is provided through a variety of sources. Typically, decision-making is aimed at supporting a "minimum regret" as opposed to a "maximum win" strategy (Martin et al., 1997). In a "maximum win" strategy, the best estimates of wind, currents, and the initial distribution of the pollutant is collected and the resulting forecast taken as the threat. A "minimum regret" strategy uses whatever analysis techniques are available as input data. The situation unit presents the command with not only the "best guess" of where the oil will go but also with alternate possibilities that might present a significant threat. Reliable near-time data on the wind and wave conditions is essential for good decision-making in all cases.

8.2. Physical outcome

Oil spill response is site specific and occurs within a complex, dynamic, and uncertain environment. The environmental effects of oil spills vary widely depending on factors such as the amount and type of oil spilled, weather conditions, the location of the spill relative to natural resources, the quality and sensitivity of effected resources, seasonal factors, and the thoroughness and speed of cleanup and restoration efforts (Fig. 13).

Clean up operations employ one or more methods, such as mechanical systems, chemical dispersants, burning and bioremediation, depending on prevailing spill conditions. Timing is critical to effective clean up. Floating oil spreads

[9]Design criteria for offshore structures have evolved over many years to ensure their survivability. The optimal design of an offshore facility, especially floating production facilities, requires knowledge of the response of the structure to environmental loading, which in turn, is dependent on the acquisition of reliable data on current profile and wave height. In design, it is important to assess seasonal and inter-annual variability in dynamic conditions, but it is seldom possible or cost-effective to undertake multiple-year site-specific measurement programs in support of field development.

Fig. 13. Oil spill response strategies.

Table 4
Estimated unit cost elements per barrel spilled and reaching shore

OCS planning area	Control[a] ($)	Cleanup ($)	Property lost ($)	Recreation and tourism ($)	Wildlife and ecological[a] ($)
Straits of Florida	(64, 99)	(565, 872)	272	(133, 448)[b]	30[b]
Eastern GOM	(66, 103)	(546, 843)	46	(90, 320)	154
Central GOM	(55, 85)	(650, 1002)	46	(52, 190)	154
Western GOM	(58, 90)	(249, 385)	46	(143, 514)	116
Average	(61, 94)	(503, 776)	103	(107, 368)	114

Source: MMS.
[a]Per barrel spilled.
[b]Mid-Atlantic region.

rapidly, and a slow response may allow oil to spread over a large area so that boom is not effective in containment. Floating oil also emulsifies as it mixes with water lending treatment with dispersants ineffective after a given time window has passed.

8.3. Economic outcome model

There are many social costs associated with an oil spill. Many costs can be measured as direct economic cost, such as the cost of clean up, while indirect cost such as damage or harm to wildlife cannot be measured in a market transaction. Indirect social costs are typically valued using ''willingness-to-pay'' techniques or an assessment of the loss in consumer surplus. The estimated unit cost of a barrel of oil spilled or reaching shore across the OCS planning areas is summarized in Table 4 (Estimating the Environmental Cost of OCS Oil and Gas Development and Marine Oil Spills, 1991). The total estimated cost for control, cleanup, property lost, recreation and tourism, and wildlife for the GOM region is assumed to range between $888 and 1445 per barrel of oil spilled.

Table 5
Number and volume of spills for the 8th Coast Guard district

Year	Number of spills	Volume of spills (1000 barrels)
1990	3205	117
1991	3572	14
1992	3616	23
1993	3477	15
1994	3465	26
1995	3363	36
1996	4678	19
1997	4699	15
1998	4224	11
1999	3836	18
2000	4177	21
Average (1973–2000)	3132	74

Source: US Coast Guard.

The average volume of spills from 1973 to 2000 in the US Coast Guard District 8 (Texas, Louisiana, Mississippi, Alabama, Florida panhandle) was 74,000 bbl (Table 5). Roughly one half of the 74,000 bbl spilled came from tank vessels and 60% of the volume involved crude or heavy oil. Eleven percent of the total volume of oil spill occurred in the open ocean (12–200 miles) which would not normally realize a significant improved response with enhanced ocean forecasting, and thus, the cost savings is reduced proportionally by this amount.

The impact of a 1% improvement in oil spill response is estimated to result in the following cost savings:

(74,000 bbl/yr)\$(888/bbl–1445/bbl)(0.89)(0.01) = \$0.58–0.95 M/yr.

9. Conclusion

The importance of the GOM to domestic oil and gas production will grow in the future. The GOM currently accounts for 27% of US oil production and 17% gas production, and these numbers are expected to rise as oil production approaches 2.3 MMbbl and natural gas 13.24 Bcf per day by 2011 (Melancon et al., 2004). Any supply disruption in the GOM, especially under tight market conditions, can be expected to have a significant impact on US energy markets.

Hurricanes pose a growing threat to GOM production as larger, more complex, deepwater platforms produce the majority of hydrocarbons in the region (Baud et al., 2002). Since a greater amount of GOM production is being produced from a smaller number of structures, GOM production is increasingly susceptible to volatility due to extreme weather events. Hurricane frequency and intensity tend to follow 20-to-30 year cycles, and within that rhythm, scientists are forecasting an increased level of activity over the next decade.

Technological advancements in exploration and production over the past half century have been remarkable, but no matter how ingenious, operators still cannot overcome extreme weather events. Over the past 2 years, the vulnerability of offshore production in the GOM has been brought to light by extensive damage to oil and gas facilities and pipelines.

Table 6
Summary of potential benefits of improved ocean observation systems to energy development activities and oil spill response management in the GOM

Application	Nature of benefit	Annual potential benefits (\$M)
Drilling activity	Improved operations	(0.3, 1.5)
Construction activity	Improved operations	(0.8, 1.3)
Supply vessels	Improved operations	(1.5, 2.5)
Evacuation	Improved operations	(1.3, 2.5)
Lost production	Reduced production	(11.3, 22.5)
Oil spill response	Improved response	(0.6, 1.0)
Total		(15.8, 31.3)

For effective planning and decision-making, reliable forecasts of weather and ocean current conditions are required. Weather information is valuable, and to the extent that improved ocean observation systems can improve the data on which weather/ocean forecasts is based, is potentially very beneficial for operational decisions and pollution management. Primary applications of ocean observation data are to provide nowcasts/forecasts of weather, wind speed, surface wave, current, and general circulation patterns. Order of magnitude benefits derived from ocean observation systems to energy related activities in the GOM are conservatively estimated to range between \$15.8 and 31.3 million (Table 6). The total benefits derived are expected to be a positive multiple of this factor.

Acknowledgment

The authors would like to acknowledge helpful discussions held with the following personnel: Ken Schaudt, Marathon; Norman Guinasso, Jr., Texas A&M University; Robert Martin, Texas General Land Office; Patrick Michaud, Conrad Blucher Institute for Surveying and Science; Mark Luther, University of South Florida; Greg Stone, Louisiana State University; Cort Cooper, Paul Versowsky, Max Regan, Sandy Furr, ChevronTexaco; David Epps, BP, Allan Alrady, J. Ray McDermott; Charlie Colgan, University of Maine; Hauke Kite-Powell, Woods Hole Oceanographic Institution.

This paper was prepared on behalf of the National Oceanographic Partnership Program, Office of Naval Research. The opinions, findings, conclusions, or recommendations in this paper are those of the authors, and do not necessarily reflect the views of the Office of Naval Research. Funding for this research was provided in part through the Office of Naval Research.

References

Abraham, K.S., 2005. Battering of U.S. GOM structures brings discussion of standards. World Oil 226 (11), 51–60.

Adams, R., Brown, M., Colgan, C., Flemming, N., Kite-Powell, H., McCarl, B., Mjelde, J., Solow, A., Teisberg, T., Weiher, R., 2000. The Economics of Sustained Ocean Observation: Benefits and Rationale for Public Funding. National Ocean and Atmospheric Administration and Office of Naval Research, Washington, DC.

API RP 2A, 2000. Planning, Design, and Constructing Fixed Offshore Platforms. American Petroleum Institute, Dallas, TX (1969, 1st ed.; 2000, 21st ed.).

Barrilleaux, M., Deegan, J., Waligura, J., Walker, G., 2001. Dynamically Positioned Completion Operations Risk Analysis. OTC 12953, Houston, TX, pp. 151–159.

Baud, R.D., Peterson, R.H., Doyle, C., Richardson, E., 2002. Deepwater Gulf of Mexico: America's emerging frontier. OCS Report MMS 2002-022, US Department of the Interior, Minerals Management Service, Gulf of Mexico Region, New Orleans, 2002.

Blaha, T., et al., 2000. Gulf of Mexico ocean monitoring system. Oceanography 13 (2), 10–17.

Blake, E.S., Rappaport, E.N., Jarrell, J.D., Landsea, C.W., 2005. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2004. Tropical Prediction Center, National Hurricane Center, Miami, FL.

Cole, R., Weisberg, R., Donovan, J., Merz, C., Russell, R., Subrmanian, V., Luther, M., 2003. The evolution of a coastal monitoring system. Sea Technology, 24–31 (February).

Corona, E.N., Lynch, R.D., Riffle, D., Cardone, V.J., Cox, A.T., 1996. Typhoon emergency response and planning for the South China Sea. OTC 8117, Offshore Technology Conference, Houston, TX, pp. 855–868.

Daniels, G.R., 1994. Hurricane Andrew's impact on natural gas and oil facilities on the Outer Continental Shelf. OCS Report MMS 94-0031, US Department of the Interior, Minerals Management Service, Engineering and Technology Division.

DeLuca, M., 2004. Current affairs. Offshore Engineer 29 (2), 20–22 (February).

Dwyer, M.G., Campo, J.J., Kesler, K.K., 2005. Ivan the terrible. Offshore, 50–54 (February).

Energy Information Administration, 2005. Hurricane Katrina's impact on the U.S. oil and natural gas market. Daily Reports.

Epps, D.S., 1997. Weather impacts on energy activities in the U.S. Gulf Coast. In: Proceedings of the Workshop on the Social and Economic Impacts of Weather, April 2–4, Boulder, CO.

Estimating the Environmental Cost of OCS Oil and Gas Development and Marine Oil Spills, 1991. A General Purpose Model. Vol. I—Economic Analysis of Environmental Cost. US Department of the Interior, Minerals Management Service, OCS Study MMS 91-043.

Guidelines for Marine Operations: Marine Casualty Response: Salvage Engineering, 1986. London Offshore Consultants Limited, Oilfield Publications, Inc., Houston, TX.

Jenkins, P.B., 1975. Drilling costs. SPE 5266, Paper Presented SPE-European Spring Meeting, April 14–15, London, UK.

2000 Joint Association Survey on Drilling Costs, 2001. American Petroleum Institute, Washington, DC.

Kelly, F.J., Guinasso Jr., N.L., Lee III, L.L., Chapline, G.F., Magnell, B.A., Martin Jr., R.D., 1998. Texas Automated Buoy System (TABS): a public resource. In: Proceedings of the Oceanology International 1998 Exhibition and Conference, vol. 1, Brighton, UK, pp. 103–112.

Ketkar, K.W., 2002. The oil pollution act of 1990: a decade later. Spill Science and Technology Bulletin 7 (2), 45–52.

Kite-Powell, H.L.H., Colgan, C., 2001. Potential Economic Benefits of Coastal Ocean Observing Systems: The Gulf of Maine. National Ocean and Atmospheric Administration and Office of Naval Research, and Woods Hole Oceanographic Institution, Washington, DC.

Lyle, D., 2005. Experience blunts Katrina's wrath. E&P 78 (10), 17–19.

Martin, R.A., Kelly, F.J., Lee III, L.L., Guinasso Jr., N.L., 1997. Texas Automated Buoy System (TABS): real-time currents for oil spill response. In: Proceedings of the 1997 International Oil Spill Conference, April 7–10, 1997, Fort Lauderdale, FL.

Melancon, J.M., Bongiovanni, R., Baud, R.D., 2004. Gulf of Mexico oil and gas production forecast: 2004–2013. OCS Report MMS 2004-065, US Department of the Interior, Minerals Management Service, New Orleans.

Michaud, P.R., Thurlow, C., Jeffress, G.A., 1994. Collection and dissemination of marine information from the Texas Coastal Ocean Observation Network. In: US Hydrographic Conference Proceedings, Hydrographic Society Special Publication No. 32, Norfolk, Virginia, 1994, pp. 168–173.

National Oceanographic Partnership Program (NOPP), Ocean Research Advisory Panel (ORAP), 1999. An Integrated Ocean Observing System: A Strategy for Implementing the First Steps of a U.S. Plan. Washington, DC.

National Oceanographic Partnership Program (NOPP), 1999. Toward a U.S. plan for an integrated, sustained ocean observing system. A report prepared on behalf of the National Ocean Research Leadership Council, Washington, DC.

National Research Council, 1998. Oil Spill Risks from Tanks Vessel Lightering. National Academy Press, Washington, DC.

National Research Council, 2002. Oil in the Sea III: Inputs, Fates, Effects, Ocean Studies Board and Marine Board. National Academy Press, Washington, DC.

Ocean US, 2002. An Integrated and Sustained Ocean Observation System (IOOS) for the United States: Design and Implementation. Arlington, VA.

Outer Continental Shelf Oil and Gas Leasing Program, 2001. Draft Environmental Impact Statement, vol. 1. October 2001, U.S. Department of the Interior, Minerals Management Service, OCS EIS/EA, MMS 2001-79.

Paganie, D., Buschee, P., 2005. Operators begin cleanup, repair from Katrina, Rita. Offshore 65 (10), 24–35.

Report of the US Commission on Ocean Policy, 2004. Washington, DC. Available at http://www.oceancommission.gov.

Rowe, S.J., Grittner, S., Walters, G., Shilling, R., Brendling, W.J., 2001. Using risk-based simulation models to assist in planning deepwater exploration and production programs, west of Shetland and in the Gulf of Mexico. In: Proceedings of the 2000 Offshore Technology Conference, Paper #12952, Houston, TX.

Szabo, D., Stephans, R., Smith, R., 2003. Subsea current analysis evolves. Hart's E&P 78 (12), 36–37.

Vincent, M., Burwell, D., Luther, M., Galperin, B., 2000. Real-time data acquisition and modeling in Tampa Bay. In: Spaulding, M., Blumberg, A. (Eds.), Estuarine and Coastal Modeling. ASCE, Reston, VA, pp. 427–440.

Wind, Waves, and Weather, 2004. RDS Unit V, 4th ed. Petex Publications, Houston, TX.

Wright, B., 2004. Ivan the terrible wreaks havoc. Upstream, 8–10.