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1. INTRODUCTION

A study was conducted in the spring of 2010 to determine the probability of avoiding severe weather and sea conditions generated by historical hurricanes to improve the evasion tactics of dynamically-positioned (DP) drilling vessels operating in the deepwater areas of the Gulf of Mexico. Instead of remaining in place when threatened by a hurricane, the DP drilling vessels secure well operations, pull riser, and evade the hurricane.

The study considers several factors affecting the measure of success of an evasion including inherent errors in forecasting hurricane strength, track and speed of advance; types and speeds of vessels; vessel sensitivity to wind and wave conditions; evasion time and direction of evasion; location of the vessel relative to the hurricane track; and water depth limitations. This study focuses on the required evasion time for DP vessels of various types and speeds to avoid undesirable met-ocean conditions.

The results provide a statistical basis for the required evasion time and could be part of a hurricane evasion plan to achieve an acceptable level of risk.

2. HISTORICAL HURRICANE AND WAVE DATA

Three main components of hurricane-related data were necessary for this study. High-quality estimates of the actual wind field produced by hurricanes as they traversed the Gulf of Mexico were essential. Quality analyses of the actual significant wave heights produced by the hurricane were also needed. A third necessary component was the forecast tracks of hurricanes between times shortly before they entered the Gulf of Mexico focus area and shortly after they exited the region.

2.1 Hurricane Selection Criteria

For this investigation we considered tropical cyclones that were forecast to track across a focus area in the

northern half of the Gulf of Mexico (within U.S. waters) and approximated by a trapezoid with vertices at the following latitude/longitudes: 31.0°N/82.7°W, 24.0°N/80.5°W, 24.0°N/98.5°W, 31.0°N/97.5°W as seen in Figure 1. In order to avoid distorting evasion statistics with numerous storm evasions that did not produce severe metocean conditions, only those tropical cyclones classified as hurricanes or forecast to be hurricanes within the study area were considered.

Although historical tropical cyclone track information exists for the Atlantic basin since the mid 1800s, only the period since 1988 contains the wind field extents that were necessary for this study. The *Extended Best Track* dataset (1988-2009) contains the best-estimated wind radii in each of the 4 quadrants (NE, SE, SW, and NW) of a tropical cyclone at every 6 hours during its lifetime (Demuth et al. 2006). The wind radii are given for the 18, 26, and 33 ms⁻¹ (35, 50, and 65 KT) winds, which correspond to the tropical storm threshold, a strong tropical storm, and the hurricane threshold, respectively. Figure 1 shows the tracks of the candidate tropical cyclones from 1988-2009 and the focus area. There were no hurricanes that entered the focus area during 2010.

The National Hurricane Center's (NHC) real-time forecast tracks (contained within advisories that are issued every 6 hours) were sought to match up with the extended best track database. Out of the 47 candidate tropical cyclones in the focus area since 1988 (see Figure 1), 10 were missing from the NHC archives at the time of writing and are in the process of being converted from hard copy archive to an electronic format. Hence, only 37 tropical cyclones contained sufficient detail to be used in the study.

Table 1 shows that Hurricane Cindy in 2005 was the only one of these 37 storms that was not forecast to be a hurricane at some point during their lifetime. Hurricane Cindy was reclassified as a hurricane in the post-season report, so it was included (Stewart 2006). Of the other 36 storms that were forecast to be hurricanes in the focus area, 24 verified as hurricanes in the focus area. See Table 1 for the details of each tropical cyclone.

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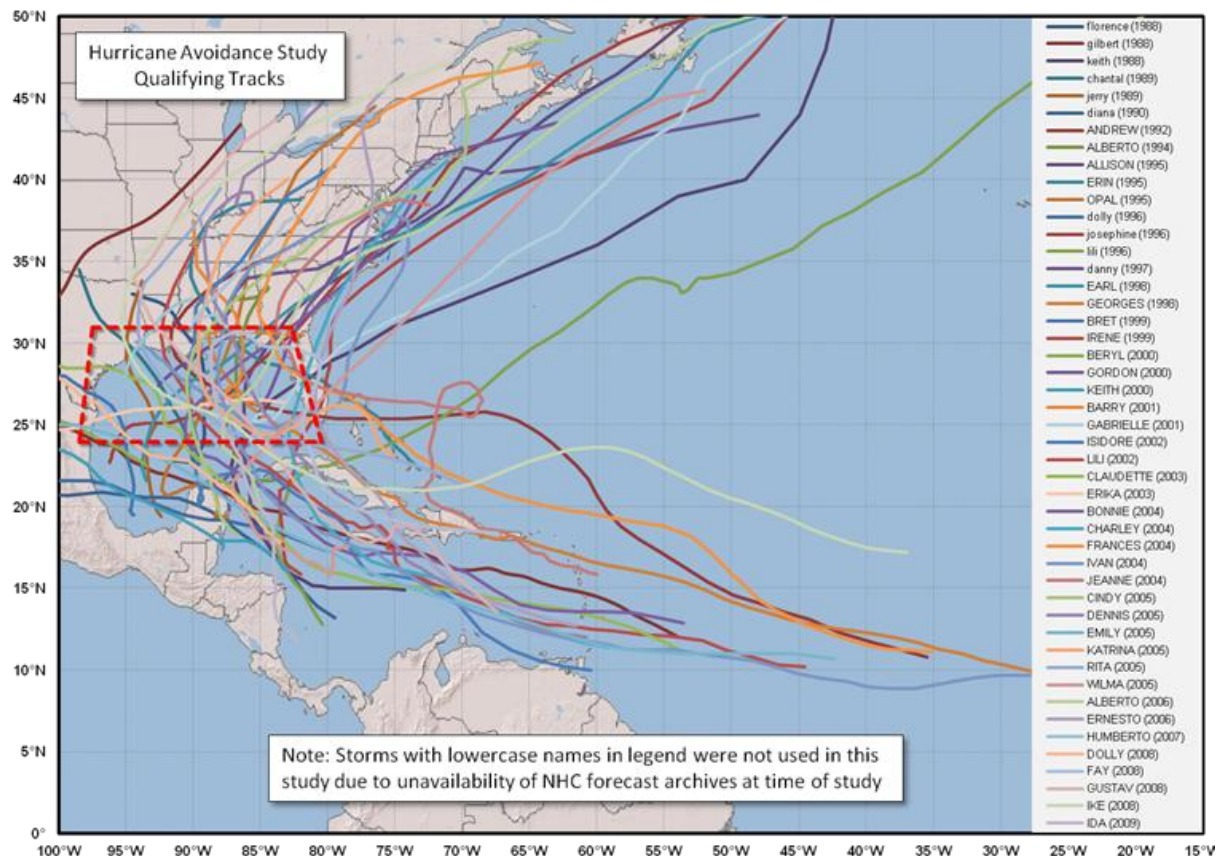


Figure 1. The original 47 candidate tropical cyclone tracks with red dashed trapezoid encompassing the approximate focus area for this study. Those storms with lowercase names were not included because NHC forecast data was unavailable.

2.2 Historical Significant Wave Data

The historical marine data was sourced from the NOAA WAVEWATCH III Hindcast Reanalysis produced by NOAA's Environmental Modeling Center (NOAA EMC 2010). Two separate data sets from this source were utilized that cover the Gulf of Mexico focus area. A 0.167° latitude/longitude resolution gridded reanalysis of significant wave heights is available for the 2005-2010 seasons, while a lower resolution 0.25° latitude/longitude resolution is used from 1999-2004.

No quality marine reanalysis data for significant wave heights exists for the hurricane seasons of interest before 1999 from U.S. government agencies, so a technique based on the Sverdrup-Munk-Bretschneider (SMB) calculations (Sverdrup and Munk 1947; Bretschneider 1952, 1958) was used to recreate significant wave heights on a grid starting from only wind and swell fields.

Reanalysis wind fields from NOAA did not appear to match wind observations well either near or away from a hurricane's core, so a simple background wind field from the southeast at 8 ms^{-1} (15 KT) with the Extended-Best Track wind radii data superimposed on top of it and interpolated was used instead. This southeast flow is representative of typical summer Gulf wind conditions. Swells originating from outside the Gulf of Mexico were also assumed to be zero. These assumptions affected significant wave heights below 6.1 m (20 ft) more than those above 6.1 m.

To evaluate the results of the SMB-based technique verses reality, the SMB-based technique was used to create significant wave fields for all of the storms, including those since 1999 that had NOAA WAVEWATCH III Hindcast Reanalysis data. Figure 2 shows the difference between the SMB estimates and the reanalysis actuals for significant wave heights during Lili (2002), a small but intense hurricane and Ike (2008), a large moderate strength hurricane. In

both storms, significant wave heights near the hurricane's track are overestimated by the SMB technique and those away from the storm's center are underestimated.

Storm ID	Storm Name	Year	Forecast to be Hurricane in Focus Area?	Existed as Hurricane in Focus Area?	Forecasts Available from NHC?
AL0788	FLORENCE	1988	UNKNOWN	YES	NO
AL0888	GILBERT	1988	UNKNOWN	YES	NO
AL1288	KEITH	1988	UNKNOWN	NO	NO
AL0489	CHANTAL	1989	UNKNOWN	YES	NO
AL1489	JERRY	1989	UNKNOWN	YES	NO
AL0590	DIANA	1990	YES	NO	NO
AL0492	ANDREW	1992	YES	YES	YES
AL0194	ALBERTO	1994	YES	NO	YES
AL0195	ALLISON	1995	YES	YES	YES
AL0595	ERIN	1995	YES	YES	YES
AL1795	OPAL	1995	YES	YES	YES
AL0496	DOLLY	1996	YES	NO	NO
AL1096	JOSEPHINE	1996	YES	NO	NO
AL1296	LILI	1996	YES	NO	NO
AL0597	DANNY	1997	YES	YES	NO
AL0598	EARL	1998	YES	YES	YES
AL0798	GEORGES	1998	YES	YES	YES
AL0399	BRET	1999	YES	YES	YES
AL1399	IRENE	1999	YES	YES	YES
AL0500	BERYL	2000	YES	NO	YES
AL1100	GORDON	2000	YES	YES	YES
AL1500	KEITH	2000	YES	NO	YES
AL0301	BARRY	2001	YES	NO	YES
AL0801	GABRIELLE	2001	YES	NO	YES
AL1002	ISIDORE	2002	YES	NO	YES
AL1302	LILI	2002	YES	YES	YES
AL0403	CLAUDETTE	2003	YES	YES	YES
AL0803	ERIKA	2003	YES	YES	YES
AL0204	BONNIE	2004	YES	NO	YES
AL0304	CHARLEY	2004	YES	YES	YES
AL0604	FRANCES	2004	YES	NO	YES
AL0904	IVAN	2004	YES	YES	YES
AL1104	JEANNE	2004	YES	NO	YES
AL0305	CINDY	2005	NO	YES	YES
AL0405	DENNIS	2005	YES	YES	YES
AL0505	EMILY	2005	YES	YES	YES
AL1205	KATRINA	2005	YES	YES	YES
AL1805	RITA	2005	YES	YES	YES
AL2405	WILMA	2005	YES	YES	YES
AL0106	ALBERTO	2006	YES	NO	YES
AL0606	ERNESTO	2006	YES	NO	YES
AL0907	HUMBERTO	2007	YES	YES	YES
AL0408	DOLLY	2008	YES	YES	YES
AL0608	FAY	2008	YES	NO	YES
AL0708	GUSTAV	2008	YES	YES	YES
AL0908	IKE	2008	YES	YES	YES
AL1109	IDA	2009	YES	YES	YES

Table 1. Table of criteria for the original 47 candidate systems used in this study. Those shaded in pink were ultimately not used.

Figures 3 and 4 show the influence of the two calculation techniques on the overall color criteria outcome for a grid of vessels that did not evade for hurricanes Lili and Ike, respectively. The impact on the color criteria was more significant than specific wave height differences for the purposes of this study. The color criteria will be explained in detail in the next section.

The main limitation of the SMB-based technique used is it did not properly transport the swells away from the position that they were generated. A full wave model or using a different set of parametric equations besides SMB may have yielded a more accurate result, and is a possible area for future work. A better estimate of significant waves for storms before 1999 would likely yield slightly higher instances of orange and red conditions and slightly lower chances of avoiding them that are presented in the results section below.

3. SIMULATION METHODOLOGY

In the simulations for this study, historical storm track forecasts and analyses of both the actual wind and sea conditions are used. Each NHC advisory contains a forecast track and since 1988 the NHC has issued new advisories at least every 6 hours during a storm's lifetime. A separate simulation was run for each advisory in each evasion direction. The simulations were conducted for all advisories for each storm between the first advisory when any of the vessels on the starting grid were closest to a forecast hour ≤ 72 and the last advisory when all points on the grid were closest to forecast hour zero. This study uses a total of 684 advisories from 37 tropical cyclones.

A separate simulation was run for each advisory, using two possible evasion directions, and a range of vessel speeds from 1.5 to 4.1 ms^{-1} (3 to 8 KT). The evasion directions are limited to a variable southwestward direction perpendicular to the forecast track (between 180 to 270 degrees) or straight eastward direction (90 degree), as typically practiced by mariners in the Gulf of Mexico. All vessels evade simultaneously to either direction.

The DP vessels can evade a hurricane in either an eastward or south to west direction. Each forecast advisory (produced every 6 hours) is used as a separate track prediction from which all the vessels evade simultaneously. Each vessel's position relative to the forecast track is noted and all vessels evade in one of the possible directions attempting to avoid the hurricane. Extensive data is gathered during the vessel evasion that allows thorough analysis. The following are some of the many variables tracked for each vessel in each simulation:

- Vessel's starting point: latitude, longitude
- Vessel's starting position relative to the forecast track: distance to right or left of

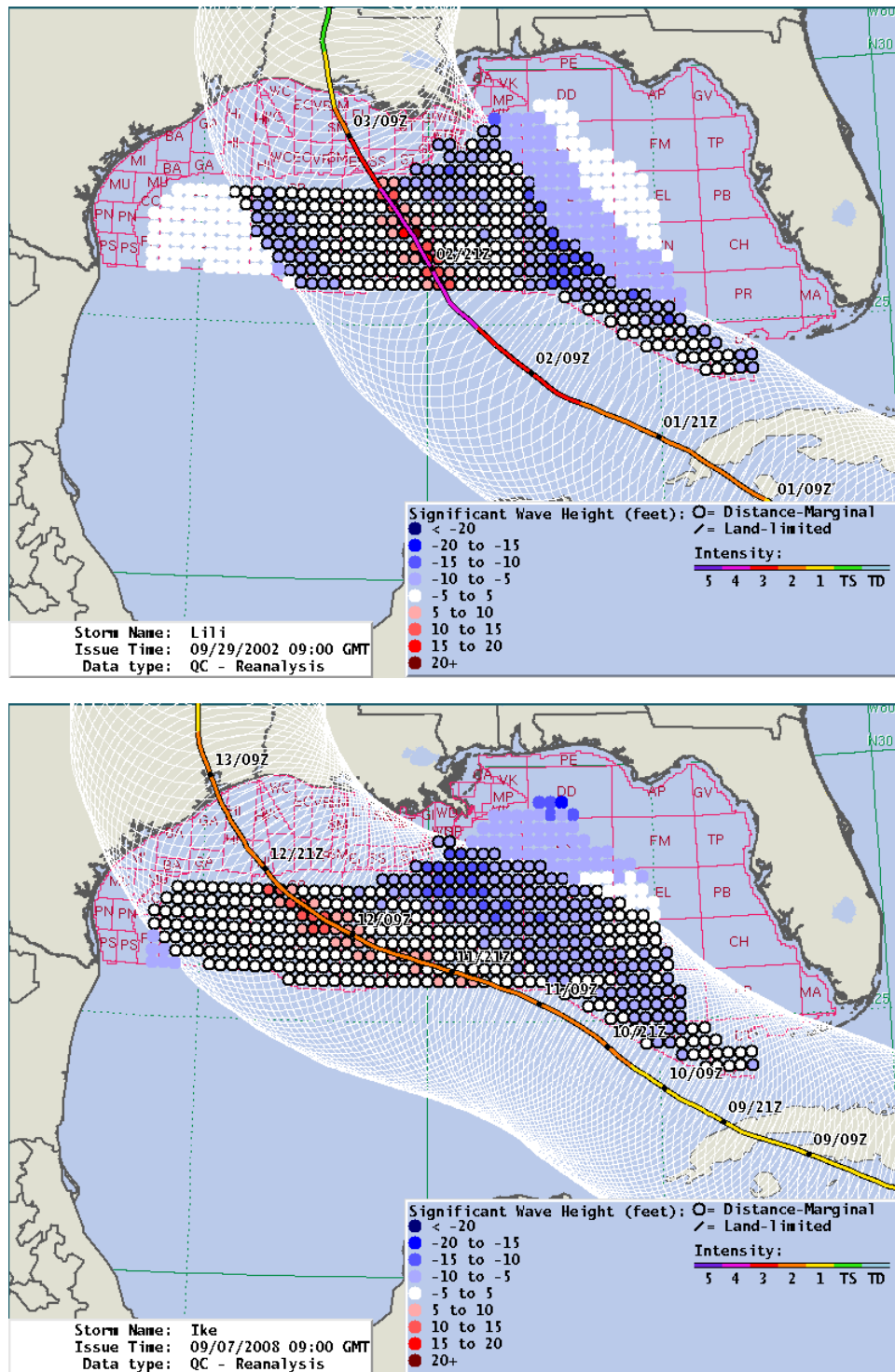


Figure 2. Differences in the SMB estimated minus WAVEWATCH III hindcast wave conditions for Hurricane Lili (top) and Hurricane Ike (bottom). Areas of red indicate overestimates by the SMB technique for significant wave heights and areas of blue indicate underestimates.

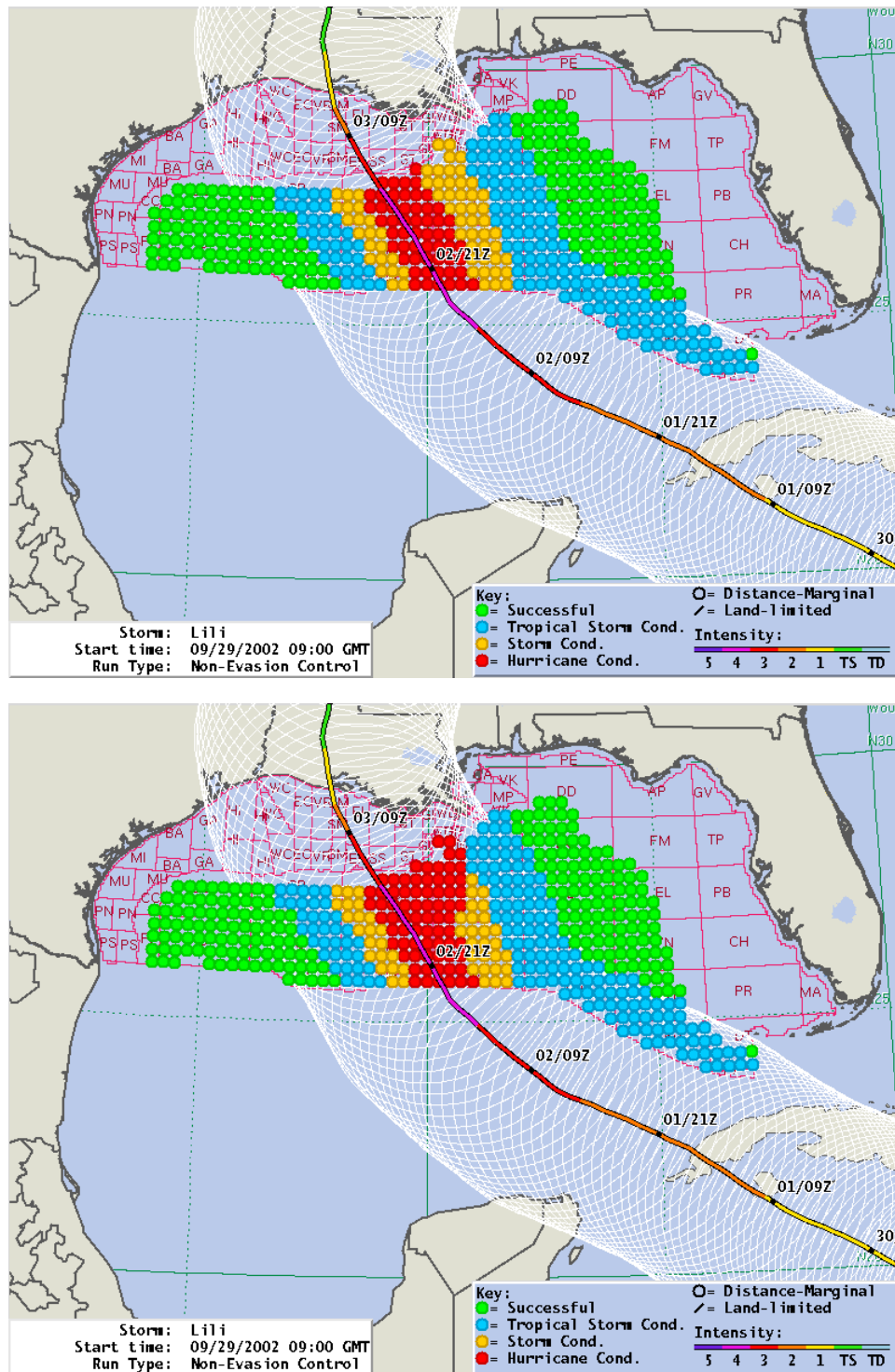


Figure 3. Hurricane Lili's SMB estimated criteria (top) versus the WAVEWATCH III hindcast conditions (bottom). The met-ocean conditions are colorized per the client's defined categories (Tables 2 and 3). Note the SMB-based technique slightly underestimates the extent of severe conditions to the right of small hurricanes.

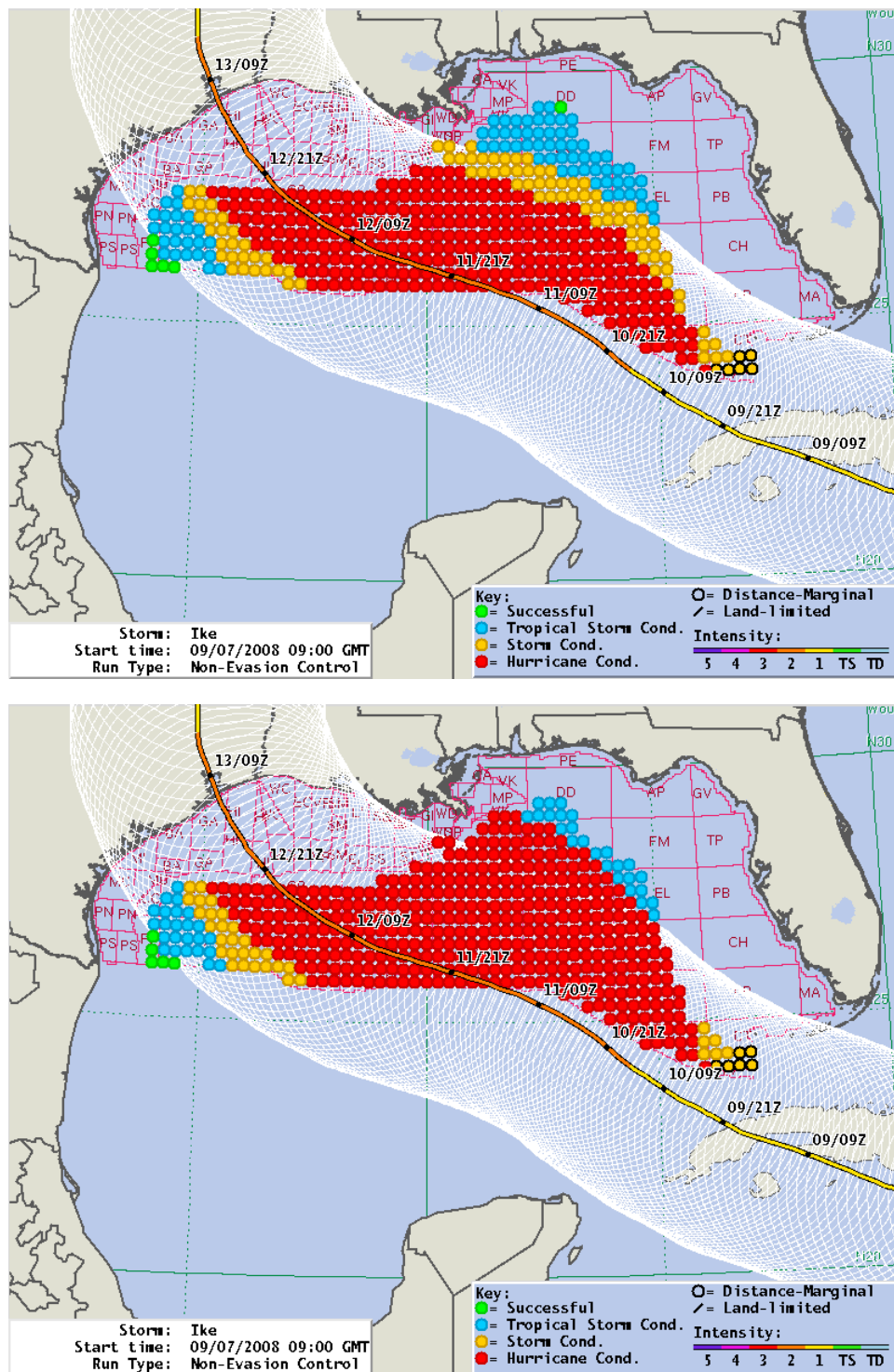


Figure 4. Hurricane Ike's SMB estimated criteria (top) versus the WAVEWATCH III hindcast conditions (bottom). The met-ocean conditions are colorized per the client's defined categories (Tables 2 and 3). Note the SMB-based technique underestimates the extent of severe conditions, especially on the right side of the track, of very large hurricanes.

Criteria	Sustained Wind Speed	Significant Wave Height	Semi-submersible outcome	Ship outcome
Green	$\leq 18 \text{ ms}^{-1}$ (34 KT)	& $\leq 6.1 \text{ m}$ (20 ft)	<i>Successful</i>	<i>Successful</i>
Blue	$> 18 \text{ ms}^{-1}$ (34 KT)	or $> 6.1 \text{ m}$ (20 ft)	<i>Marginal</i>	<i>Critical</i>
Orange	$> 26 \text{ ms}^{-1}$ (50 KT)	or $> 7.6 \text{ m}$ (25 ft)	<i>Critical</i>	<i>Unsuccessful</i>
Red	$> 33 \text{ ms}^{-1}$ (64 KT)	or $> 9.1 \text{ m}$ (30 ft)	<i>Unsuccessful</i>	<i>Unsuccessful</i>
Distance-Marginal	Vessel distance to storm center $< 278 \text{ km}$ (150 NM)		<i>Distance-Marginal</i>	<i>Distance-Marginal</i>
Land-Restricted	Evasion path restricted by shallow water before higher color criteria reached		<i>Land-Restricted</i>	<i>Land-Restricted</i>

Table 2. Color criteria for greatest sustained wind and significant wave height endured by a vessel during the hurricane evasion path and the outcomes of each color per vessel class.

Graphical Indicators of Vessel Criteria Reached	
Criteria	Graphical Indicator
Green	Green dot at original vessel location
Blue	Blue dot at original vessel location
Orange	Orange dot at original vessel location
Red	Red dot at original vessel location
Distance-Marginal	Bold outline surrounding dot at original vessel location for non-Green colors
Land-Restricted	Slash through dot at original vessel location

Table 3. Indicators used in graphics for color, distance, and land criteria.

- forecast track and time of closest point of approach of forecast track
- Evasion characteristics: direction and speed of movement
- Maximum met-ocean conditions vessel encountered during evasion: maximum wind and significant wave conditions

The simulations were carried out for vessel speeds of 1.5, 1.8, 2.3, 3.1 and 4.1 ms^{-1} (3, 3.5, 4.5, 6 and 8 KT). The slower speeds typically represent DP

semi-submersible type vessels and the higher speeds are generally characteristic of DP drill ships.

For each simulation, a total of 491 vessel starting points populate a 0.25° latitude by 0.25° longitude grid that covers the U.S. Waters of the northern Gulf of Mexico. This makes each starting point $\leq 28 \text{ km}$ (15 NM) from the closest other starting point. The grid is restricted to only the points with water depths $\geq 457 \text{ m}$ (1500 ft) to simulate the potential starting points of deepwater drilling vessels.

One issue with eastward evasions is they can result in being trapped by the Florida Peninsula. To prevent grounding, evasion paths are restricted to

water depth ≥ 30 m (100 ft) deep. When an evasion path is restricted by land (< 30 m water depth), the vessel is stopped and remains stationary until the storm passes by. The maximum wind speed and wave conditions are recorded and included in the statistics for successful evasion. Change of evasion direction during each hurricane is not considered in the study. Transocean provided input for the types and speeds of DP vessels to evaluate and the preferred evasion directions in which the vessels should travel to avoid a hurricane's destructive winds and seas. The vessel characteristics evaluated are shown in Tables 2 and 3.

3.2 Color Criteria and Categories for Successful Evasions

Table 2 shows the outcomes of each vessel type for a given threshold of wind and wave criteria. If sustained winds remained at or below 18 ms^{-1} (34 KT) and significant wave heights remained at or below 6.1 m (20 ft) during the entire evasion, the vessel is classified as meeting the Green criteria, and the starting point of the vessel is indicated on the map with a green dot. Both the semi-submersibles and ships consider Green criteria to be successful. On simulation maps, the Green, Blue, Orange, and Red colors denote the maximum thresholds of sustained wind and/or significant wave height experienced during a particular evasion path.

The vessel response to wave and wind action varies with the type of vessel. Semi-submersibles are more steady and move less than ships in high waves. Severe motions can affect the performance of the crew, their safety and ability to perform their duties as soon as the vessel returns to drilling. Severe motions also can also potentially cause damage to vessel equipment. Accordingly, the study assigns various met-ocean conditions for successful (or tolerable) outcomes and unsuccessful evasions for each vessel type.

Table 2 indicates that a ship is considered to have a less favorable outcome than a semi-submersible for both Blue and Orange conditions. Blue conditions are considered 'Critical' for a ship, but only 'Marginal' for a semi-submersible. Orange conditions are considered 'Unsuccessful' for a ship, while they are only considered 'Critical' for a semi-submersible. Red conditions for both vessel types are classified as 'Unsuccessful'.

3.2 Distance-Marginal Evasions

For the purpose of this study, it is assumed in the hurricane evacuation plan that the vessels are to remain at least 278 km (150 NM) from a hurricane's

center. It is expected that the met-ocean conditions at this distance are favorable, preferably at 'Green' conditions level. Vessels should leave early enough to allow for this distance threshold to be met. For vessels with a slower speed, the evasion may need to start between 24 and 72 hours before the predicted time of the hurricane's closest approach. For example, if a 1.5 ms^{-1} (3-KT) vessel is currently located 56 km (30 NM) to the left/west of the forecast track for a storm moving straight north, it would take approximately 50 hours traveling at 1.5 ms^{-1} (3 KT) to get to a point 278 km (150 NM) to the left (or west) of the storm's track.

It should be noted, that sometimes the waves are relatively high even at 278 km (150 NM) from the eye. This may occur in very large hurricanes such as Ike (2008).

A vessel is considered distance-marginal when at any time during its evasion path it comes within 278 km (150 NM) of the center of the storm. On the study graphics, this is denoted as a bold circle around the colored dot, but is only indicated for non-Green colored dots for the purpose of avoiding distractions.

3.3 Land-Restricted Evasions

A vessel that evades in a certain direction until the storm center passes it at its closest relative location will in some cases run into land. In this study, a vessel was considered to have hit land when it reached shallow water < 30 m (100 ft) in depth. At that point, the vessel is stopped and remains stationary in > 30 m (100 ft) deep waters until the storm passes by. In cases where a higher color threshold is not experienced after a vessel is forced to stop due to shallow water, the vessel is not considered Land-Restricted because land was not a factor in the category of met-ocean conditions the vessel experienced. However, in cases a vessel was stopped and then experiences a higher-level color condition, it is considered to be Land-Restricted. Graphically, this is indicated by placing a slash or "/" through the colored dot at the original vessel location, but it is only indicated on non-Green colored dots for the purpose of avoiding distractions.

It is possible for vessels to be both Land-Restricted and Distance-Marginal. In that case, both a bold border around the non-Green dot and a slash will be present.

In most cases in this study (unless otherwise indicated), Land-Restricted cases are not used when computing evasion performance statistics. However, Distance-Marginal cases are used when computing the evasion performance statistics since they don't impact the color category of met-ocean conditions experienced.

In a real-world situation, a captain would likely change the vessel evasion direction, sometimes drastically, before traversing into shallow water. Sometimes the direction would be changed during the whole evasion process, while other times it would be changed only after getting near shore and then going approximately parallel to the coast. Due to the complexities, changing the direction of evasion based on land along the evasion path is outside of the scope of this study, but it is a potential area of future work.

3.4 Evasion Direction

In the simulations hurricane avoidance maneuvers are restricted to be either a variable southwestward direction dependent on the storm's forecast track or a non-variable straight eastward direction as is the practice by captains. The variable southwestward evasion direction is determined by first finding the hour of the forecast track where the storm makes its closest approach to the vessel's starting location. Then a direction that is between due south (180°) and due west (270°) that is closest to perpendicular from the forecast track at the forecast hour of closest approach is determined. If a direction between south (180°) and west (270°) is perpendicular to the forecast track at this point, it is used for that vessel's evasion direction. If not, either a direction straight south or straight west was used, whichever direction is closest to 90° from the forecast track.

The eastward direction was held at 90° for all cases for this study and did not vary based on the forecast track. Due to this, some simulations where a hurricane was moving westward had the possible eastward evasion path take the vessel straight into the storm. Varying the eastward evasion direction, or even changing the evasion directions to be simply left-of-track or right-of-track directions are areas of potential future work, but is outside of the scope of this particular study.

Captains traditionally favor the southwestward evasion direction over the eastward evasion direction in most cases. This is because in the Gulf of Mexico, evading to a direction east of the forecast track will generally subject the vessel to the higher winds and significant wave heights that occur on the right side of a hurricane's track. Eastward evasions are also subject to being trapped by the Florida Peninsula with no place to go.

In each simulation, vessels were restricted to evading in the designated direction for the entire duration of the evasion. The evasion direction was not adjusted during the evasion, even if the forecast track changed or the vessel needed to avoid running into shallow water near land. In real-life, captains

would probably re-evaluate their status and evasion direction with each new track forecast from the National Hurricane Center or ImpactWeather.

4. RESULTS

4.1 Southwest and East Evasion Graphics

The simulations were performed for five vessel speeds, for 684 storm advisories using the southwest and east evasion directions.

An example of the output map is seen in Figure 5 for Katrina hurricane in 2005, advisory 8. In these graphics the storm name, advisory number, start time, vessel speed, and evasion direction are shown in the legend. The forecast storm track (in blue) and actual measured track (in red) for the specific advisory are plotted with forecast or actual positions labeled every 12 hours. The vessel starting locations are color-coded according to the worst met-ocean conditions they experience during the evasion for the advisory given. All the vessels in the entire grid evade in the given direction at the time of the advisory. If the vessel was Distance-Marginal or Land-Limited, this is also indicated. This form of the output is useful in examining visually the vessel outcomes for a specific advisory.

Notice that vessels starting to the right of the forecast track, even with close agreement with the actual track, are the most impacted for the southwest evasion. When evading southwest, these vessels first move toward the storm before crossing the track and attempting to get away. In the east evasion many of these vessels to the right of the forecast track encountered Blue or Green conditions even when starting avoidance maneuvers at advisory 15. It may not be practical for vessels in the left of the track to move eastward towards the hurricane, but the figure is shown for comparison purposes.

In this study the vessels are examined in a time and distance coordinate system relative to the forecast track (or actual track in the perfect forecast case). For a case where a vessel is considered to be 185 km (100 NM) to the right of the forecast track it is shorthand for saying, "a vessel's starting location is 185 km (100 NM) to the right of its closest point of approach to the forecast track." The vessel may also be considered 24 hours away from the forecast track, which for the purposes of this study means "the forecast position of the tropical cyclone is 24 hours away from the closest point of approach of the vessel's starting position." In other words, it is the forecast hour along the track which is the closest to the vessel's starting position.

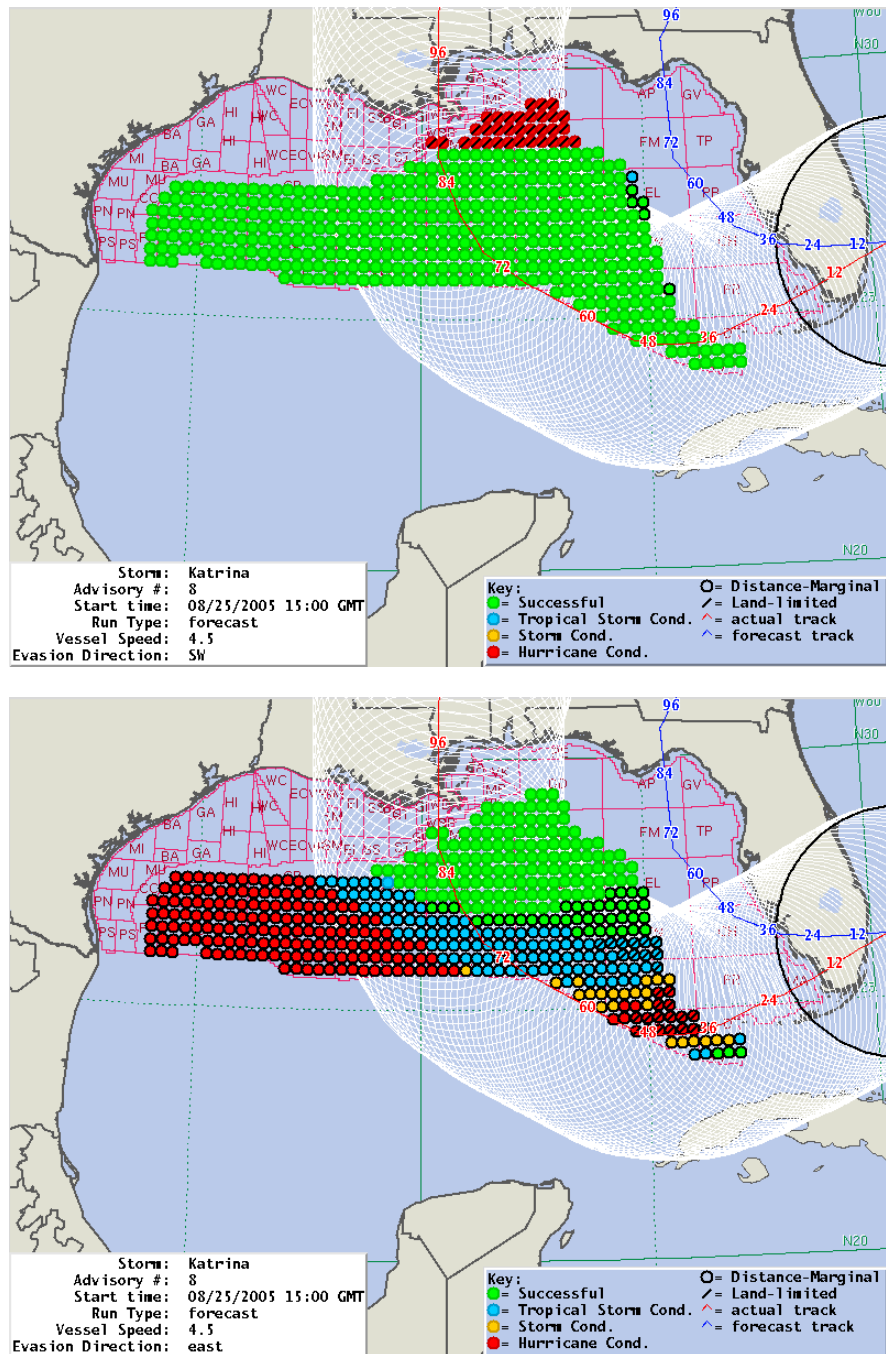


Figure 5. Hurricane Katrina Advisory 8 4.5-KT evasion in southwest direction (top) vs. east direction (bottom).

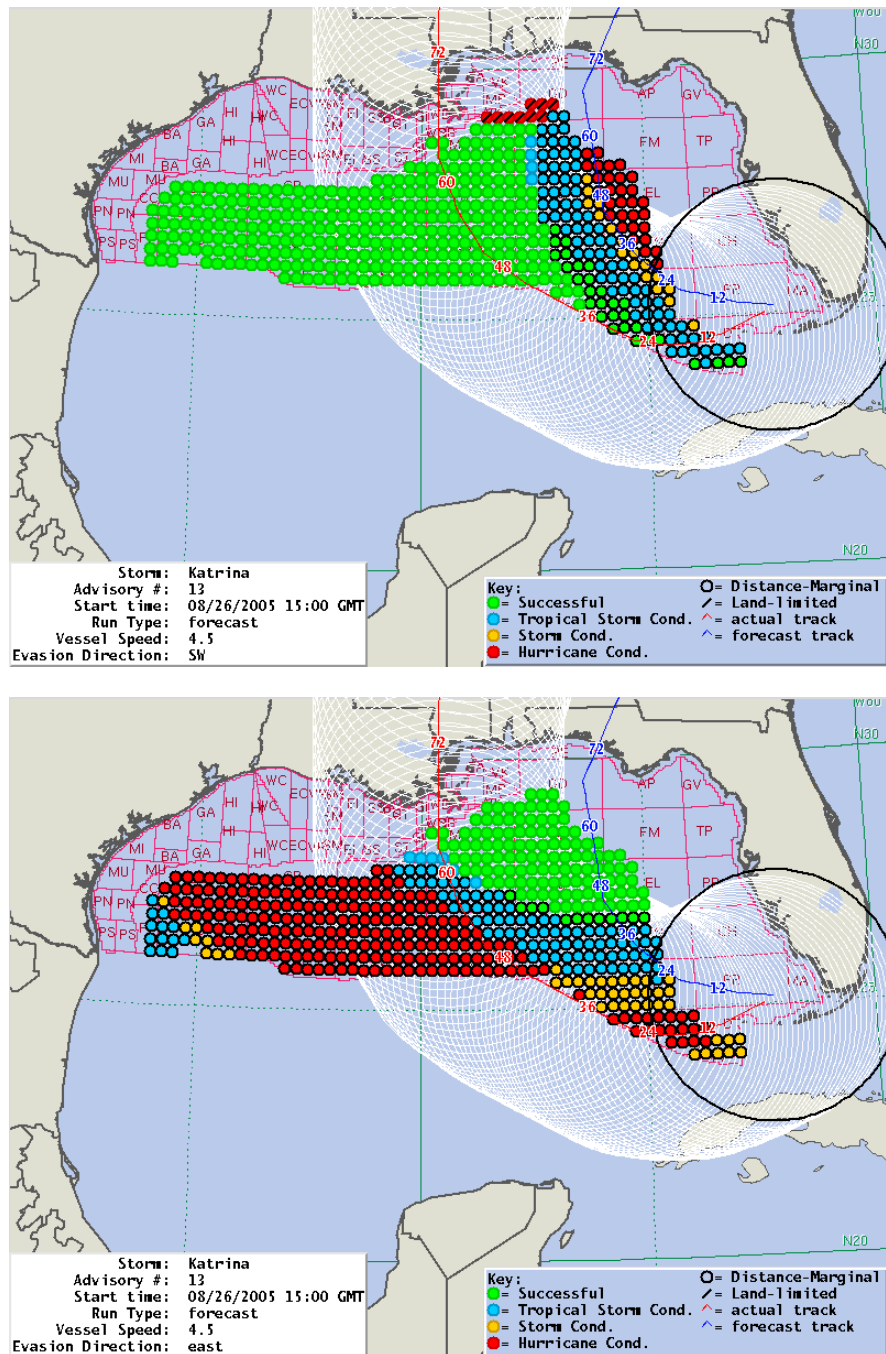


Figure 6. Hurricane Katrina Advisory 13 4.5-KT evasion in southwest direction (top) vs. east direction (bottom).

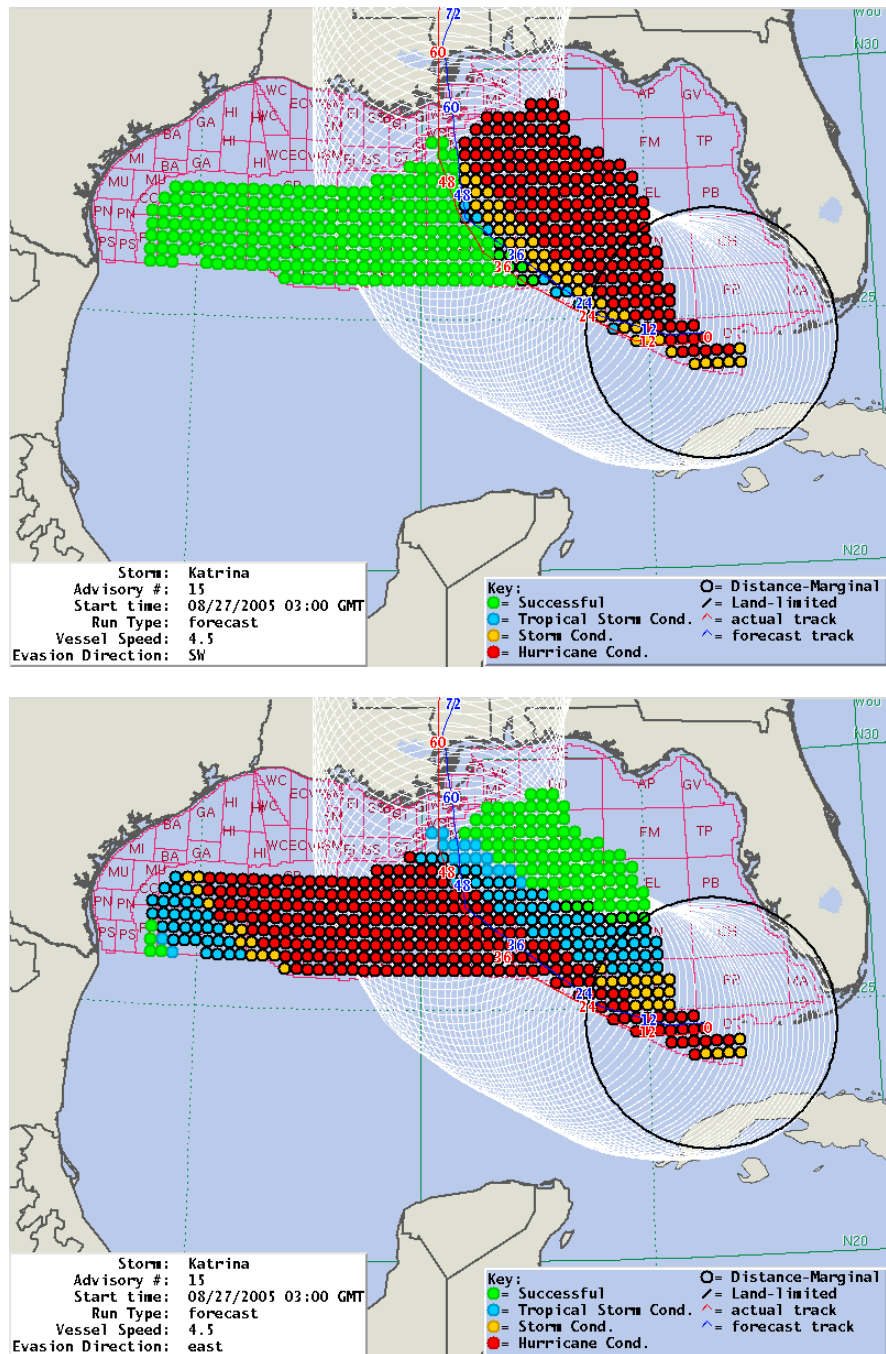


Figure 7. Hurricane Katrina Advisory 15 4.5-KT evasion in southwest direction (top) vs. east direction (bottom).

By the 8th advisory Katrina is located near South Florida and is forecast to have the center reach the Gulf of Mexico in 36 hours. But it moved faster than forecast to the southwest bringing it into the southeastern Gulf of Mexico in just over 12 hours. In the top graphic in Figure 5, even though the actual track was quite different from the forecast track, evasions beginning at the valid time of advisory 8 for the 2.3-ms^{-1} (4.5-KT) vessels in the southwest direction generally resulted in successful (green) outcomes. The exceptions were those vessels that were trapped by shallow water near the Mississippi River Delta. In real life these vessels would have maneuvered around the Delta and land-limited points like these are not included when computing evasion success statistics. The vessels in this simulation took a track perpendicular to the forecast track. The results of the east evasion (bottom graphic in Figure 5) were not very good.

If the 2.3-ms^{-1} (4.5-KT) vessels waited 24 more hours (advisory 13), as seen in Figure 6, they were more likely to encounter Red conditions even when evading to the southwest. There was not enough time for some of the vessels to evade. This was further exacerbated by the fact that there was still significant error in the forecast track, but not as much as 24 hours earlier in advisory 8.

By advisory 15 in Figure 7, the forecast track comes into close agreement with the actual track. However, by this point it is too late for many vessels to begin a successful evasion. Notice that vessels starting to the right of the forecast track that evade to the southwest first have to move toward the storm track before crossing it and attempting to get away. In the east scenario many of these vessels to the right of the forecast track encountered blue or green conditions even when starting avoidance maneuvers as late as advisory 15 since Katrina passed far enough to their south and west.

4.2 Southwest and East Success Rates

Although Blue and Orange conditions are not desirable, they are generally tolerable depending on

the vessel class (semi-submersible vessels can tolerate Orange conditions while ships cannot). Red met-ocean conditions are not acceptable for either vessel type. The rates of the Green or Blue outcomes (for a ship) or the rates of Green, Blue, or Orange outcomes (for a semi-submersible) can be grouped together and referred to as “tolerable” outcomes. .

The rates of tolerable outcomes for the for all storms for the entire Gulf of Mexico focus area can be displayed in one comprehensive table for each evasion direction, vessel class, and speed. Tables 4a-4b and 5a-5b show the tolerable outcomes for the fastest and slowest ships studied. The vessels were organized into one of twenty 46.3-km (25-NM) distance bins and one of eleven 6-hour forecast hour bins that were determined by their initial position relative to the forecast track. The forecast hour time bins increase along the y-axis of each table. The starting distance to the left of the track is indicated by a negative distance bin on the left half of the x-axis while distances to the right of the track are shown as positive distance bins on the right half of the table.

These tables were colorized to accentuate particular values of tolerable outcomes for each distance and time bin. Table sets 4 and 5 have each cell color-coded so that rates < 50% are red, rates < 95% are yellow, and rates > 99% are green. Note that vessel speeds of 2.3 ms^{-1} (4.5 KT) and less are evaluated for both ships and semi-submersibles, while those with speeds of 3.1 ms^{-1} (6 KT) and greater are only evaluated for ships since semi-submersibles are not typically that fast. It should also be noted that met-ocean and/or surface currents could cause the vessel to travel at a slower speed than it is capable of, and using a slower chart is advisable in this case.

While the east evasion rates were not as favorable for as many starting positions as those seen in the southwest evasion, there were some time-distance bins that could achieve at least a 99% chance of avoiding intolerable conditions for all vessels. These zones were mainly concentrated far to the right or left of the forecast track with low starting hours.

4a

Probability of Avoiding Unsuccessful Conditions 3-kt Ship, All Storms, Southwest Direction																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	99.8%	99.9%	99.9%	100.0%	99.9%	98.7%	97.9%	97.6%	95.8%	92.8%	90.8%	84.0%	69.3%	61.4%	63.6%	65.7%	71.6%	74.6%	78.2%	83.2%	
60 to 66	100.0%	100.0%	100.0%	100.0%	100.0%	98.8%	95.9%	94.2%	89.2%	88.4%	79.1%	74.0%	58.1%	46.2%	42.3%	44.4%	43.8%	54.7%	65.4%	72.5%	
54 to 60	100.0%	100.0%	100.0%	100.0%	100.0%	98.4%	94.6%	93.9%	90.7%	83.3%	69.0%	63.0%	47.7%	35.4%	27.0%	33.8%	42.8%	50.3%	61.3%	71.5%	
48 to 54	100.0%	100.0%	100.0%	100.0%	100.0%	99.5%	94.9%	94.4%	92.6%	86.7%	58.0%	49.7%	39.5%	30.2%	26.1%	26.6%	42.6%	47.6%	60.1%	68.9%	
42 to 48	99.8%	99.6%	99.7%	99.7%	100.0%	99.8%	96.8%	94.8%	93.5%	89.8%	56.6%	45.5%	37.3%	36.3%	34.9%	43.2%	51.3%	59.2%	66.0%	80.6%	
36 to 42	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.4%	97.2%	95.7%	92.9%	49.2%	36.1%	32.8%	33.4%	29.9%	30.8%	36.6%	54.0%	68.9%	81.8%	
30 to 36	100.0%	100.0%	100.0%	99.8%	99.8%	100.0%	99.8%	96.5%	96.1%	86.4%	40.7%	38.1%	34.5%	38.1%	37.4%	40.8%	55.8%	65.8%	78.5%	85.6%	
24 to 30	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.8%	97.3%	89.7%	72.6%	34.7%	30.5%	24.7%	23.7%	28.2%	38.3%	52.2%	67.0%	74.0%	77.4%	
18 to 24	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%	99.5%	90.2%	75.5%	60.7%	29.1%	31.0%	28.4%	27.0%	36.9%	48.6%	65.2%	77.2%	79.7%	84.2%	
12 to 18	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	95.3%	81.3%	65.3%	45.6%	22.8%	25.1%	24.3%	24.4%	33.2%	44.2%	67.5%	77.9%	80.6%	89.9%	
6 to 12	100.0%	100.0%	100.0%	100.0%	100.0%	99.4%	87.3%	71.4%	57.3%	33.7%	20.9%	24.7%	27.3%	33.4%	45.3%	60.8%	80.0%	85.7%	93.7%	97.7%	

4b

Probability of Avoiding Unsuccessful Conditions 8-kt Ship, All Storms, Southwest Direction																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.2%	93.5%	95.7%	97.0%	96.9%	96.2%	93.5%	91.4%	89.2%	89.6%	91.0%	
60 to 66	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	83.6%	92.9%	97.7%	99.4%	96.8%	94.7%	91.2%	88.6%	89.1%	92.2%	
54 to 60	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	74.8%	82.7%	86.3%	93.2%	90.6%	90.9%	90.1%	84.9%	84.9%	85.5%	
48 to 54	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	71.3%	78.4%	80.1%	81.6%	84.9%	82.3%	82.5%	75.4%	73.0%	81.2%	
42 to 48	100.0%	100.0%	100.0%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	99.3%	77.6%	80.0%	81.9%	81.9%	83.4%	81.4%	81.1%	79.3%	81.1%	80.1%	
36 to 42	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	78.8%	73.6%	72.9%	64.8%	61.8%	63.2%	68.0%	67.5%	72.7%	68.0%	
30 to 36	100.0%	100.0%	100.0%	100.0%	99.8%	99.8%	100.0%	100.0%	99.8%	98.9%	76.6%	74.7%	67.3%	62.3%	58.0%	58.8%	64.0%	63.4%	69.3%	75.1%	
24 to 30	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.7%	70.0%	61.2%	46.5%	38.0%	39.1%	44.2%	49.3%	50.9%	59.0%	69.9%	
18 to 24	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	98.8%	95.1%	56.0%	51.2%	40.4%	37.8%	37.9%	41.8%	54.8%	64.2%	68.4%	81.9%	
12 to 18	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	97.4%	89.7%	78.2%	40.0%	33.9%	30.2%	27.8%	25.8%	35.7%	55.2%	67.6%	74.9%	85.2%	
6 to 12	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	95.7%	83.4%	71.6%	53.7%	28.1%	27.7%	28.9%	32.9%	45.3%	54.7%	72.2%	80.7%	95.9%	

Tables 4a-4b. Probabilities of avoiding intolerable conditions at a given starting position relative to the forecast track using statistics from all storms evading to the southwest. In the case of ships, intolerable evasion outcomes involved cases were orange or red met-ocean criteria were encountered. Only two vessel speeds are shown in the example.

5a

Probability of Avoiding Unsuccessful Conditions 3-kt Ship, All Storms, East Direction																						
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	74.4%	72.5%	70.1%	67.5%	62.0%	57.5%	53.1%	54.1%	53.3%	47.0%	44.2%	61.5%	73.8%	80.8%	83.5%	87.3%	91.0%	92.3%	90.0%	85.7%		
60 to 66	72.2%	65.9%	64.1%	60.7%	55.7%	46.6%	45.3%	48.6%	50.2%	42.1%	43.0%	48.0%	63.5%	75.7%	82.1%	90.4%	96.2%	97.1%	96.0%	95.1%		
54 to 60	77.3%	69.6%	66.6%	62.9%	59.1%	46.0%	37.0%	42.4%	40.3%	38.8%	42.8%	46.1%	56.5%	71.4%	79.5%	89.1%	94.0%	96.8%	96.1%	95.5%		
48 to 54	80.6%	77.3%	70.7%	60.7%	54.3%	42.4%	27.8%	28.1%	34.4%	32.9%	35.8%	46.6%	59.3%	68.3%	77.4%	83.0%	88.4%	95.7%	97.9%	96.7%		
42 to 48	91.7%	86.8%	77.2%	68.2%	58.0%	49.9%	35.9%	29.2%	29.6%	30.0%	28.9%	38.6%	50.3%	62.3%	77.4%	79.2%	83.2%	85.7%	92.3%	92.2%		
36 to 42	97.4%	94.2%	86.4%	71.3%	62.5%	48.9%	27.3%	22.5%	26.8%	28.2%	30.7%	36.3%	42.7%	61.9%	76.3%	81.5%	89.7%	91.6%	98.3%	96.6%		
30 to 36	99.7%	98.4%	96.2%	85.5%	66.2%	55.5%	35.7%	22.7%	25.1%	29.4%	31.8%	31.8%	36.4%	51.0%	72.9%	82.3%	92.4%	95.9%	99.1%	99.2%		
24 to 30	100.0%	100.0%	99.6%	93.8%	74.7%	53.5%	37.2%	24.1%	20.1%	25.3%	25.6%	27.5%	31.8%	45.6%	75.1%	85.4%	92.7%	96.3%	98.2%	98.5%		
18 to 24	100.0%	100.0%	100.0%	98.9%	83.6%	62.5%	40.7%	24.2%	17.9%	22.6%	22.0%	27.8%	29.9%	41.1%	71.1%	83.7%	89.4%	96.5%	98.1%	97.3%		
12 to 18	100.0%	100.0%	100.0%	100.0%	89.5%	72.6%	51.7%	32.2%	18.8%	18.6%	20.0%	23.5%	25.6%	41.1%	64.0%	77.1%	90.7%	96.2%	98.3%	98.3%		
6 to 12	100.0%	100.0%	100.0%	100.0%	97.6%	85.2%	64.1%	41.8%	25.7%	19.9%	18.3%	22.3%	26.6%	42.1%	61.0%	75.6%	90.5%	96.5%	99.0%	99.0%		

5b

Probability of Avoiding Unsuccessful Conditions 8-kt Ship, All Storms, East Direction																						
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																					
	Starting Position Left of Track										Starting Position Right of Track											
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	84.4%	84.5%	80.1%	77.2%	77.9%	80.2%	82.0%	86.9%	81.8%	69.8%	71.2%	85.7%	92.2%	92.8%	93.6%	95.8%	95.7%	97.1%	98.9%	99.6%		
60 to 66	70.6%	64.2%	66.8%	59.2%	63.7%	60.1%	59.9%	70.3%	78.1%	75.6%	72.0%	77.5%	87.7%	91.7%	96.7%	98.2%	99.6%	100.0%	100.0%	100.0%		
54 to 60	74.0%	71.6%	73.9%	72.9%	69.2%	62.1%	61.9%	58.6%	69.9%	76.0%	77.3%	76.3%	83.3%	93.1%	98.1%	98.4%	99.7%	100.0%	100.0%	100.0%		
48 to 54	74.8%	65.5%	68.5%	71.8%	78.2%	68.7%	64.3%	64.5%	62.6%	70.0%	77.6%	78.7%	82.9%	91.9%	97.7%	99.7%	100.0%	100.0%	100.0%	100.0%		
42 to 48	72.9%	65.8%	65.0%	63.9%	67.5%	68.3%	60.0%	59.8%	60.3%	63.1%	75.9%	82.3%	86.6%	91.7%	93.6%	95.5%	95.5%	92.8%	91.5%	91.2%		
36 to 42	77.1%	63.7%	61.4%	58.1%	55.3%	48.8%	44.5%	50.0%	52.3%	59.7%	72.8%	80.5%	83.2%	89.0%	95.3%	98.2%	100.0%	100.0%	99.6%	99.0%		
30 to 36	80.4%	73.8%	61.8%	53.0%	45.5%	35.6%	29.7%	33.9%	43.8%	51.3%	58.7%	72.4%	78.9%	85.9%	91.9%	94.2%	95.5%	94.4%	93.6%	93.3%		
24 to 30	83.6%	70.6%	60.5%	47.7%	36.4%	28.4%	28.7%	29.6%	32.2%	39.8%	46.6%	55.5%	74.6%	86.4%	92.7%	97.6%	99.8%	100.0%	100.0%	100.0%		
18 to 24	90.4%	81.3%	73.0%	62.7%	49.3%	35.9%	24.1%	21.8%	25.2%	32.5%	35.8%	40.8%	59.1%	77.2%	86.6%	93.1%	98.5%	98.8%	97.6%	99.5%		
12 to 18	96.7%	90.4%	81.5%	71.8%	58.1%	41.3%	30.4%	20.0%	23.1%	26.0%	30.3%	33.5%	42.7%	69.1%	81.4%	92.7%	98.6%	99.8%	100.0%	100.0%		
6 to 12	99.5%	99.0%	96.4%	89.1%	79.3%	62.8%	42.0%	26.9%	21.8%	22.6%	24.7%	31.4%	37.6%	55.6%	72.2%	86.4%	96.6%	99.6%	100.0%	100.0%		

Tables 5a-5b. Probabilities of avoiding intolerable conditions at a given starting position relative to the forecast track using statistics from all storms evading to the east. In the case of ships, intolerable evasion outcomes involved cases were orange or red met-ocean criteria were encountered. Only two vessel speeds are shown in the example.

6a

Probability of No Successful Evasion Direction 3-kt Ship, All Storms																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	3.6%	4.0%	5.9%	5.8%	4.4%	4.0%	4.0%	2.6%	1.8%	0.8%	
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	6.1%	6.1%	8.2%	6.0%	3.4%	2.4%	3.4%	1.8%	0.7%	0.8%	
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.2%	11.0%	11.9%	13.5%	9.6%	7.9%	4.5%	4.3%	1.7%	1.4%	
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.2%	1.2%	20.3%	18.5%	17.3%	14.5%	11.2%	10.7%	8.6%	3.6%	0.8%	
42 to 48	0.2%	0.4%	0.3%	0.3%	0.0%	0.0%	0.3%	0.0%	0.6%	3.5%	26.5%	32.5%	29.4%	21.5%	13.0%	10.3%	5.3%	2.6%	0.3%	0.6%	
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.6%	0.9%	3.9%	37.1%	44.2%	42.6%	26.7%	16.4%	14.6%	8.5%	6.8%	0.7%	1.4%	
30 to 36	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	2.7%	2.1%	9.4%	46.8%	50.1%	47.5%	36.9%	22.1%	14.7%	6.5%	2.9%	0.7%	0.4%	
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	2.7%	10.3%	23.6%	59.0%	59.5%	58.0%	49.5%	23.4%	14.1%	6.8%	3.4%	1.2%	1.5%	
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	9.8%	23.4%	36.7%	66.5%	62.5%	60.7%	51.8%	26.1%	16.3%	10.6%	3.3%	1.7%	2.7%	
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.7%	18.7%	34.7%	52.6%	72.6%	69.6%	69.5%	55.2%	34.2%	22.5%	9.1%	3.6%	1.7%	1.1%	
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	12.7%	28.6%	42.7%	65.8%	76.6%	72.1%	68.0%	54.0%	37.2%	23.2%	8.5%	2.8%	0.2%	0.2%	

6b

Probability of No Successful Evasion Direction 8-kt Ship, All Storms																				
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.1%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
42 to 48	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30 to 36	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.2%	4.7%	1.2%	0.0%	0.2%	1.0%	1.4%	0.0%	0.0%	0.2%	0.0%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	15.9%	16.8%	9.5%	6.4%	4.6%	2.7%	0.4%	0.0%	0.6%	0.0%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.7%	4.3%	31.1%	37.5%	29.7%	17.0%	10.6%	4.8%	0.8%	0.0%	0.0%	0.0%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.6%	10.1%	20.5%	49.4%	56.4%	51.7%	30.1%	18.1%	7.0%	1.4%	0.2%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.3%	16.6%	28.4%	45.5%	67.1%	64.8%	60.6%	43.1%	25.4%	12.5%	3.2%	0.4%	0.0%	0.0%

Tables 6a-6b. Probabilities of no tolerable evasion outcome in either direction given a starting position relative to the forecast track using statistics from all storms. Cases where no tolerable evasion direction occurred signify that either red or orange metocean criteria were reached for ships in both possible directions.

There is, of course, a tendency for faster vessels to have better outcomes than slower vessels. Vessels left of the track had the advantage for southwest evasions. This is mainly due to the climatology of tropical cyclone tracks in the Gulf of Mexico where storms tend to travel mainly towards the west and/or north. They did not have to cross the forecast track before moving away from it.

Eastbound vessels were at an advantage when starting from a position to the right of the forecast track. If the vessel is right of the forecast track, the tropical cyclone will tend to move away from the vessel helping to more quickly put distance between the vessel and the storm when evading east.

A southwest evasion from right of track often means heading toward the track before being able to move away from it. Since eastbound vessels

could only travel due east (90°) and not a variable direction like the south-to-west evasions, the vessels sometimes did not move in an optimum direction. Allowing variation in the east bound evasions would have likely improved the evasion results for the east evasions right of the forecast track and is a potential area of future work.

There are situations where east or southwest evasions are equally tolerable and other cases when neither are tolerable. Table set 6 shows the percentage of all evasion statistics in each time and distance bin that had no tolerable outcomes in either direction and thus resulted in unsuccessful conditions. This table set has each cell color-coded so that rates of intolerable conditions are as follows: > 50% are red, rates > 5% are yellow, and rates < 1% are green.

Caution should be taken when using charts like table 6 as guidance because achieving tolerable conditions may require the captain to pick the best direction. It is a good resource though to see what starting positions relative to the forecast track should be avoided because neither direction is tolerable.

From table set 6 it becomes apparent that vessels within 139 km to 185 km (75 NM to 100 NM) right of the forecast track had some of the lowest chances of a tolerable evasion outcome. As expected, vessel speed was also a crucial factor in these rates. The slowest ship always needs to be at least 36 hours in time from the forecast track to have at least 50% chance of one of the directions resulting in a tolerable evasion for every distance bin. For the fastest ship it had to be at least 18 hours ahead of the forecast storm position to achieve at least a 50% rate of tolerable outcomes for every distance bin. Slower vessels would need additional lead time to achieve a tolerable evasion outcome.

4.3 Effect of Forecast Errors

Figures 8 and 9 show track and intensity errors from historical National Hurricane Center forecast tracks are greater for longer forecast lead times. There has been a significant reduction in total track errors since 1989 while in the same period, there has been little or no improvement in intensity errors.

There are two types of forecast track errors: cross-track and along-track errors. Cross-track errors could cause a storm to track into and impact a different area than forecast. Along-track errors cause a change in the timing of the forecast, but not in the general region the storm was expected to affect. A tropical cyclone may arrive sooner or later than forecast. A faster-than-forecast storm will shorten the evasion window, and a slower-than-forecast storm will allow for more time than originally expected to evade.

Let us reexamine the earlier example of Hurricane Katrina in 2005 to see the effects of forecast error on evasion outcomes. An early advisory (number 8) in Figure 10 had a track forecast that was well to the right of the actual track, meaning it contained large cross-track errors. This resulted in all the vessels in the focus area being left of the forecast track, but to the right of the actual track. In Figure 10, the vessels between the forecast track (blue line) and the actual track (red line) evading in a southwestward direction actually tracked toward the storm due to the large track forecast error. Recall that once an evasion begins the vessel continues in the same direction for the duration of the simulation run. In a real-world situation the vessel may choose to change directions based on a later advisory.

By Katrina's advisory 14, the cross-track error has decreased markedly as seen in Figure 11. In this case, vessels starting to the right of the forecast track suffered through the most severe met-ocean conditions when evading to the southwest and would have been better served evading to the east as seen in Figure 12. At that time, vessels in the southeastern Gulf of Mexico would have been too late to begin a meaningful evasion.

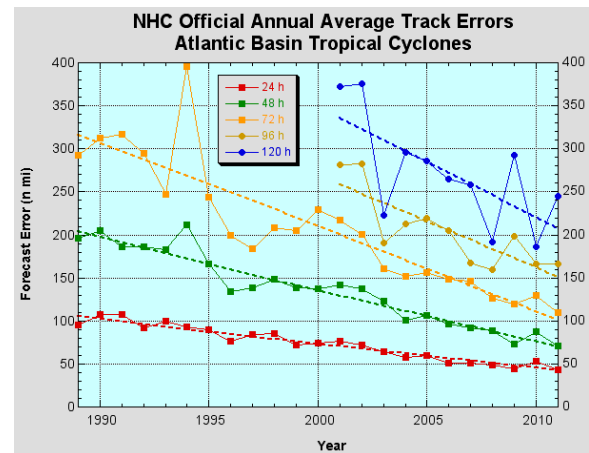


Figure 8. National Hurricane Center's annual average track errors since 1989.

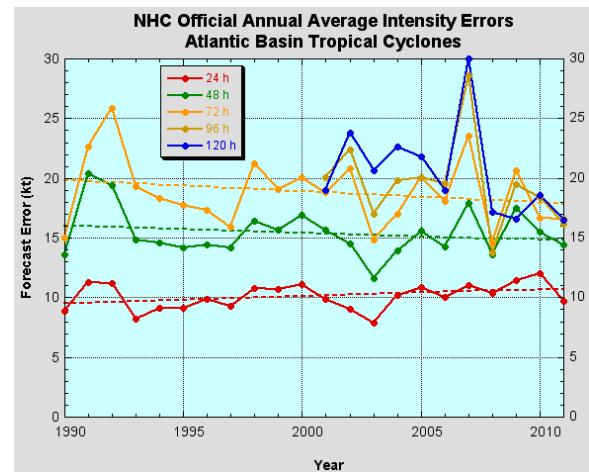


Figure 9. National Hurricane Center's annual average intensity errors since 1990.

4.4 Perfect Forecast Success Rates

Forecast error can be eliminated in hypothetical situations by examining the data with respect to the actual track instead of the forecast track. In essence, the virtual vessels then respond to a “perfect forecast” instead of a forecast that inherently contains errors.

Perfect forecast scenarios remove situations like that examined for Katrina above where a vessel might accidentally intersect the storm instead of move away from it. Forecast error can actually be beneficial in some cases, but harmful in other cases, but overall it creates uncertainty in the decision-making process when evading a hurricane.

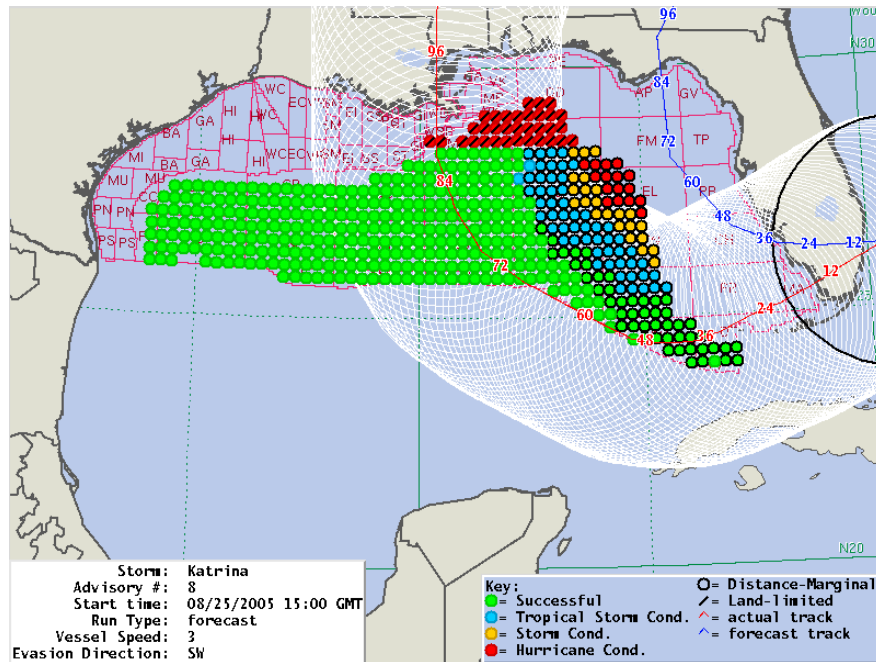


Figure 10. 1.5-ms^{-1} (3-KT) vessel evasion relative to the forecast track in the southwest direction for Hurricane Katrina for advisory 8.

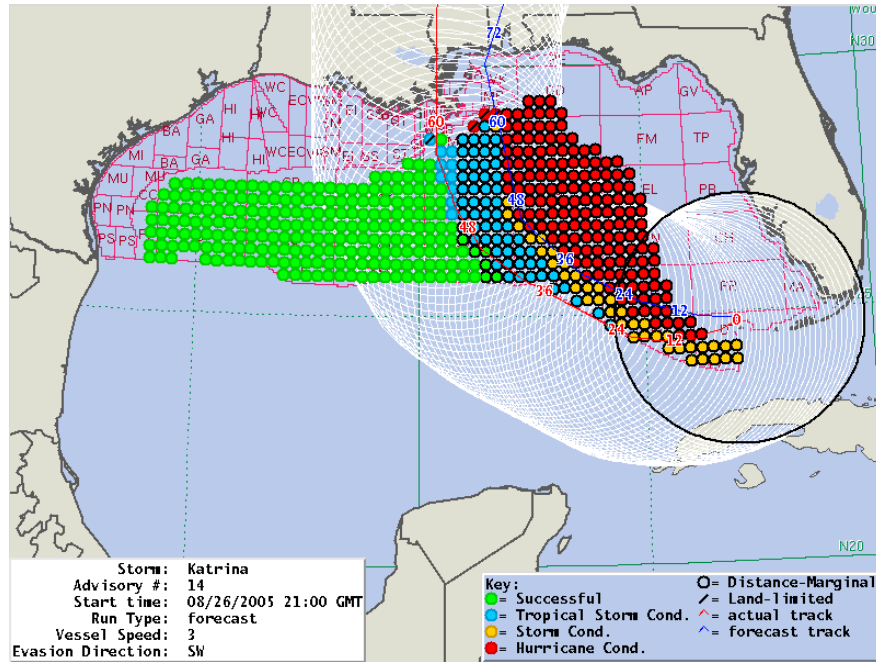


Figure 11. 1.5-ms^{-1} (3-KT) vessel evasion relative to the forecast track in the southwest direction for Hurricane Katrina advisory 14.

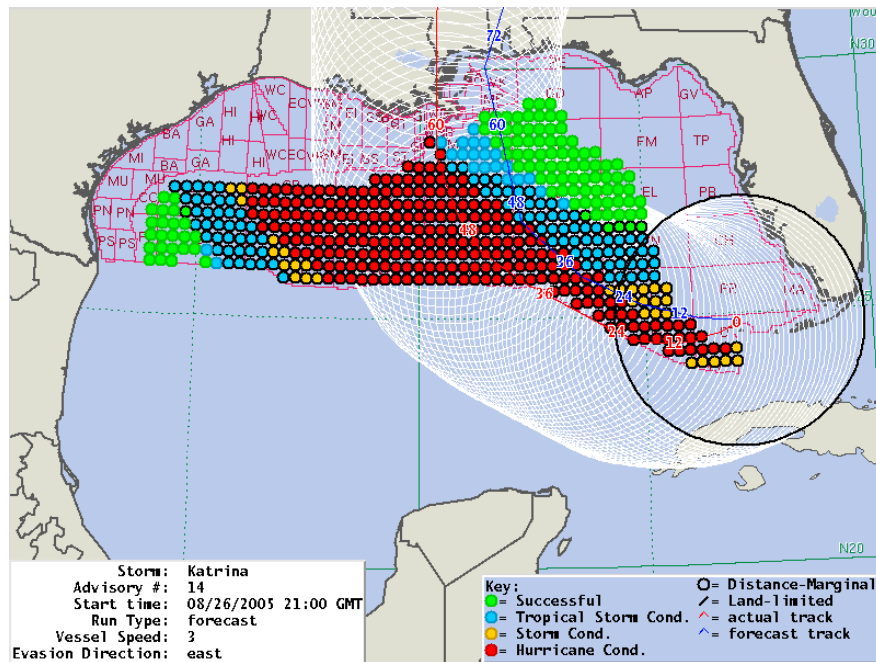


Figure 12. 1.5-ms^{-1} (3-KT) vessel evasion relative to the forecast track in the east direction for Hurricane Katrina advisory 14.

Table sets 7 and 8 compare the southwest and east evasion directions between the actual and forecast tracks, while table set 9 shows percentages of no tolerable evasion direction (in either direction) for a given starting position.

By eliminating forecast error, there is generally an increase in the rates of avoiding “intolerable conditions” for the vessels. One can compare the perfect forecast charts with the charts based on real forecast tracks to see the sharpness between success and failure becomes more defined when eliminating forecast error. Preferred positions (like left of the track and evading to the southwest) have their success rates increased, while starting positions evading towards a storm track have their success rates decreased.

4.5 Largest Storms

During the study, the authors noticed that the largest and most intense hurricanes had significantly larger areas of Orange and Red conditions. All the storms in the study were objectively ranked for their damage potential by using each hurricane’s maximum Hurricane Severity Index (HSI) within the focus area (Hebert et al. 2010).

ImpactWeather’s HSI ranks hurricanes on a 1 to 50 point scale, with half of the points attributed to their maximum sustained winds and half attributed to their size. Eight of the 26 storms had a total HSI of 25 points with a size component of at least 10 points. These storms are listed in Table 10.

These largest 8 storms made up about 31% of the forecast data points and had lower rates of avoiding intolerable conditions compared to the entire data set of all of the tropical cyclones used in study. The lower success rates were especially evident for vessels evading east and left of track and for vessels evading to the southwest and right of track.

Table sets 11, 12, and 13 show a selected comparison of the largest storms to the entire set of storms. Since larger storms have broader wind fields and are able to generate higher significant waves over a significantly larger area, it follows that they would be more hazardous to evade. If a particular storm is already large or forecast to become large, it is advisable to use these charts as guidance rather than the table sets 4-6 which include all types of hurricanes. In general, vessels should allow more time and evade earlier for larger storms.

5. SUMMARY AND DISCUSSION

The purpose of this study is to provide insight about the risks associated with DP drilling vessels moving at various speeds to avoid severe met-ocean conditions caused by hurricanes.

While maintaining a 278 km (150 NM) distance from the hurricane’s center is a useful benchmark, it may not be adequate (especially to the right of the track) for a large hurricane where high waves can extend across a very large area in the Gulf. The simulations conducted are based on historical hurricane paths, predictions of hurricane tracks that were made in real-time, and the best estimates of met-ocean conditions that occurred. The starting position relative to the forecast track of each vessel was recorded and information was gathered about the maximum met-ocean conditions experienced while moving in either a variable southwest or fixed east directions.

Throughout this study it became apparent that being right of the track made for the most challenging and difficult evasions. The right side of the track corresponds to the “dirty” side of the hurricane where met-ocean conditions are the most severe. Vessels evading to the southwest had to literally move toward the forecast track, and often the actual storm, before they could begin to move away from it. This problem could be exacerbated by forecast error as seen in examples of Hurricane Katrina. The difficulties can be reduced by giving longer lead times to vessels in those critical zones 0-139 km (0-75 NM) right of track, and even longer lead times to slower vessels in that position.

The results provide a statistical basis for the evasion time to be used in the overall hurricane preparation time. These statistics will be incorporated into the Hurricane Evacuation Plan that stakeholders can agree upon to achieve acceptable risk during hurricane preparation and evasion operations. The simulations could also be used in a Gulf of Mexico training program for captains to assist in the decision-making process for evading hurricanes. Finally, some guidance is being considered to aid the tactical decision-making process regarding when to leave the site and in which direction to go based on the forecast track, intensity of the approaching hurricane and vessel characteristics.

The tropical meteorologist can communicate his confidence in the track and intensity forecast, as well as the likelihood of a track deviation to the left or right of the forecast track. Sometimes a track deviation in a certain direction may have implications in the storm’s size or intensity as well. This extra information from a tropical meteorologist and the captain’s reaction is not something that any model or automated process can replicate with today’s current technology. While this work can help decision makers determine when they should plan to begin an evasion to achieve high rates of success, other sources such as the tropical meteorologist’s insight should also be utilized to maximize the chance of a tolerable evasion outcomes.

7a

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, Southwest Direction																						
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	100.0%	100.0%	100.0%	100.0%	100.0%	99.6%	99.3%	99.1%	99.7%	96.8%	91.3%	92.0%	87.4%	83.4%	77.7%	76.0%	72.0%	71.6%	75.9%	79.3%		
60 to 66	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.4%	81.5%	87.2%	84.0%	80.7%	67.4%	60.5%	66.0%	72.2%	79.6%	83.4%		
54 to 60	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.0%	72.9%	79.9%	76.5%	69.3%	57.6%	52.1%	62.0%	64.2%	71.6%	76.4%		
48 to 54	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	97.8%	64.9%	73.0%	71.6%	54.3%	46.0%	42.8%	47.7%	51.4%	61.2%	69.8%		
42 to 48	100.0%	99.8%	99.7%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	97.2%	71.1%	71.8%	64.6%	54.2%	47.4%	49.7%	49.8%	54.9%	62.3%	72.2%		
36 to 42	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.3%	69.0%	59.7%	48.6%	44.8%	35.8%	36.2%	39.6%	48.9%	61.6%	73.9%		
30 to 36	100.0%	100.0%	100.0%	99.8%	99.8%	100.0%	99.8%	100.0%	99.5%	95.6%	59.3%	52.0%	43.3%	42.6%	42.1%	41.7%	51.4%	60.2%	72.6%	82.6%		
24 to 30	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.6%	93.0%	44.7%	36.6%	29.0%	26.3%	28.1%	34.2%	48.8%	60.2%	69.8%	79.0%		
18 to 24	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%	99.7%	99.1%	91.5%	76.0%	38.3%	35.3%	31.2%	28.3%	32.8%	45.1%	60.6%	72.0%	77.1%	85.0%		
12 to 18	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.9%	90.2%	75.9%	58.7%	27.8%	26.8%	25.6%	25.2%	27.5%	40.3%	61.2%	74.5%	79.6%	85.2%		
6 to 12	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	91.9%	76.3%	62.9%	42.4%	22.5%	26.0%	26.9%	32.9%	44.2%	58.3%	78.6%	86.1%	91.9%	96.5%		

7b

Perfect Forecast Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, Southwest Direction																						
Starting Hour Relative to CPA of Actual Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Actual Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	100.0%	100.0%	100.0%	100.0%	99.3%	98.7%	100.0%	99.7%	99.7%	99.2%	81.6%	82.5%	82.7%	80.0%	68.9%	58.5%	64.2%	62.4%	64.8%	76.4%		
60 to 66	100.0%	100.0%	100.0%	100.0%	99.7%	99.4%	99.4%	99.7%	99.7%	99.3%	82.0%	79.9%	80.6%	72.3%	58.8%	49.2%	61.1%	58.9%	65.7%	78.7%		
54 to 60	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	99.5%	99.7%	99.8%	99.1%	82.8%	80.2%	73.1%	59.7%	45.4%	45.3%	53.3%	53.5%	65.0%	75.9%		
48 to 54	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	99.5%	99.8%	99.8%	98.9%	83.2%	79.0%	59.7%	47.0%	42.1%	41.4%	46.3%	53.1%	64.2%	75.4%		
42 to 48	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	99.5%	99.8%	99.8%	99.0%	80.8%	69.7%	43.9%	39.3%	39.5%	40.9%	52.1%	60.5%	69.9%	87.4%		
36 to 42	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	99.5%	99.8%	99.8%	98.5%	73.2%	48.5%	34.2%	32.6%	36.5%	44.3%	57.2%	63.0%	77.2%	95.7%		
30 to 36	100.0%	100.0%	100.0%	100.0%	99.7%	99.5%	99.6%	99.8%	99.8%	97.8%	55.6%	34.7%	28.3%	27.8%	40.9%	52.2%	63.4%	69.4%	85.7%	96.7%		
24 to 30	100.0%	100.0%	100.0%	100.0%	99.5%	99.1%	99.6%	99.8%	99.3%	94.3%	39.5%	27.1%	24.3%	29.5%	42.7%	55.6%	69.6%	77.6%	91.7%	98.7%		
18 to 24	100.0%	100.0%	100.0%	100.0%	99.5%	99.1%	99.6%	99.4%	96.4%	79.8%	29.0%	19.6%	23.8%	33.0%	45.0%	59.3%	75.4%	83.8%	95.0%	99.2%		
12 to 18	100.0%	100.0%	100.0%	100.0%	99.8%	99.6%	99.4%	96.7%	83.6%	63.0%	20.2%	17.5%	24.2%	39.6%	47.9%	63.1%	79.5%	89.7%	96.4%	99.4%		
6 to 12	100.0%	100.0%	100.0%	100.0%	99.8%	99.6%	96.8%	83.9%	68.5%	39.2%	18.1%	21.0%	25.1%	42.4%	52.1%	66.5%	84.4%	92.5%	97.7%	99.5%		

Tables 7a-7b. A comparison of the probabilities of avoiding intolerable conditions based on the forecast track (7a) and the actual track (7b) in the southwest direction for all of the storms used. In the example shown for a ship, intolerable conditions are orange or red met-ocean conditions.

8a

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, East Direction																						
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	78.4%	77.3%	71.5%	65.7%	63.4%	59.2%	58.5%	60.4%	60.1%	53.4%	65.3%	77.0%	78.5%	85.2%	94.1%	97.6%	96.9%	96.7%	94.9%	93.9%		
60 to 66	71.4%	71.4%	62.1%	58.6%	57.5%	54.4%	51.3%	50.2%	55.0%	55.8%	65.3%	67.9%	74.3%	81.6%	89.2%	94.5%	97.9%	96.7%	95.2%	93.5%		
54 to 60	71.9%	70.4%	67.3%	59.0%	57.4%	51.4%	52.8%	49.2%	47.9%	52.8%	66.6%	67.0%	75.4%	80.5%	84.9%	91.9%	97.3%	96.8%	95.0%	94.3%		
48 to 54	69.7%	65.2%	66.4%	56.9%	53.4%	42.0%	39.1%	49.3%	44.7%	43.8%	57.7%	64.8%	76.5%	80.7%	83.2%	89.8%	97.0%	97.1%	96.6%	95.7%		
42 to 48	79.9%	69.9%	66.4%	59.9%	53.2%	47.8%	38.5%	39.1%	41.6%	39.4%	42.5%	58.2%	70.5%	81.5%	84.4%	86.4%	88.2%	89.4%	85.3%	86.0%		
36 to 42	90.5%	77.7%	70.0%	62.0%	50.1%	42.9%	31.6%	30.2%	33.3%	36.1%	36.8%	49.9%	65.2%	81.2%	86.2%	90.1%	94.4%	95.8%	96.8%	96.9%		
30 to 36	97.9%	92.1%	80.5%	69.4%	52.5%	44.6%	28.6%	24.6%	27.4%	32.0%	36.6%	39.2%	49.3%	71.3%	83.2%	87.8%	94.4%	95.2%	97.6%	98.7%		
24 to 30	99.8%	97.9%	88.8%	76.9%	52.0%	39.0%	27.2%	23.8%	23.8%	26.0%	30.3%	33.1%	41.4%	66.1%	84.7%	91.7%	95.3%	99.2%	98.8%	99.4%		
18 to 24	100.0%	100.0%	98.0%	86.6%	70.4%	46.8%	29.2%	19.1%	20.8%	23.7%	25.8%	30.5%	37.6%	56.9%	78.0%	87.6%	93.3%	98.1%	98.5%	98.9%		
12 to 18	100.0%	100.0%	100.0%	93.3%	80.5%	61.9%	40.9%	23.9%	19.0%	19.9%	21.2%	25.1%	31.4%	51.9%	73.5%	83.2%	93.7%	98.4%	99.0%	100.0%		
6 to 12	100.0%	100.0%	100.0%	99.3%	92.5%	79.3%	56.7%	34.5%	21.9%	20.2%	19.8%	25.9%	32.6%	47.9%	67.1%	80.0%	93.5%	97.8%	99.2%	100.0%		

8b

Perfect Forecast Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, East Direction																					
Starting Hour Relative to CPA of Actual Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Actual Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	62.7%	49.6%	35.6%	26.3%	34.0%	36.9%	38.6%	38.6%	59.4%	67.2%	79.4%	90.0%	94.9%	99.0%	99.3%	97.4%	96.2%	94.7%	93.3%	92.3%	
60 to 66	69.2%	53.5%	40.1%	26.0%	22.9%	27.8%	34.8%	35.6%	50.3%	64.8%	71.6%	89.6%	93.6%	97.3%	97.5%	96.8%	94.9%	93.1%	90.9%	89.0%	
54 to 60	74.2%	61.4%	46.7%	35.0%	22.8%	16.8%	24.9%	29.9%	40.2%	54.6%	67.3%	85.6%	92.8%	96.1%	97.7%	97.4%	96.7%	95.8%	94.6%	93.3%	
48 to 54	78.1%	67.0%	53.4%	42.4%	29.5%	17.7%	12.0%	22.5%	34.7%	43.0%	57.8%	78.8%	91.1%	94.8%	97.1%	97.6%	97.0%	96.2%	95.2%	94.2%	
42 to 48	80.3%	72.7%	56.4%	39.5%	29.8%	23.3%	14.6%	14.6%	28.6%	39.2%	47.1%	72.0%	89.5%	94.1%	96.4%	97.7%	97.4%	96.8%	95.9%	95.5%	
36 to 42	87.3%	76.7%	66.7%	41.3%	28.1%	23.6%	22.1%	16.9%	23.5%	31.4%	40.5%	60.8%	87.2%	93.1%	95.8%	97.0%	97.3%	96.4%	96.3%	98.4%	
30 to 36	95.5%	86.7%	73.4%	48.3%	30.1%	23.5%	23.0%	19.5%	25.7%	26.8%	33.0%	51.5%	79.8%	91.7%	95.3%	96.0%	97.0%	96.8%	97.9%	99.6%	
24 to 30	98.8%	94.8%	86.8%	66.3%	41.3%	27.2%	22.5%	14.3%	19.9%	25.3%	28.5%	37.3%	68.1%	87.6%	94.0%	94.2%	96.4%	98.5%	99.7%	100.0%	
18 to 24	100.0%	99.0%	95.2%	82.5%	61.8%	33.1%	22.7%	14.7%	14.9%	17.9%	25.0%	29.4%	48.2%	80.1%	91.4%	94.1%	96.8%	99.5%	100.0%	100.0%	
12 to 18	100.0%	100.0%	99.6%	95.1%	81.0%	56.8%	33.1%	15.8%	13.3%	13.8%	19.2%	27.5%	38.2%	64.4%	86.1%	94.4%	97.7%	99.8%	100.0%	100.0%	
6 to 12	100.0%	100.0%	100.0%	99.6%	93.1%	77.1%	57.1%	24.4%	13.5%	16.1%	16.8%	23.8%	34.6%	57.1%	73.8%	90.7%	97.4%	99.1%	100.0%	100.0%	

Tables 8a-8b. A comparison of the probabilities of avoiding intolerable conditions based on the forecast track (8a) and the actual track (8b) in the southwest direction for all of the storms used. In the example shown for a ship, intolerable conditions are orange or red met-ocean conditions.

9a

Probability of No Successful Evasion Direction 4.5-kt Ship, All Storms																				
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.6%	1.9%	1.8%	1.5%	1.0%	0.8%	0.3%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%	1.1%	0.3%	0.0%	0.7%	0.7%	0.0%	0.7%	0.8%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.4%	0.5%	0.3%	0.0%	0.9%	0.0%	0.3%	1.4%	1.2%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	5.2%	0.8%	0.4%	0.0%	1.0%	2.7%	1.3%	0.7%	0.9%	1.0%
42 to 48	0.0%	0.2%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	9.3%	7.3%	3.3%	0.2%	1.8%	4.5%	2.8%	0.0%	0.7%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	16.4%	17.1%	13.3%	5.4%	5.5%	6.4%	3.2%	1.0%	0.4%	0.7%
30 to 36	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.2%	0.0%	0.5%	2.6%	26.6%	33.3%	32.0%	14.5%	8.7%	6.8%	2.1%	1.0%	0.2%	0.4%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	5.3%	43.5%	49.2%	46.6%	25.6%	13.5%	8.0%	4.5%	0.8%	1.5%	1.2%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	7.4%	21.3%	54.1%	56.2%	52.8%	37.1%	19.2%	11.7%	6.7%	1.9%	1.3%	0.7%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%	9.8%	23.8%	38.8%	65.9%	68.1%	65.0%	46.4%	25.9%	16.6%	6.3%	1.6%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.1%	23.7%	37.1%	57.6%	74.4%	70.0%	65.3%	50.8%	31.6%	18.9%	5.4%	1.5%	0.2%	0.0%

9b

Perfect Forecast Probability of No Successful Evasion Direction 4.5-kt Ship, All Storms																				
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	1.5%	3.5%	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%
42 to 48	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	4.1%	6.9%	4.9%	2.1%	0.2%	0.0%	0.0%	0.0%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.7%	9.4%	19.4%	10.7%	5.6%	2.8%	1.1%	0.0%	0.0%	0.0%	0.0%
30 to 36	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.2%	2.2%	30.8%	34.8%	17.3%	7.0%	3.4%	1.8%	0.0%	0.0%	0.0%	0.0%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.7%	5.7%	47.9%	51.7%	29.6%	11.0%	3.9%	2.8%	0.4%	0.0%	0.0%	0.0%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	3.6%	20.6%	59.3%	63.2%	48.9%	18.1%	5.9%	3.4%	1.2%	0.0%	0.0%	0.0%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	3.3%	16.4%	37.1%	73.2%	69.1%	57.1%	33.4%	12.2%	4.9%	1.9%	0.2%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	3.2%	16.1%	31.4%	60.7%	79.6%	73.1%	62.7%	41.0%	25.7%	9.3%	2.6%	0.9%	0.0%	0.0%

Tables 9a-9b. Comparison of the probabilities of no tolerable evasion direction given a starting position relative to the forecast track (9a) and the actual track (9b) using statistics from all storms. Cases where no tolerable evasion outcome occurred signify that either red or orange met-ocean criteria was reached in both possible directions for ships in the example shown.

Year	Storm Name	HSI Size Pts	HSI Total Pts
1995	OPAL	25	44
1998	GEORGES	19	28
2004	IVAN	24	40
2005	KATRINA	25	50
2005	RITA	19	41
2005	WILMA	21	34
2008	GUSTAV	16	26
2008	IKE	24	34

Table 10. The largest storms in the sample size.

11a

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, Southwest Direction																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	100.0%	100.0%	100.0%	100.0%	100.0%	99.6%	99.3%	99.1%	99.7%	96.8%	91.3%	92.0%	87.4%	83.4%	77.7%	76.0%	72.0%	71.6%	75.9%	79.3%	
60 to 66	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.4%	81.5%	87.2%	84.0%	80.7%	67.4%	60.5%	66.0%	72.2%	79.6%	83.4%	
54 to 60	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.0%	72.9%	79.9%	76.5%	69.3%	57.6%	52.1%	62.0%	64.2%	71.6%	76.4%	
48 to 54	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	97.8%	64.9%	73.0%	71.6%	54.3%	46.0%	42.8%	47.7%	51.4%	61.2%	69.8%	
42 to 48	100.0%	99.8%	99.7%	99.8%	100.0%	100.0%	100.0%	100.0%	100.0%	97.2%	71.1%	71.8%	64.6%	54.2%	47.4%	49.7%	49.8%	54.9%	62.3%	72.2%	
36 to 42	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.3%	69.0%	59.7%	48.6%	44.8%	35.8%	36.2%	39.6%	48.9%	61.6%	73.9%	
30 to 36	100.0%	100.0%	100.0%	99.8%	99.8%	100.0%	99.8%	100.0%	99.5%	95.6%	59.3%	52.0%	43.3%	42.6%	42.1%	41.7%	51.4%	60.2%	72.6%	82.6%	
24 to 30	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.6%	93.0%	44.7%	36.6%	29.0%	26.3%	28.1%	34.2%	48.8%	60.2%	69.8%	79.0%	
18 to 24	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%	99.7%	99.1%	91.5%	76.0%	38.3%	35.3%	31.2%	28.3%	32.8%	45.1%	60.6%	72.0%	77.1%	85.0%	
12 to 18	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.9%	90.2%	75.9%	58.7%	27.8%	26.8%	25.6%	25.2%	27.5%	40.3%	61.2%	74.5%	79.6%	85.2%	
6 to 12	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	91.9%	76.3%	62.9%	42.4%	22.5%	26.0%	26.9%	32.9%	44.2%	58.3%	78.6%	86.1%	91.9%	96.5%	

11b

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, Largest Storms, Southwest Direction																						
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	96.6%	84.2%	86.2%	76.6%	69.3%	57.0%	60.6%	64.1%	72.7%	74.9%	80.2%		
60 to 66	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.7%	67.9%	79.6%	80.2%	78.7%	61.0%	56.3%	68.5%	73.0%	70.2%	74.6%		
54 to 60	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.0%	52.9%	69.1%	67.7%	66.8%	56.4%	57.1%	67.1%	60.9%	56.3%	67.8%		
48 to 54	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	96.0%	46.9%	60.3%	61.1%	52.9%	47.7%	48.6%	55.5%	47.0%	44.3%	50.0%		
42 to 48	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	94.7%	57.1%	58.8%	54.2%	42.3%	35.6%	31.2%	32.8%	43.6%	55.7%	63.0%		
36 to 42	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	96.8%	54.3%	47.4%	38.4%	28.9%	21.7%	24.7%	25.5%	30.6%	40.9%	44.9%		
30 to 36	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.2%	92.2%	42.5%	34.7%	25.8%	20.1%	18.8%	12.9%	16.9%	17.5%	24.5%		
24 to 30	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	96.7%	85.9%	23.5%	16.4%	11.0%	10.8%	3.9%	5.6%	10.1%	15.5%	19.2%		
18 to 24	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.2%	82.4%	51.2%	15.5%	9.8%	5.7%	3.0%	2.0%	5.7%	12.9%	21.2%	28.4%	38.0%		
12 to 18	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	97.4%	75.7%	46.9%	22.2%	8.8%	1.3%	0.8%	1.2%	1.4%	2.4%	11.0%	16.1%	22.6%	27.9%		
6 to 12	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	80.7%	44.7%	22.4%	12.5%	3.4%	0.0%	0.0%	2.3%	10.3%	15.4%	39.6%	49.2%	50.0%	80.0%		

11c

Difference in the Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms vs. Largest Storms, Southwest Direction																						
Starting Hour Relative to CPA of Actual Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Actual Track																					
	Starting Position Left of Track											Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250		
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.7%	0.9%	0.3%	-0.2%	-7.1%	-5.9%	-10.8%	-14.1%	-20.7%	-15.5%	-7.9%	1.1%	-1.0%	0.9%		
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.6%	-13.6%	-7.6%	-3.8%	-2.0%	-6.3%	-4.2%	2.5%	0.8%	-9.4%	-8.8%		
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.0%	-20.0%	-10.8%	-8.8%	-2.5%	-1.2%	5.0%	5.1%	-3.3%	-15.3%	-8.6%		
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.8%	-17.9%	-12.7%	-10.4%	-1.5%	1.8%	5.9%	7.8%	-4.4%	-16.9%	-19.8%		
42 to 48	0.0%	0.0%	0.2%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	-2.5%	-14.1%	-13.0%	-10.4%	-11.8%	-11.8%	-18.5%	-17.1%	-11.2%	-6.6%	-9.2%		
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.5%	-14.7%	-12.3%	-10.2%	-16.0%	-14.0%	-11.5%	-14.1%	-18.3%	-20.7%	-29.0%		
30 to 36	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.2%	0.0%	-0.3%	-3.4%	-16.8%	-17.3%	-17.5%	-22.5%	-23.4%	-28.8%	-34.5%	-42.7%	-48.1%	-51.3%		
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.9%	-7.1%	-21.2%	-20.3%	-18.0%	-15.5%	-24.2%	-28.6%	-38.8%	-44.7%	-50.5%	-60.0%		
18 to 24	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.3%	0.1%	-9.1%	-24.8%	-22.9%	-25.5%	-25.5%	-25.3%	-30.8%	-39.5%	-47.7%	-50.8%	-48.8%	-46.9%		
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.6%	-14.5%	-28.9%	-36.5%	-19.0%	-25.6%	-24.8%	-24.0%	-26.1%	-37.9%	-50.2%	-58.4%	-57.0%	-57.3%		
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-11.2%	-31.6%	-40.5%	-29.8%	-19.1%	-26.0%	-26.9%	-30.6%	-33.9%	-42.9%	-39.0%	-37.0%	-41.9%	-16.5%		

Table 11a-11c. A comparison of the probabilities of avoiding intolerable conditions at a given starting position relative to the forecast track using statistics from all storms (11a) and just the largest storms (11b) evading to the southwest. The difference in the probabilities is given in 11c with values in shades of white ($\geq 0\%$), yellow ($\leq -5\%$), and red ($\leq -25\%$). In the case of ships, intolerable evasion outcomes involved cases where orange or red met-ocean criteria were encountered.

12a

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms, East Direction																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	78.4%	77.3%	71.5%	65.7%	63.4%	59.2%	58.5%	60.4%	60.1%	53.4%	65.3%	77.0%	78.5%	85.2%	94.1%	97.6%	96.9%	96.7%	94.9%	93.9%	
60 to 66	71.4%	71.4%	62.1%	58.6%	57.5%	54.4%	51.3%	50.2%	55.0%	55.8%	65.3%	67.9%	74.3%	81.6%	89.2%	94.5%	97.9%	96.7%	95.2%	93.5%	
54 to 60	71.9%	70.4%	67.3%	59.0%	57.4%	51.4%	52.8%	49.2%	47.9%	52.8%	66.6%	67.0%	75.4%	80.5%	84.9%	91.9%	97.3%	96.8%	95.0%	94.3%	
48 to 54	69.7%	65.2%	66.4%	56.9%	53.4%	42.0%	39.1%	49.3%	44.7%	43.8%	57.7%	64.8%	76.5%	80.7%	83.2%	89.8%	97.0%	97.1%	96.6%	95.7%	
42 to 48	79.9%	69.9%	66.4%	59.9%	53.2%	47.8%	38.5%	39.1%	41.6%	39.4%	42.5%	58.2%	70.5%	81.5%	84.4%	86.4%	88.2%	89.4%	85.3%	86.0%	
36 to 42	90.5%	77.7%	70.0%	62.0%	50.1%	42.9%	31.6%	30.2%	33.3%	36.1%	36.8%	49.9%	65.2%	81.2%	86.2%	90.1%	94.4%	95.8%	96.8%	96.9%	
30 to 36	97.9%	92.1%	80.5%	69.4%	52.5%	44.6%	28.6%	24.6%	27.4%	32.0%	36.6%	39.2%	49.3%	71.3%	83.2%	87.8%	94.4%	95.2%	97.6%	98.7%	
24 to 30	99.8%	97.9%	88.8%	76.9%	52.0%	39.0%	27.2%	23.8%	23.8%	26.0%	30.3%	33.1%	41.4%	66.1%	84.7%	91.7%	95.3%	99.2%	98.8%	99.4%	
18 to 24	100.0%	100.0%	98.0%	86.6%	70.4%	46.8%	29.2%	19.1%	20.8%	23.7%	25.8%	30.5%	37.6%	56.9%	78.0%	87.6%	93.3%	98.1%	98.5%	98.9%	
12 to 18	100.0%	100.0%	100.0%	93.3%	80.5%	61.9%	40.9%	23.9%	19.0%	19.9%	21.2%	25.1%	31.4%	51.9%	73.5%	83.2%	93.7%	98.4%	99.0%	100.0%	
6 to 12	100.0%	100.0%	100.0%	99.3%	92.5%	79.3%	56.7%	34.5%	21.9%	20.2%	19.8%	25.9%	32.6%	47.9%	67.1%	80.0%	93.5%	97.8%	99.2%	100.0%	

12b

Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, Largest Storms, East Direction																					
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	59.6%	66.5%	62.4%	55.4%	65.5%	60.9%	58.3%	51.4%	49.1%	42.2%	50.3%	62.9%	70.8%	81.4%	91.3%	97.8%	98.7%	100.0%	98.7%	95.4%	
60 to 66	40.2%	57.3%	44.0%	45.6%	53.9%	61.8%	66.4%	58.1%	55.6%	41.6%	49.8%	52.8%	60.0%	74.2%	85.2%	95.9%	100.0%	100.0%	100.0%	100.0%	
54 to 60	34.3%	41.9%	38.4%	35.6%	45.1%	55.3%	64.3%	59.6%	55.6%	49.7%	58.0%	55.6%	66.3%	70.2%	78.9%	90.8%	99.3%	100.0%	100.0%	100.0%	
48 to 54	21.6%	25.0%	30.1%	23.6%	25.8%	30.8%	36.3%	52.6%	51.5%	43.9%	51.3%	59.7%	65.7%	68.3%	73.7%	87.8%	98.6%	100.0%	100.0%	100.0%	
42 to 48	39.3%	27.6%	24.5%	15.2%	13.7%	17.3%	21.9%	27.6%	34.0%	31.0%	35.1%	46.8%	55.7%	68.6%	72.0%	79.6%	84.8%	84.2%	79.5%	76.5%	
36 to 42	68.9%	40.0%	36.7%	26.1%	7.1%	2.5%	9.0%	12.6%	17.0%	20.4%	18.6%	32.9%	48.3%	68.0%	74.8%	84.5%	93.9%	97.0%	100.0%	100.0%	
30 to 36	91.7%	76.0%	54.4%	40.7%	18.3%	10.7%	1.9%	3.7%	5.9%	9.2%	10.9%	8.9%	24.1%	54.7%	69.8%	79.5%	90.4%	93.3%	95.3%	94.8%	
24 to 30	99.1%	93.3%	66.9%	50.0%	22.7%	15.0%	4.9%	0.0%	0.0%	4.1%	4.7%	7.2%	14.3%	47.9%	72.8%	83.4%	89.7%	99.2%	100.0%	100.0%	
18 to 24	100.0%	100.0%	94.6%	66.8%	38.4%	17.9%	10.4%	1.9%	0.0%	0.8%	0.4%	2.9%	7.1%	33.3%	59.6%	72.5%	85.6%	99.2%	100.0%	100.0%	
12 to 18	100.0%	100.0%	100.0%	82.8%	55.9%	29.6%	15.0%	6.1%	1.6%	0.0%	0.0%	0.0%	3.6%	22.9%	52.9%	68.5%	88.4%	98.4%	100.0%	100.0%	
6 to 12	100.0%	100.0%	100.0%	97.7%	78.1%	49.3%	22.0%	11.3%	5.2%	2.5%	1.4%	0.0%	1.5%	14.0%	37.9%	55.6%	86.6%	95.0%	98.8%	100.0%	

12c

Difference in the Probability of Avoiding Unsuccessful Conditions 4.5-kt Ship, All Storms vs. Largest Storms, East Direction																					
Starting Hour Relative to CPA of Actual Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Actual Track																				
	Starting Position Left of Track										Starting Position Right of Track										
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250	
66 to 72	-18.8%	-10.7%	-9.1%	-10.3%	2.1%	1.7%	-0.3%	-9.0%	-11.0%	-11.2%	-15.0%	-14.1%	-7.7%	-3.8%	-2.8%	0.1%	1.8%	3.3%	3.8%	1.5%	
60 to 66	-31.2%	-14.1%	-18.2%	-13.0%	-3.6%	7.4%	15.2%	7.9%	0.6%	-14.2%	-15.5%	-15.0%	-14.3%	-7.4%	-4.0%	1.5%	2.1%	3.3%	4.8%	6.5%	
54 to 60	-37.6%	-28.5%	-28.9%	-23.4%	-12.3%	3.9%	11.4%	10.4%	7.7%	-3.1%	-8.6%	-11.3%	-9.1%	-10.3%	-6.0%	-1.1%	2.0%	3.2%	5.0%	5.7%	
48 to 54	-48.1%	-40.2%	-36.2%	-33.3%	-27.6%	-11.2%	-2.9%	3.3%	6.8%	0.1%	-6.4%	-5.1%	-10.8%	-12.4%	-9.5%	-2.0%	1.6%	2.9%	3.4%	4.3%	
42 to 48	-40.6%	-42.3%	-41.9%	-44.7%	-39.5%	-30.5%	-16.6%	-11.4%	-7.6%	-8.4%	-7.5%	-11.4%	-14.9%	-12.9%	-12.4%	-6.8%	-3.4%	-5.2%	-5.8%	-9.4%	
36 to 42	-21.6%	-37.7%	-33.4%	-36.0%	-43.1%	-40.4%	-22.5%	-17.6%	-16.3%	-15.7%	-18.2%	-17.0%	-16.9%	-13.3%	-11.4%	-5.7%	-0.5%	1.2%	3.2%	3.1%	
30 to 36	-6.2%	-16.1%	-26.1%	-28.7%	-34.2%	-34.0%	-26.7%	-20.9%	-21.4%	-22.8%	-25.7%	-30.3%	-25.2%	-16.6%	-13.3%	-8.3%	-4.0%	-1.8%	-2.4%	-4.0%	
24 to 30	-0.7%	-4.6%	-21.9%	-26.9%	-29.3%	-24.1%	-22.3%	-23.8%	-23.8%	-22.0%	-25.6%	-25.9%	-27.1%	-18.2%	-11.8%	-8.3%	-5.6%	0.0%	1.2%	0.6%	
18 to 24	0.0%	0.0%	-3.5%	-19.7%	-32.0%	-28.9%	-18.8%	-17.2%	-20.8%	-22.9%	-25.4%	-27.5%	-30.5%	-23.5%	-18.4%	-15.1%	-7.7%	1.1%	1.5%	1.1%	
12 to 18	0.0%	0.0%	0.0%	-10.5%	-24.7%	-32.3%	-25.9%	-17.8%	-17.3%	-19.9%	-21.2%	-25.1%	-27.8%	-29.1%	-20.6%	-14.6%	-5.3%	0.0%	1.0%	0.0%	
6 to 12	0.0%	0.0%	0.0%	-1.6%	-14.4%	-30.0%	-34.6%	-23.2%	-16.7%	-17.7%	-18.4%	-25.9%	-31.1%	-33.9%	-29.2%	-24.4%	-6.9%	-2.8%	-0.4%	0.0%	

Table 12a-12c. A comparison of the probabilities of avoiding intolerable conditions at a given starting position relative to the forecast track using statistics from all storms (12a) and just the largest storms (12b) evading to the southwest. The difference in the probabilities is given in 12c with values in shades of white ($\geq 0\%$), yellow ($\leq -5\%$), and red ($\leq -25\%$). In the case of ships, intolerable evasion outcomes involved cases where orange or red met-ocean criteria were encountered.

13a

Probability of No Successful Evasion Direction 4.5-kt Ship, All Storms																				
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	0.6%	1.9%	1.8%	1.5%	1.0%	0.8%	0.3%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%	1.1%	0.3%	0.0%	0.7%	0.7%	0.0%	0.7%	0.8%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.4%	0.5%	0.3%	0.0%	0.9%	0.0%	0.3%	1.4%	1.2%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	5.2%	0.8%	0.4%	0.0%	1.0%	2.7%	1.3%	0.7%	0.9%	1.0%
42 to 48	0.0%	0.2%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	9.3%	7.3%	3.3%	0.2%	1.8%	4.5%	2.8%	0.0%	0.0%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	16.4%	17.1%	13.3%	5.4%	5.5%	6.4%	3.2%	1.0%	0.4%	0.7%
30 to 36	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.2%	0.0%	0.5%	2.6%	26.6%	33.3%	32.0%	14.5%	8.7%	6.8%	2.1%	1.0%	0.2%	0.4%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	5.3%	43.5%	49.2%	46.6%	25.6%	13.5%	8.0%	4.5%	0.8%	1.5%	1.2%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	7.4%	21.3%	54.1%	56.2%	52.8%	37.1%	19.2%	11.7%	6.7%	1.9%	1.3%	0.7%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%	9.8%	23.8%	38.8%	65.9%	68.1%	65.0%	46.4%	25.9%	16.6%	6.3%	1.6%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.1%	23.7%	37.1%	57.6%	74.4%	70.0%	65.3%	50.8%	31.6%	18.9%	5.4%	1.5%	0.2%	0.0%

13b

Probability of No Successful Evasion Direction 4.5-kt Ship, Largest Storms																				
Starting Hour Relative to CPA of Forecast Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Forecast Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.9%	3.5%	4.6%	4.9%	2.9%	1.6%	0.0%	0.0%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%	0.0%	0.0%	0.0%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	7.9%	0.9%	0.0%	0.0%	0.9%	1.1%	0.7%	0.0%	0.0%	0.0%
42 to 48	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.4%	14.7%	10.9%	5.9%	0.4%	3.6%	7.2%	4.8%	0.0%	0.0%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	29.8%	27.2%	20.7%	10.0%	10.9%	11.4%	6.1%	3.0%	0.0%	0.0%
30 to 36	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	5.0%	48.9%	58.2%	55.6%	29.2%	19.8%	16.5%	6.6%	3.3%	0.0%	0.0%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.3%	11.5%	72.3%	76.7%	75.6%	43.6%	24.8%	16.2%	10.3%	0.8%	0.0%	0.0%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	17.6%	48.3%	84.1%	87.6%	87.2%	65.2%	40.4%	27.5%	14.4%	0.8%	0.0%	0.0%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.6%	24.3%	53.1%	77.8%	91.2%	98.7%	95.6%	77.1%	47.1%	31.5%	11.6%	1.6%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	19.3%	55.3%	77.6%	87.5%	96.6%	100.0%	98.5%	86.0%	62.1%	44.4%	13.4%	5.0%	1.3%	0.0%

13c

Difference in the Probability of No Successful Evasion Direction 4.5-kt Ship, All Storms vs. Largest Storms																				
Starting Hour Relative to CPA of Actual Track	Starting Distance (NM) Relative to the Closest Point of Approach (CPA) of Actual Track																			
	Starting Position Left of Track										Starting Position Right of Track									
	225 to 250	200 to 225	175 to 200	150 to 175	125 to 150	100 to 125	75 to 100	50 to 75	25 to 50	0 to 25	0 to 25	25 to 50	50 to 75	75 to 100	100 to 125	125 to 150	150 to 175	175 to 200	200 to 225	225 to 250
66 to 72	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.2%	-0.3%	-1.6%	-2.7%	-3.4%	-1.9%	-0.8%	0.3%	0.0%	0.0%
60 to 66	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.6%	0.0%	1.1%	0.3%	0.0%	0.7%	-0.2%	0.0%	0.7%	0.8%
54 to 60	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%	0.4%	0.5%	0.3%	0.0%	0.9%	0.0%	0.3%	1.4%	1.2%
48 to 54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.2%	-2.7%	-0.2%	0.4%	0.0%	0.1%	1.6%	0.6%	0.7%	0.9%	1.0%
42 to 48	0.0%	0.2%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.1%	-5.5%	-3.6%	-2.6%	-0.2%	-1.9%	-2.8%	-2.0%	0.0%	0.0%	0.0%
36 to 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.9%	-13.4%	-10.1%	-7.4%	-4.7%	-5.5%	-5.0%	-2.9%	-2.1%	0.4%	0.7%
30 to 36	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%	0.2%	0.0%	-0.3%	-2.3%	-22.3%	-24.9%	-23.5%	-14.7%	-11.1%	-9.7%	-4.5%	-2.4%	0.2%	0.4%
24 to 30	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.9%	-6.2%	-28.8%	-27.6%	-29.0%	-18.0%	-11.3%	-8.3%	-5.8%	0.0%	1.5%	1.2%
18 to 24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%	-10.1%	-27.0%	-30.0%	-31.4%	-34.4%	-28.0%	-21.2%	-15.8%	-7.7%	1.1%	1.3%	0.7%
12 to 18	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-1.6%	-14.5%	-29.3%	-39.0%	-25.3%	-30.7%	-30.6%	-30.7%	-21.2%	-14.9%	-5.3%	0.0%	0.0%	0.0%
6 to 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-11.2%	-31.6%	-40.5%	-29.8%	-22.2%	-30.0%	-33.2%	-35.2%	-30.6%	-25.5%	-8.1%	-3.5%	-1.0%	0.0%

Tables 13a-13b. Comparison of the probabilities of no tolerable evasion direction given a starting position relative to the forecast track using statistics from all storms (13a) and just the largest storms (13b). The difference in the probabilities is given in 13c with values in shades of white ($\geq 0\%$), yellow ($\leq -5\%$), and red ($\leq -25\%$). Cases where no tolerable evasion outcome occurred signify that either red or orange met-ocean criteria was reached in both possible directions for ships in the example shown.

6. FUTURE WORK

Similar techniques used for Gulf of Mexico simulations could be used in other parts of the world that are affected by tropical cyclones such as the Indian Ocean, South China Sea, etc. In addition to tropical areas, similar methods could be employed for severe mid-latitude extratropical cyclones that can cause severe weather offshore Newfoundland, the North Sea, etc.

Future work to improve the simulations to more accurately reflect what might happen in a real-world situation could be performed using one or more of the following techniques:

- Adjust direction of evasion to avoid shallow water or land.
- Allow the eastward evasion direction to vary like the southwestward evasion direction or consider only directions perpendicular to the right or left of the forecast track.
- Program a vessel to vary its evasion direction and change its direction completely with new advisories.
- Use a better source or more realistic way to estimate significant wave heights before 1999
- Incorporate the 10 storms that had missing NHC archived forecast data at the time the study was conducted. Also incorporate any new hurricanes forecast or predicted to impact the Gulf of Mexico since 2010.

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