PAPER

DeepStar Metocean Studies: 15 years of Discovery

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ABSTRACT

In 1998, DeepStar began the first of many successful studies that have resolved important questions concerning meteorological and oceanographic (metocean) processes that can cause large loads or fatigue problems on deepwater facilities. In so doing, these studies have immeasurably enhanced the reliability and safety of deepwater structures and pushed the frontiers of ocean science that have traditionally been the realm of academic research. The efforts have focused on three major phenomena: the Loop Current, Topographic Rossby Waves (TRW), and storm winds. Much of the DeepStar effort has focused on improving numerical models of the respective phenomena because they can provide long historical databases at any site—data that serve as the basis for operating and extreme criteria with reasonable statistical uncertainty. Studies of the Loop include the first measurements of the Loop inflow and turbulence and evaluation of existing numerical models. Most of DeepStar's efforts on TRWs started in 2008, and in a 5-year period, it has developed a validated numerical model and used it to build a 50-year hindcast database. Efforts are underway to use those results to build a stochastic forecast model. Finally, DeepStar has analyzed a large set of wind measurements taken from the powerful recent hurricanes and found that recommended formulas for wind profiles and spectra have significant bias and will be corrected in future recommended practices.

Introduction

Almost all aspects of offshore facilities are affected by winds, waves, and currents, including operations and capital costs. Indeed, in many deeper water locations, the choice of the basic facility is heavily influenced by the meteorological and oceanographic (metocean) conditions, second only to the reservoir characteristics and water depth.

Many mysteries remain concerning metocean variables, especially deep water currents and hurricane-driven winds and waves. Nowhere is this truer than in the Gulf of Mexico, where strong ocean currents can be generated by several different processes that can vary dramatically in magnitude over space scales of a few kilometers. Several of these processes were first discovered only recently, and their quantification has been led by Joint Industry Projects (JIP) like DeepStar, rather than the traditional university oceanographers. Hurricanes have also been an area of active industry research because they dominate the loads on most production facilities in deep water. Despite their importance, major uncertainty remains concerning winds and waves, in part because few measurements have been made in strong hurricanes.

As a result of these myriad uncertainties and the importance of metocean criteria on safety and reliability, DeepStar IV began significant funding of metocean studies in 1998 and has continued this investment since then. The following sections outline the major studies in more detail. Each section is focused on a particular phenomenon, e.g., Topographic Rossby Waves (TRWs), so it frequently will cover several studies. Each section describes the study goals, business drivers, and methods and summarizes the results.

Loop Current

The Loop Current is a strong permanent current that flows through the Yucatan Straits, loops northward, and then exits through the Florida Straits where it is renamed as the Gulf Stream. About once per year, the Loop moves northward of 27°N, becomes unstable, and forms a large eddy that breaks away and drifts to the west. The Loop (which will henceforth be taken to mean the Loop proper and its associated large anticyclonic eddies) can occasionally affect shelf waters but is typically found in water depths greater than 500 m. Radial speeds within the Loop can exceed 2 m/s and generate the drag equivalent of a hurricane wave on mooring lines or generate vortex-induced vibrations that can lead to fatigue failure of risers. These effects influence the design of drilling and production risers, mooring tensions on production and drilling rigs, connection/disconnection of drilling risers, and installation of pipelines, mooring lines, tendons and hulls. Although no firm accounting has ever been done, we estimate that the Loop costs the industry on the order of $10 million/year in rig delays.

The Loop was not discovered until the late 1960s, and the first current measurements did not occur until the early 1980s. Given the importance of the Loop and its relatively recent discovery, it is not surprising that there were many important unknowns that needed to be resolved as the industry moved into deeper water.

In 1998, DeepStar initiated its first oceanographic project by measuring the incoming source of the Loop Current—in other words, the water inflow through the Yucatan Strait. Oceanographers had long wanted to take these fundamental measurements but had been frustrated by the cost and the politics of deploying instruments in the eastern half of the Straits controlled by Cuba. Not to be deterred, DeepStar contracted CICESE, an oceanographic research institution in Mexico that had a cooperative research agreement with Cuban oceanographers. CICESE deployed eight moorings across the Yucatan Straits with 33 single-point current meters and eight acoustic Doppler current profilers (ADCPs). In addition, they conducted four ship surveys across the Strait during the 18 months that the moorings were in place. Results were documented in Abascal et al. (2003). The major benefit of the study was to provide the first careful measurement of the inflow boundary condition for numerical models of the Loop. Such models are an important tool for developing design and operating conditions and, perhaps most importantly, for forecasting.

After the Yucatan Straits measurements, DeepStar quickly turned to answering another key question about the Loop Current: How turbulent is it? At the time, designers were worried about the ability of turbulence to excite higher modes in the tendons of Tension Leg Platforms (TLPs) and spars. Current speed fluctuations can affect these structures both by direct forcing and by reducing the effectiveness of VIV suppressing strakes. These effects have often been seen in model basins where the turbulence intensity is 10-20% of the mean velocity. Oceanic turbulence levels were thought to be much lower, but there was essentially no field data to prove that assumption. DeepStar filled the gap by funding measurements in a Loop Current eddy using a unique instrumentation system. The results are described by Mitchell et al. (2007).

Measurements were made within the eddy and across the strong frontal boundary that separates the eddy from the surrounding waters. A towed vehicle, the TOMI (Towed Ocean Microstructure Instrument), was equipped with a special 300-kHz ADCP that had its four beams directed fore, port, starboard, and down. The along-beam velocities resolved structures with wavelengths of 4-60 m. The vehicle also carried shear probes for measuring velocity fluctuations in the dissipation range (0.5-100 cycles per meter) and other environmental sensors for measuring temperature, salinity, depth, and vehicle orientation. The towed body is shown in Figure 1.

FIGURE 1

The TOMI instrument that was used to measure turbulence. The ADCP transducers are mounted on the bottom mast (forward looking), at the base of the (orange) upper mast (port and starboard looking), and behind the lower mast on the main body (downwards looking).

Tows were conducted at 25-, 50-, 100-, and 150-m depths around the northern edge of the Loop Eddy in currents of up to 1.7 m/s. Turbulence was detected with the shear probes, but mostly in the 130–150 m depth range around the local salinity maxima. The level of turbulence was weak, and it was distributed intermittently in both space and time. The most energetic events of turbulence had eddy scales of at most 4 m and velocity scales of only 1 cm/s. The typical and average values were more than 10 times smaller.

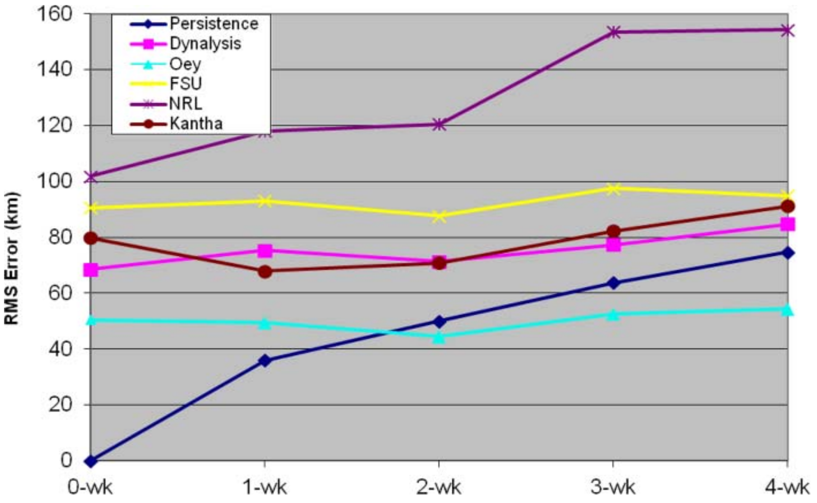
After taking some basic physical measurements in the Loop Current, DeepStar's next effort was to understand the accuracy of available models. While many models were available at the time, none had been rigorously validated. To fill this gap, DeepStar initiated a study in 2004 to compare five existing forecast models. The modelers were asked to run a 1-year historical period for which DeepStar had a proprietary, detailed set of measurements never before seen by the modelers. Models were spun up by assimilating publicly available measurements such as satellite altimetry. On the first day of each month, the models were run for 4 weeks without any data assimilation. Model performance was judged by comparing the forecasted to the observed distance of the nearest major Loop or eddy front to seven sites scattered over much of the deep Gulf east of 94°W. Model results were compared to persistence (the major fronts were assumed to remain stationary) for the entire month. Figure 2 compares the RMS (root mean square) error accumulated for the 12 runs at all seven sites. Only one of the models was found to beat persistence after about 12 days, but not by much. Perhaps most striking was the substantial error exhibited by all the models right from the start (0 week). This strongly suggests that the satellite imagery used to spin up the models was far from perfect, probably because it failed to resolve the meanders and frontal lobes commonly found on the Loop and its eddies. While these features may have relatively short length scales (order 50 km), they can significantly affect the error metrics. The fact that the models did poorly even in a nowcast mode suggested they may have had substantial errors even in a hindcast mode.

The overall conclusion of the Phase 1 study was that the models were too inaccurate in forecast mode to be of much value to Industry operations, but that further work was justified given the substantial benefits that could be had from an accurate forecast.

Towards the end of the first model intercomparison study, a new model appeared on the scene that was quite different to the others tested in Phase 1. AEF's model was a so-called "feature" model, which utilized proprietary drifting buoys as well as satellite imagery to spin-up the model. Given the promise of this new approach, DeepStar decided to fund a Phase 2 study using the AEF model and the Oey model, winner of the Phase 1 study. Figure 3 compares the error from the two models with that of persistence. The AEF model consistently beat the Oey model and overtook persistence at about 1 week. Its forecast error stayed flat until the end of the second week and then slowly climbed until it was double the initial error after 4 weeks where it remained steady until nearly 7 weeks. Overall, the conclusion was that the AEF model could provide forecasts with useful accuracy, but its success depended on having access to detailed *in situ* measurements from drifting buoys or other similar sources. Such measurements cost upwards of $50,000/mo.

FIGURE 2

Comparison of forecast error from five Loop models with persistence.



TRWs

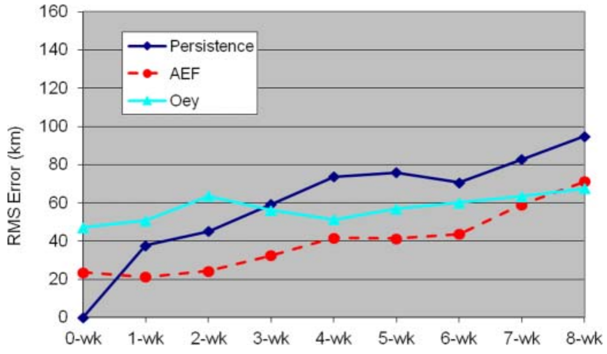
In the late 1990s, British Petroleum (BP) measured currents reaching about 1 m/s near the seafloor in about 2,000 m of water along an underwater feature known as the Sigsbee Escarpment. While the currents were most intense near the bottom, they remained substantial for hundreds of meters above the seafloor, finally reaching ambient conditions at about 1,000 m. The Bureau of Ocean Energy Management (BOEM; formally known as Minerals Management Service) deployed three current meters nearby for 18 months and observed similarly large currents. Figure 4 shows the time series of these currents. Subsequent analysis of the BOEM measurements by Hamilton and Lugo-Fernandez (2001) suggested that the currents were driven by Topographic Rossby waves (TRW), a 200-km-long wave with periods of 10-14 days.

TRWs can generate current speeds at the bottom near the Escarpment that far exceed those generated by any other phenomena. Such currents dominate the metocean extreme and fatigue loads on pipelines and risers, especially flexible risers (steel catenary risers or SCRs).

DeepStar began its study of TRWs in 2003 by taking measurements of the cross-Escarpment variation of the waves, a characteristic that had not been studied before. Eight current meters were placed near the seafloor across the Escarpment at 91°08′W,

FIGURE 3

Comparison of forecast error from two Loop models with persistence.

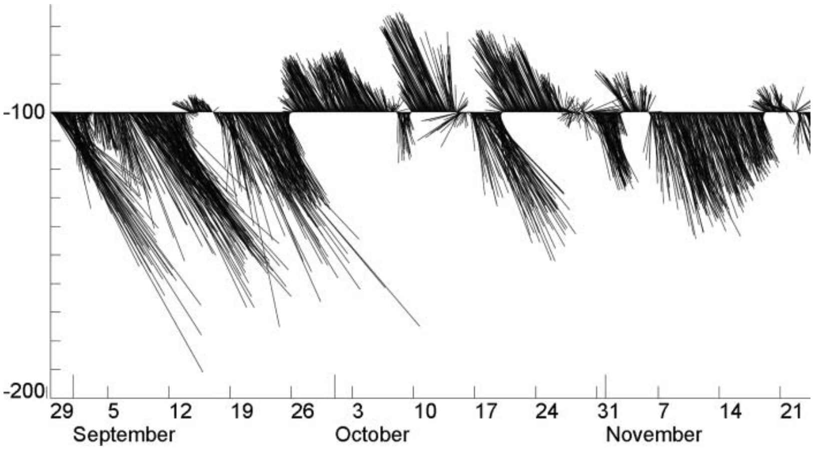


as depicted in Figure 5. BOEM had a through-column mooring, L4, deployed just to the south of the DeepStar array. Over the 1-year deployment, about a half-dozen TRWs were measured and showed the strongest currents occurred near the base of the Escarpment at S2 and S3. Only about 10 km north at S6 speeds dropped off rapidly to less than half those observed at S2. In contrast, the reduction on the down-dip side of the Escarpment was much smaller, e.g., L4 was about 30% less than S2.

In 2008, DeepStar restarted its efforts on TRWs because of increased exploration activity along the Escarpment and reports from drilling rigs that were adversely affected by strong bottom currents. That year, two projects were started. The first involved taking more current measurements, but this time with moorings spread along the Escarpment as well as across. Figure 6 shows the four DeepStar moorings as well as other moorings deployed by Chevron and Shell, which overlap in time and were later obtained by DeepStar. The 1 year of measurements showed strong variation along the Escarpment and confirmed the strong cross-escarpment variation first observed in the 2003 DeepStar measurements.

FIGURE 4

Time series of near-bottom current vectors measured near the Sigsbee Escarpment. The vectors pointing up are flowing towards the northeast; those pointing down are flowing southwest.



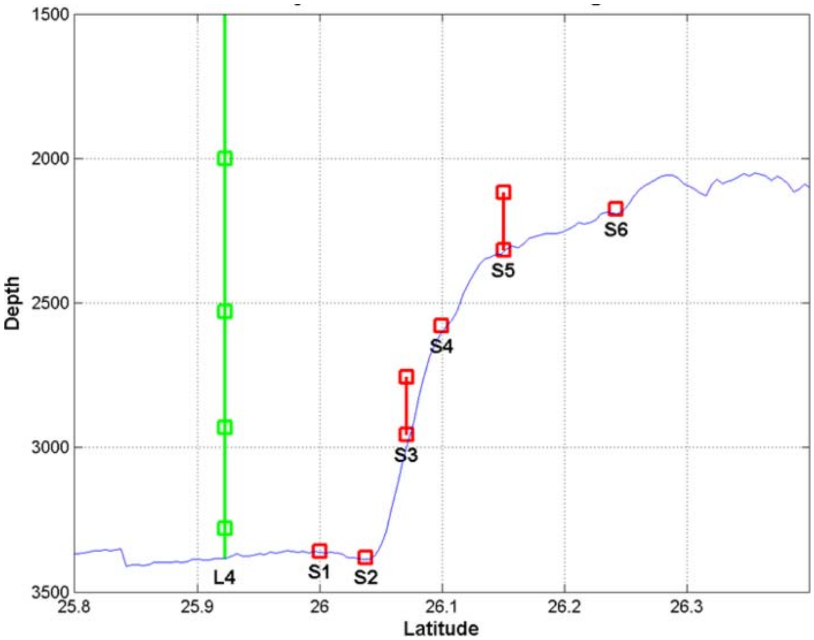
The second project, begun in 2008, focused on the development of a numerical model with the goal of eventually using it to develop operational and design criteria. Without a model, the industry would have had to develop criteria based on measurements of only a few TRWs at a few locations. The latter was especially troubling, because the measurements showed that TRW-generated currents varied significantly over length scales of a few kilometers.

Florida State University (FSU) was contracted to develop the model and soon discovered that the numerical discretization in standard ocean current models generated substantial numerical errors when dealing with the sharp bathymetric gradients of the Escarpment. A more advanced numerical technique was implemented, and the model was then used to hindcast the BOEM and DeepStar measurements (Dukhovskoy et al., 2009). Results were encouraging so a second modeling phase was kicked off, culminating in a well-validated model as suggested in the excellent comparison shown in Figure 7. In the process, FSU discovered that the TRWs were being generated by the collision of the Loop (or a recently detached eddy) on the outer slope of the Mississippi Fan, just south of the Delta (Morey et al., 2010).

With the successful validation of the model, DeepStar now had a tool that could be used to develop operational and extreme criteria. FSU developed the needed database by allowing the

FIGURE 5

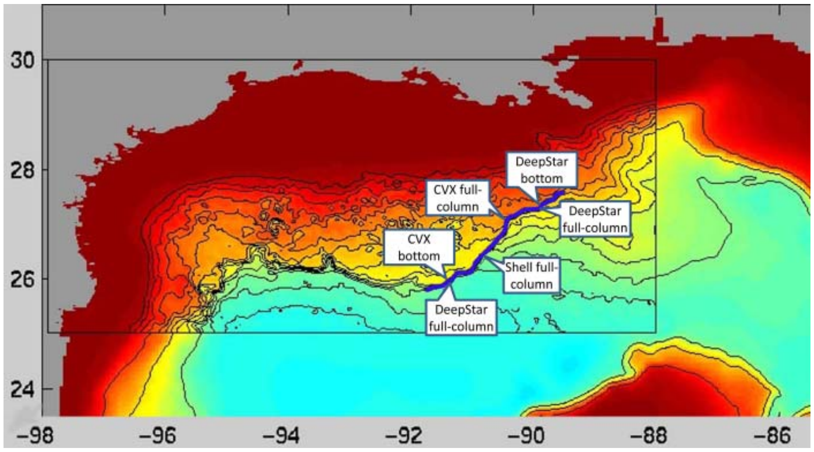
Cross section of the current meters deployed across the Sigsbee Escarpment.



model to free run for a 50-year period. It was a daunting computation effort since it involved running a high-resolution (800 m grid size) nested model covering the Sigsbee Escarpment inside a 3.5 km model covering the northern Caribbean and portions of the southeast Atlantic. Figure 8 shows the model domain. Results from the 50-year run were archived and are now being used by the Industry to develop design criteria.

FIGURE 6

Location of current measurements taken during 2008-2009. The dark blue curve shows the base of the Sigsbee Escarpment.



Finally, FSU recently started to apply their model results to develop a predictive capability that can eventually forewarn drillers and installers of major facilities, of an approaching TRW that might threaten their operations. Initial results have shown that the numerical model cannot predict the phase of TRWs very well since there are essentially no operational measurements in the lower deep water column available for model initialization or data assimilation. Instead of direct use of the model, FSU is using the 50-year database to develop a stochastic model based on independent variables like the position of the Loop. This approach will not suffer the phase issues and should also provide uncertainty estimates.

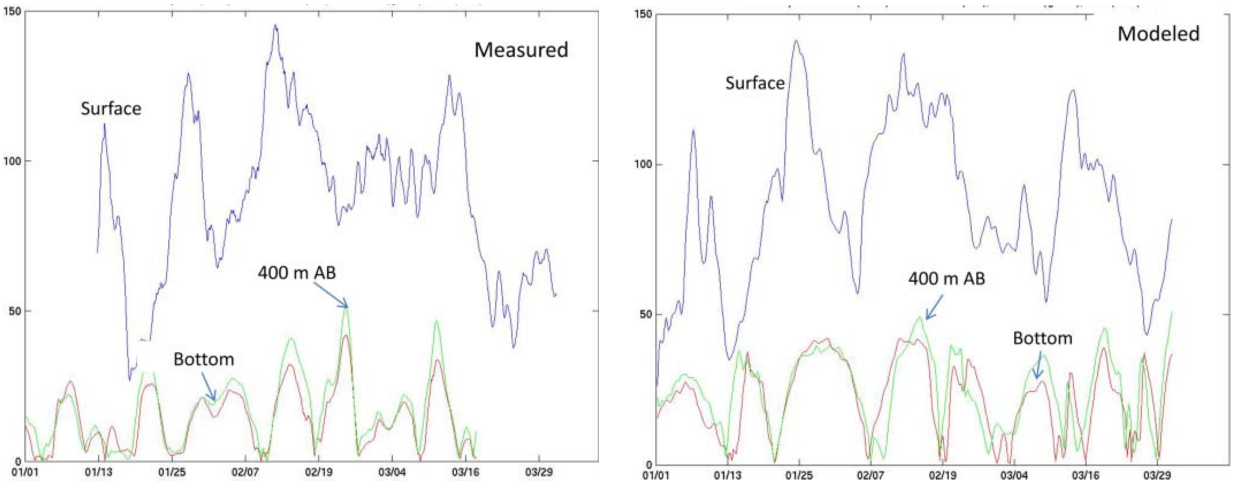
Hurricane Winds

In 2010, DeepStar funded a study to bring together all available hurricane wind data sets made in and around the Gulf since 1998, quality control them, and then analyze them in an effort to check the validity of the present American Petroleum Institute (API, 2012) recommended equations for hurricane winds. The data sets included dozens of offshore platform anemometer records, measurements from National Oceanic and Atmospheric Administration (NOAA) buoys, Coastal-Marine Automated Network (C-MAN), Automated Surface Observing System (ASOS), and National Ocean Service (NOS) stations, tower arrays of anemometers deployed along the coast, coastal weather radars, and dropsonde observations made by hurricane hunter aircraft.

The first phase of this study was completed in 2012 by Applied Research Associates, Inc., Texas Tech University, and the University of Florida

FIGURE 7

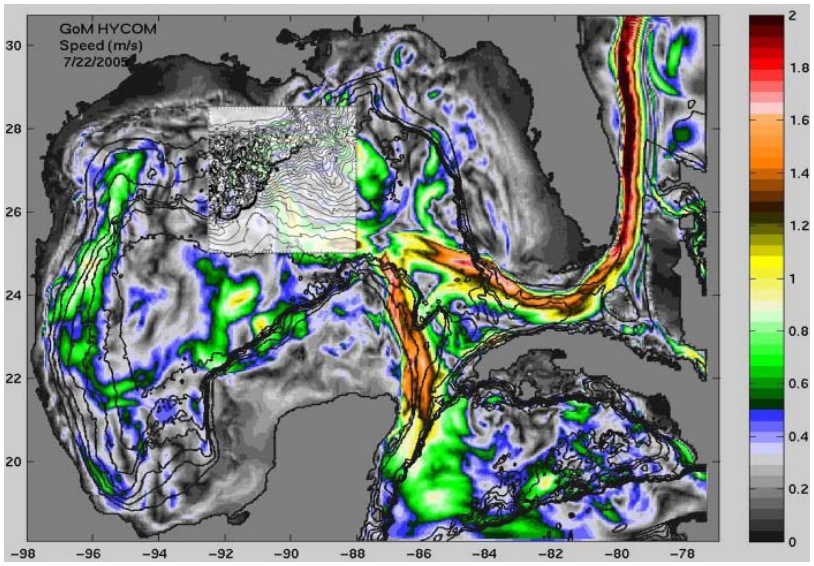
Comparison of model and observed current at three depths taken at one of the moorings shown in Figure 6.



and identified deficiencies in the API (2012) equations for gust factors, profiles, and spectra when applied to hurricanes. Figure 9 compares measured speed profiles to the API (2012) and Engineering Sciences Data Unit (ESDU, 1974, 1982, 1983) calculated profiles. While the API (2012) profile compares well within a few 10 s of meters of the sea surface, a 10% discrepancy appears at the higher elevations typical of platform deck heights (30-60 m). Such a discrepancy translates to more than 20% in the static drag force. On the other hand, the API (2012) equation for gust factors was found to underestimate the observations as shown in Figure 10.

FIGURE 8

Contours showing the sea surface height over the large-scale (3.5 km) model. Insert shows the nested model around the Sigsbee Escarpment with a resolution of 800 m.



The second phase of the study is now underway, with the analysis extended to tropical storm wind records made off the northwest coast of Australia, the east coast of the United States, and a reexamination of the original Norway extratropical wind measurements used to develop the API relationships. The end goal of this phase is a revised set of wind design relations that may then be incorporated into the latest offshore standards, for both tropical and extratropical storms. The study is anticipated to be completed by late 2013.

Summary and Conclusions

In 1998, DeepStar began what was to become a highly insightful set of projects in the field of meteorology and oceanography (metocean). The first project focused on measuring the

FIGURE 9

Comparison of measured wind profiles with recommended profiles from API and ESDU for three different central pressure bins.

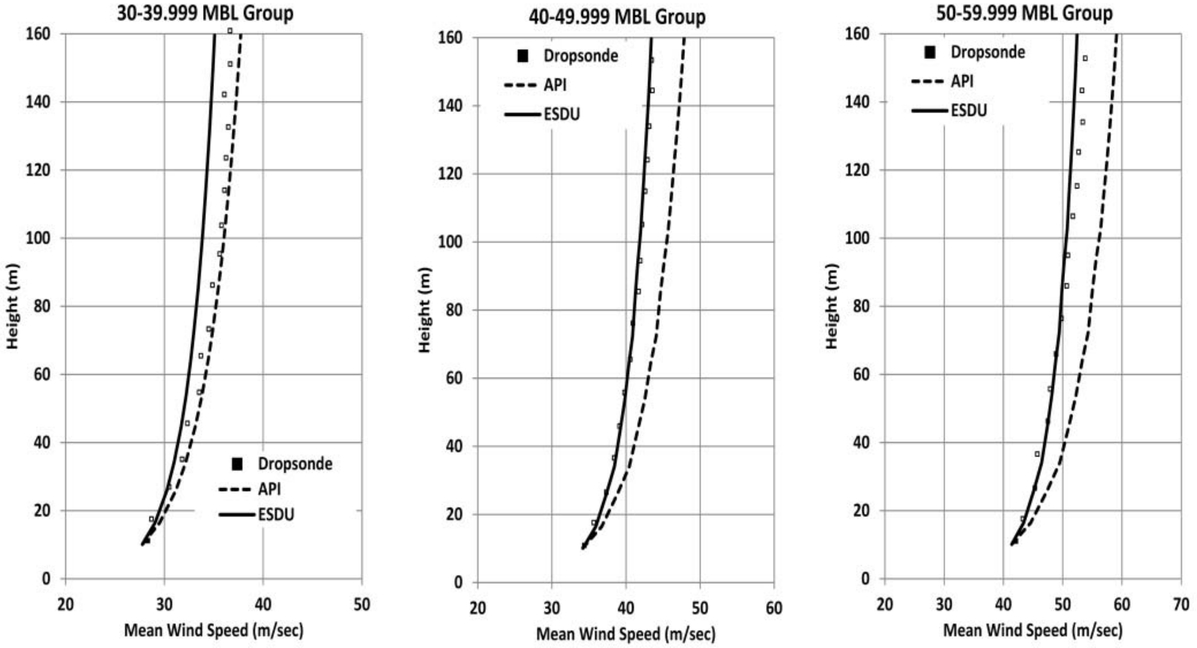
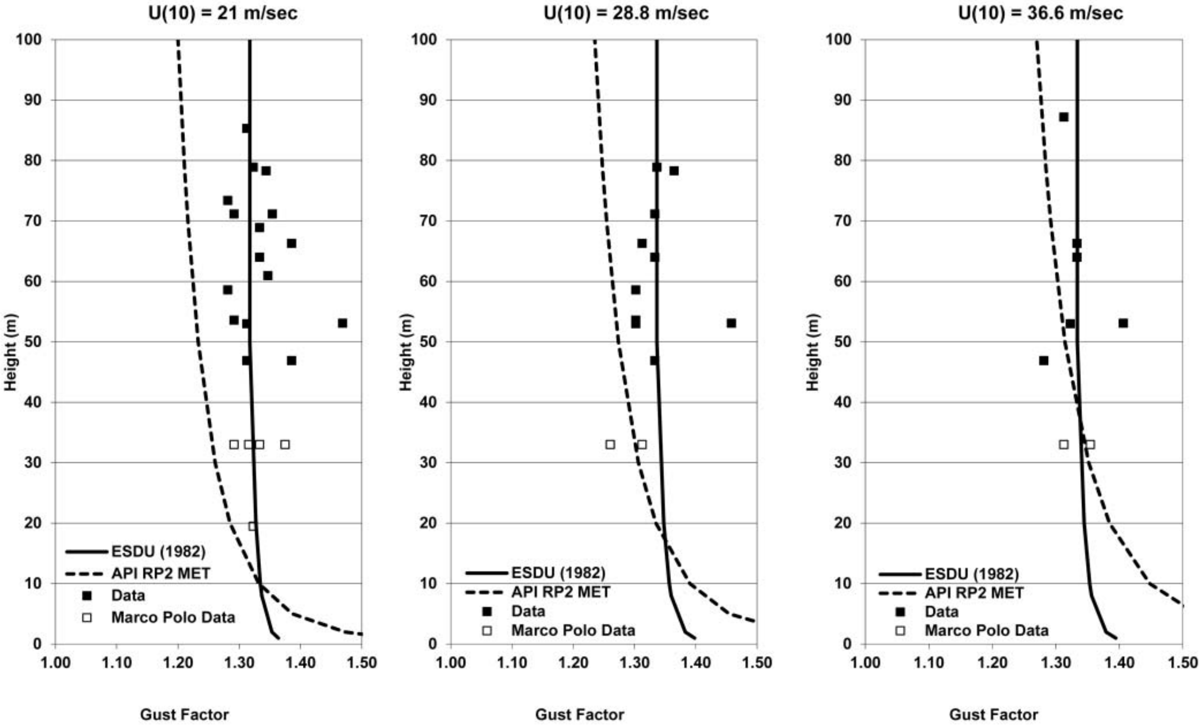


FIGURE 10

Comparison of measured gust factors with recommended factors from API and ESDU for three different wind speeds.



flow of the Loop Current through the Yucatan Straits—fundamental information that had never been gathered. This was followed by measurements of turbulence in the Loop Current; a study driven by concerns about resonance in tendons, moorings, and risers. Field measurements were completed in 2003, which dismissed that concern. In 2004, attention was turned to finding the best available forecast model of the Loop Current, a tool that could save the Industry millions of dollars by helping it avoid downtime during drilling and installation of large facilities like spars. Two studies were done comparing the ability of eight existing forecast models. Results showed that many of the models were much worse than simply assuming that the Loop remained unchanged (persistence) and revealed that the models were primarily limited by the accuracy of their initial conditions. This knowledge has been used in other Industry efforts to improve forecast models. In 2004, a six-phase effort was begun to quantify Topographic Rossby Waves (TRW)—a wave with a length of 200 km first measured in the Gulf in 1998 and capable of generating currents of 1 m/s (2 kt) near the sea floor. Phases 1 and 2 deployed arrays of current meters that recorded several TRWs. These measurements were then used to develop and validate a numerical model—the first to successfully simulate the full strength of these powerful waves. Phase 5 used the TRW model to develop a 50-year hindcast database that provides accurate operational and extreme current criteria throughout much of the deepwater Gulf. Phase 6 is using the model to develop a probabilistic forecast that can warn drill rigs and installation operations of an approaching TRW. Most recently, DeepStar has funded work to analyze the wealth of wind data collected during the recent extreme hurricanes. This study has revealed that the present Industry standard for hurricane wind spectra, profiles, and gusts can be improved, so revisions will soon be adopted.

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