TITLE:

Quantification of Stokes drift as a mechanism for surface oil advection in the Gulf of Mexico

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Key points:

Surface water wave motion substantially contributes to transport of material transport at the surface

Swell from tropical cyclones causes much greater transport

Waves have relatively greater impact in shelf waters

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ABSTRACT:

Wave-driven transport, also known as Stokes drift, is the motion of a particle due to the orbital motion induced by a passing wave. Stokes drift has previously been qualitatively shown to have a signature in ocean surface transport, with most studies focused exclusively in near-shore regions. However, Stokes drift has never been quantified beyond theoretical studies and case studies limited to small regions. Here, Stokes drift is calculated directly from Wavewatch III model data in the Gulf of Mexico for April-July 2010. Its magnitudes are compared between deep and shelf water areas, and against the magnitudes of surface currents and parameterized wind drift. These comparisons are also made specifically for the time period surrounding the passage of Hurricane Alex through the southwestern Gulf of Mexico. While there is not a major difference between the absolute magnitudes of Stokes drift in shelf vs. deep water areas or when compared to wind drift, Stokes drift is larger in shelf water areas relative to surface currents than in deep water. During Hurricane Alex, wave heights and there for Stokes drift magnitudes were much larger in the immediate area of the storm, which also led to much larger Stokes drift magnitudes in the oil spill region as the swell had propagated away from the storm and throughout the Gulf of Mexico.

TEXT:

1. INTRODUCTION

1.1 Background

On 20 April 2010, the *Deepwater Horizon* (DWH), a floating exploratory oil drilling platform, was drilling a well in the Gulf of Mexico at a depth of approximately 1,600 m when the well experienced a catastrophic blowout. That caused a large fire on the platform which led to the deaths of 11 workers, the sinking of the platform, and a leaking oil well on the ocean floor. From that moment until 15 July 2010, the well leaked approximately 58,000 barrels of oil per day into the Gulf [MacDonald 2010]. Some of this oil remained below the water surface, while the rest made it to the surface and was carried throughout the northeastern Gulf of Mexico.

First responders subsequently undertook efforts to prepare for and prevent the arrival of the oil to shorelines, through deployment of equipment such as booms and oil-collecting ships. One element of these efforts was the use of oil spill forecast models to predict the future locations and tracks of the oil slicks, in order to more efficiently and effectively deploy those resources. These models typically incorporate weather and ocean current forecasts, and in some cases also lesser mechanisms such as wave- and wind-driven transport. For this study, we consider the effect of waves (known as Stokes drift) on the movement of oil in the Gulf of Mexico during the months in which the oil spill occurred.

1.2 Stokes Drift

Stokes drift is the lateral displacement of a particle in the direction of wave motion, due to the orbital motion of a passing wave train in a body of water. This effect was described by Stokes [1847] for finite-amplitude gravity waves. The displacement is due to the orbital motions not forming closed loops, which itself is due to the diminishing effects of horizontal displacement with increasing depth. The forward motion of a particle on the surface at the crest of a wave (top of the orbit) is larger than the counter-motion backward at the trough of the wave (bottom of the orbit). The net displacement over a single wave period is the result of a second-order term in the overall wave motion equation, and so is sometimes disregarded in models.

There have been many studies in the past relating to the theoretical importance of Stokes drift to the overall transport of surface oil in the ocean. For example, Sobey and Barker [1997] used an idealized model of a near-shore region with along-shore current and onshore waves to determine the relative importance of Stokes drift. They found that Stokes drift was responsible for onshore beaching of surface oil in their model, in part due to the natural refracting of waves towards the shore by shoaling. Le Hénaff and Kourafalou [2012] found that including wind-induced drift (which includes Stokes drift) was beneficial to accurately modeling the movement of surface oil; hence we are interested in better quantifying contribution of Stokes drift.

Stokes' [1847] wave theory is predicated on the assumption of a homogeneous, incompressible fluid with uniform depth through which the wave is passing, and with the wave itself being of constant velocity and form throughout. For the consideration of determining Stokes drift velocities for a single ocean wave over a single wave period, these assumptions can be considered valid.

Stokes drift (U_s) averaged over a single wave period is given by

$$U_s = \frac{a^2 \sigma k \cosh(2k(H-z))}{2\sinh^2(kH)} \tag{1}$$

where a is wave amplitude, k is the wave number, σ is the wave frequency, z is the depth being considered, and H is the depth of the water column on which the wave is occurring. Variables commonly found in wave models, however, include wave height (h), wave period (T), and wavelength (L) [Monismith 2004]. Using the equations

$$h = 2a \,, \tag{2}$$

$$T = \frac{2\pi}{\sigma} \,, \tag{3}$$

and

$$L = \frac{2\pi}{k} \,, \tag{4}$$

and assuming $z = 0$ since for this study only Stokes drift at the surface is being considered, equation 1 becomes

$$U_S = \frac{\pi^2 h^2}{LT} \frac{\cosh(2kH)}{2\sinh^2(kH)} \tag{5}$$

This form of the equation accounts for both shallow and deep water waves. As waves move close to the coast the water becomes shallower, changing the wave characteristics relative to the deep water waves. The horizontal grid spacing of our ocean model limits the conditions to deep water in the vast majority of our cases; however we use the full equation to avoid artificial distinctions between shallow and deep water waves. Consequently there is little adjustment in wave direction and Stokes drift due to shoaling. Models that cover conditions closer to the coast would have to consider shoaling and its impact on wave transport. Le Hénaff and Kourafalou [2012] used a model in which Stokes drift was derived using two dimensional wave spectra. We tested both approaches in the Gulf of Mexico, and found that the results were practically identical. That assumption is expected to be valid in a semi-enclosed basin, but should not be used in a large ocean basin.

Stokes drift is often included in models via an approximation based on the wind speed and direction. This approximation includes surface motion due to Ekman transport, Stokes drift and directly wind forced drift, and the result is called “wind drift” [Weber 1983]. The common range of values for this combined transport used in models is 2-5% of the 10 m wind speed at an angle 20° to the right of the wind direction [Hackett et al. 2006]. This approximation arose out of necessity, at a time when ocean and wave models were of insufficient resolution to allow for direct accounting of either Stokes drift or Ekman transport. However, this parameterization requires several assumptions, including wind wave equilibrium (that is, a steady sea state), and sufficient time for a full Ekman balance to develop, neither of which are reasonable in real-world conditions. Modern ocean models no longer require this approximation to be made, since Ekman transport can be more directly modeled. Additionally, modern wave models allow for Stokes drift to be calculated directly, which makes using a wind speed approximation for wind drift unnecessary and unreasonable (because it results in double the Ekman motion).

One reason for considering Stokes drift separately from using the wind speed-derived approximation is that Stokes drift can be present even without the presence of wind. Swell, by definition, is a wave that has propagated away from its area of formation. Stokes drift will be present for any wave, even swell, so therefore it will be present when swell is the only present portion of the wave spectrum. This is a situation that often occurs when there is calm, or with a very weak wind or recent wind such that the local wind wave field is not fully developed. Swell can also be present for higher local wind speeds if the swell waves are very large. A tropical cyclone is one example of a storm system that can create swell in the Gulf of Mexico.

Similarly, when considering oil as the material being transported, it is important to note the effect its presence on the ocean surface has on local waves. Oil has been observed and modeled to modify the wave field by damping out the shorter waves [Banger and Garrett 1968; Khalifa et al. 1992; Soloviev et al. 2011], reducing the surface roughness [Lindsley and Long 2012], and hence increasing the wind speed [Zheng et al. 2013]. It also can reduce air-sea friction, further inhibiting local wave development. However, this impact is minimized on swell originating away from an oil slick, which results in the presence of the Stokes drift factor in regions affected by an oil spill. Additionally, when high wind speeds occur over an oil slick, the slick tends to break apart, reducing this effect, both through turbulence in the upper ocean layer and wave breaking, mixing oil into the water column. However, wind speeds of sufficient magnitude to do this are not commonplace in the Gulf of Mexico except in tropical cyclones and winter cold frontal passages.

Basing Stokes drift calculation on wind speed at a given level also ignores the different manners in which the wind can interact with the ocean surface, and thus how the sea state will develop given a particular (e.g. 10 m) wind speed. A wind profile in a stable atmospheric surface layer (which occurs frequently at night) will result in weaker wind stress at the atmosphere/water boundary, leading to smaller waves. Conversely, an unstable atmospheric surface layer, even with the same 10 m wind speed, will result in greater wind stress at the atmosphere/water boundary, leading to larger wave heights and thus larger Stokes drift magnitudes for the same wind speed at the given height. Additionally, drift is affected by whitecapping and wave breaking, which violate the assumptions listed above. In the Gulf of Mexico, winds are usually light enough that Stokes drift is a valid approximation.

1.3 Outline

This study quantifies the effect of Stokes drift on the transport of surface oil in the Gulf of Mexico during the DWH spill. The data used in the study as well as the methods by which Stokes drift is determined from that data is presented (Chapter 2). The results of the calculation of Stokes drift in the Gulf of Mexico during the months of the oil spill are given. 24-hour displacements due to Stokes drift are also examined, as well as comparisons to surface ocean currents and wind drift (Chapter 3). The impact of a hurricane which occurred during the study period are detailed (Chapter 4). It will be shown that Stokes drift was an important factor in the transport of oil during the DWH spill, and thus it is important to accurately account for Stokes drift in models.

2. DATA AND METHODS

2.1 Wavewatch III

In order to undertake a quantitative analysis of wave transport in the Gulf of Mexico, a full, continuous gridded wave dataset is needed. This means that relying on observational data, such as wave reports from buoys and ships, is insufficient, as those sources are often temporally discontinuous and too sparsely located to provide a meaningful representation of the entire Gulf. Additionally, ship-based wave reports in particular are usually estimated rather than measured. Therefore, for this study, it is necessary to use data from a wave model to calculate Stokes drift.

2.1.1 Existing Data

An existing dataset was considered. The U.S. National Center for Environmental Prediction (NCEP) offers model hindcasts globally from the present time back to 1997, at three-hour intervals [NOAA 2009]. These wave hindcasts are forced by Global Forecast System (GFS) wind input. However, this data was incomplete in the Gulf of Mexico, as the gridded peak wave period output contained spatial gaps for undetermined reasons (Figure 1). In addition, the highest-resolution output available (1/15° grid) is only available for regions within approximately 100 km of coasts. More coarse data (1/6°) was available covering the entire Gulf, but that also contained the peak period gaps. So, in order to acquire a full, complete gridded dataset to cover the study period of April-July 2010, it became necessary to use a wave model to create high-resolution continuous wave data for the entire Gulf specifically to be used for this study. Accordingly, the Wavewatch III model was utilized.

2.1.2 Running Wavewatch III

Wavewatch III [Tolman 2009] is a spectral wind wave model that can simulate wind-generated local wave fields and swell propagating from non-local areas. It was developed by the Marine Modeling and Analysis branch of the Environmental Modeling Center, within NCEP. Wavewatch works by separating wave spectrum at each grid point into partitions by energy density peaks, as well as calculating peak and mean wave variables for the entire spectrum. The model has available a number of parameterization and other options. Wavewatch can also accept several input parameters as wave forcing and limiting mechanisms, including near-surface atmospheric winds, sea ice concentrations, and air and sea-surface temperatures. For this work, ice is not included (since the area of interest is the Gulf of Mexico, where ice is not present). Atmospheric wind and temperature and sea-surface temperature are included, in order to allow for surface stress adjustment due to stability.

The model was set up with a 1/15° grid covering the Gulf of Mexico (18-31° N, 80-100° W) with a time step of 450 seconds, nested within a coarser grid (1/2° spacing) covering all of the north Atlantic Ocean (5° S-55° N, 5-100° W) with a time step of 900 seconds (Figure 2). Boundary conditions for the coarse grid (except for the western boundary, which is entirely land) and the initialization of both grids were done using the idealized Joint North Sea Wave Observation Project (JONSWAP) spectrum [Hasselmann 1973]. This initialization was done to provide a starting point, after which the model was run for a two-week period (prior to the beginning of the study period) using model data (see below) for forcing, ensuring that any spurious wave energy in the model should be dissipated before analysis data was generated, leaving only waves driven by actual wind. Similarly, by placing the coarse grid boundaries a considerable distance from the fine grid boundaries (which received boundary conditions from the coarse grid), JONSWAP-influenced wave energy was dissipated before it propagated into the fine grid.

Although the period of interest for this work is April-July 2010, Wavewatch was initialized at 15 March 2010 00Z, and run through 10 August 2010 00Z. The early start was intended to provide a "spin-up" of the model to reduce spurious world-driven wave energy from the JONSWAP initialization. The extended run time allowed for sufficient additional data to be generated to calculate trajectories initialized as late as July 31.

Wavewatch was forced using both atmospheric wind and temperature and sea-surface temperature (SST). Using both temperatures is important, as doing so provides the model with the ability to approximate the wind profile between the height of the "measurement" wind and the surface. Forcing data for this work was obtained from NCEP's Climate Forecast System Reanalysis (CFSR) [Saha 2010]. This product originally existed only for the period from 1979-2009, but was recently extended through 2010. Atmospheric wind was taken from the 10 m wind velocities. Temperatures were used from the water surface and from a height of 2 m. Water depths were provided by NOAA's World Geophysical Data Center 2-minute Gridded Global Relief Data (ETOPO2v2) [NGDC 2001].It should be cautioned that this implementation of Wavewatch III does not include the effects of currents, which would affect the wind stress levels at the air-sea boundary (by changing the wind velocity relative to a particular point on the surface, which would then be initially moving with the current rather than only with the wave motion).

The model was set to save output data at each hour. Three output variables were used for this work: significant wave height (h), peak wave period (T), and peak wave direction (θ). Notably, the peak period output did not contain the gaps present in the already-existing data (Figure 3). All were chosen as they are commonly available in both observations and models, and can be used to calculate Stokes drift. Wavelength (L) was then calculated from the peak period (T), using the deep-water wavelength

$$L_0 = \frac{gT^2}{2\pi} \tag{6}$$

and the dispersion relation

$$L = L_0 \tanh\left(\frac{2\pi H}{L}\right) \tag{7}$$

to reach a final wavelength for use in Eq.(5). Stokes drift was then calculated at each point in the Gulf of Mexico at each hourly time step from 1 April 2010 00Z to 10 August 2010 00Z.

2.2 Methods

2.2.1 Stokes Drift

In order to provide a basic overview of Stokes drift in the Gulf of Mexico, Stokes drift was calculated using Eq.(5) at each point in the model domain, restricted to the Gulf (meaning, excluding the portions of the Caribbean Sea and Atlantic Ocean present in the model domain) at each hourly time step from 01 April 2010 00Z to 31 July 2010 23Z, so as to include the time period of and some time before and after the spill. Any points for which any data needed for calculating Stokes drift (wave height, period, length, or direction) were missing were excluded, which occurred 0.08% of the time. Additionally, grid points at which the water depth was less than 1 m were also excluded, since these locations were so near to land that waves are either breaking or likely directed onshore.

It is also useful to consider Stokes drift as a comparison between deep water and shelf water areas. Water waves in sufficiently shallow water (how shallow is dependent on wavelength) interact with the ocean bottom, resulting in changes to wave parameters such as height and speed that are included in the calculation of Stokes drift. Additionally, shelf water does not have the large (and deep) eddies of the open Gulf, but does have substantial coastal currents; therefore there could be a different distribution of surface velocities (which we will refer to as currents). Therefore, we examine the relative importance of Stokes drift and currents in the deep Gulf and on the shelves. For this study, the boundary between shallow/shelf and deep water is set at 100 meters. This provides for the approximate separation of the shallow continental shelf areas from the deep ocean.

2.2.2 Trajectories

Another method of comparing Stokes drift between deep and shelf water is with the use of trajectories. This allows for considering not how Stokes drift magnitudes change at a point, but instead considering what would happen to a theoretical particle (such as a patch of oil floating on the surface) over time due to Stokes drift. Here, with Stokes drift velocities calculated at each grid point every hour, it is possible to consider the net displacement of a particle over a period of time (here chosen to be 24 hours) due solely to Stokes drift. Particles are considered massless and infinitely small, which means they offer no resistance to their theoretical movement. In order to determine net displacements, at each hour in the data, a tracer grid was initialized at each velocity grid point in the Gulf of Mexico. For each of 24 successive hours, a new position was calculated for each position grid point based on the Stokes drift velocity field for that hour, and except for the initial advection (when all grid points were co-located with the initial velocity grid points), the velocity applied according to a Runge-Kutta interpolation of that hour's Stokes drift velocity field. If a position grid point was at any time advected off the velocity field, it was considered stopped at its last known point for the remainder of the time. Once the tracer points had been advected for 24 hours, the distance they had ended up from their initial locations was then calculated.

2.2.3 Stokes Drift and Other Transport Mechanisms

Stokes drift is, of course, not the only transport mechanism that contributes to the movement of surface oil. For this study, Stokes drift is compared to modeled surface currents the data-assimilative Gulf of Mexico (GOM) HYCOM experiment_31.0 and compared to wind drift (see section 1.2 for details) as 2% of the CFSR 10 m wind speed at a declination of 20°. The HYCOM model data is on a 1/25° spatial and 1-hour temporal grid, and does not include tidal forcing. The CFSR model data is on a 1/3° spatial and 1-hour temporal grid. Both products are hindcasts and were interpolated onto the 1/15° grid used by Wavewatch. Both HYCOM and CFSR are data-assimilative, meaning that they should be reasonably robust for this purpose. For both comparisons, magnitude of theStokes drift is divided by the magnitude of the alternative surface trnasport mechanism to produce a ratio at each grid point and time. These ratios are then compared between deep and shelf water areas.

The data-assimilative GOM HYCOM experiment_31.0 has a ~4 km (1/25°) horizontal grid spacing at the latitude of the GOM and uses 20 vertical coordinate surfaces. The model uses a hybrid vertical layering system, employing isopycnal layers in the stratified open ocean, terrain-following coordinates in coastal areas, and fixed pressure-coordinates in the mixed layer [Bleck, 2002; Chassignet et al., 2006]. Interface depths change at each time step to reflect thermohaline variability, and layers are more closely spaced in the upper ocean. Outputs are interpolated to a nominal latitude-longitude-depth grid and archived in NetCDF format. The model is run in near real time at the NAVOCEANO Major Shared Resource Center to produce seven-day forecasts and four-day hindcasts. Hourly hindcast data are publicly available on the HYCOM consortium data server (http://hycom.org/dataserver). HYCOM 31.0 uses the 3D-VAR Navy Coupled Ocean Data Assimilation (NCODA) system [Cummings, 2005; Cummings and Smedstad, 2013]. NCODA assimilates all available observations. These include surface information from satellites (SST and SSH), plus in situ temperature and salinity profiles from XBTs (expendable bathythermographs), CTDs (conductivity-temperature-depth), gliders, and Argo floats [Chassignet et al., 2007, 2009; Cummings and Smedstad, 2013; Metzger et al., 2014]. Satellite altimetry for NCODA comes from the NAVOCEANO Altimeter Data Fusion Center, which combines SSH from Jason-1, OSTM/Jason-2, Geosat, and Envisat. Vertical projection of the surface observations is achieved via generation of synthetic profiles using the Modular Ocean Data Analysis System [MODAS; Fox et al. 2002]. For a detailed description of the model and its outputs, the reader is referred to http://hycom.org/data/goml0pt04/expt-31pt0 and to Rosburg et al. [2016]. For a detailed description of HYCOM, the reader is referred to Bleck [2002], Chassignet et al. [2003], and Chassignet et al. [2006].

3. STOKES DRIFT IN THE GULF OF MEXICO

3.1 Stokes Drift in the Full Gulf of Mexico

For the Gulf of Mexico as a whole, the average Stokes drift magnitude was 3.99 km/day, while the median was 3.40 km/day (see Table 1) during the study period. This indicates that the distribution of Stokes drift magnitudes skewed towards smaller values (in fact, this is the case for all Gulf-wide Stokes drift-related distributions considered in this study) (Figure 4). In addition, there was a wide variation in the distribution of wave (and therefore Stokes drift) directions, although the vast majority of waves during the period did have at least some westward component (Figure 5).

3.2 Stokes Drift Comparison - Deep vs. Shelf Water

For waves occurring over shelf water, Stokes drift magnitudes averaged 3.70 km/day with a median of 3.09 km/day, while for deep water Stokes drift magnitudes averaged 4.12 km/day with a median of 3.52 km/day (Table 2). In addition, magnitudes in shelf water exhibited a smaller variation, with a standard deviation of 2.78 vs. 2.91 km/day in deep water (Figures 6) It is unclear whether the larger average Stokes drift magnitudes in deep water are simply the result of larger waves due to higher wind speeds, or to what extent, if any the slowing of waves due to bottom interaction was responsible.

The small difference between the average Stokes drift magnitudes for deep and shelf water is not unexpected. While conventional wisdom does hold that “shallow water” waves generally have larger Stokes drift magnitudes, this is in reference to shallow water waves which are interacting with the ocean bottom. This is not the comparison being made here. The large majority of waves occurring over shelf water (again, defined for this study as depths of 100 m or less) are in fact still deep-water waves by that definition. Waves in the Gulf of Mexico are rarely large enough to become “shallow water” waves except in very shallow water (for example, depths of less than 10 m), which in this study constitutes a very small number of grid points.

3.3 Stokes Drift Compared to Current and Wind Drift

While Stokes drift showed a small difference when comparing deep and shelf water areas, this difference is much more pronounced when comparing Stokes drift magnitudes to surface current magnitudes. In deep water areas, Stokes drift magnitudes were an average of 20.8% of the collocated surface current (Figure 7). However, in shelf water areas, Stokes drift was 36.0% of the surface current magnitude on average, with a much wider distribution of ratios (Figure 10). This means that Stokes drift is a more significant relative factor in surface transport in shelf water areas, and so accurate representation of Stokes drift in transport models is more important in these areas.

Stokes drift is a larger contribution to the total surface transport of oil in shelf water primarily due to these areas having smaller surface current magnitudes. As seen previously, there is not a large difference in Stokes drift magnitudes themselves between deep and shelf water, while large magnitudes of surface current are primarily found in the loop current and loop current eddies, which are largely confined to deep water areas.

Similar comparisons were made with Stokes drift and a percentage of the wind speed ("wind drift"). Here, 2% of the wind speed is considered, which is at the bottom of the range of wind drift parameterizations used in trajectory models. As shown in Figures 8, there is little difference in ratios when comparing between deep and shelf water areas (which is expected since both regions typically experience similar wind speeds). However, it *can* be seen that there is a wide distribution of ratios of Stokes drift to 2% of the wind speed in both figures. This indicates that there is poor correlation of Stokes drift and wind speed, implying that using wind speed as a proxy for Stokes drift is not especially accurate. Since there is sometimes swell propagating into a region from elsewhere, and sea state does not instantaneously change in response to changing wind speeds, this is not an unexpected result, however the example of the magnitude of the error highlights the importance of using more physically sound approaches to modeling surface transport.

4. STOKES DRIFT DURING A HURRICANE

While Stokes drift is induced by any wave, the largest magnitudes of Stokes drift are generally produced by the largest waves. Correspondingly, the largest waves in the Gulf of

Mexico are produced by the strongest winds, which are almost always found in tropical cyclones. In addition, large waves produced by these storms propagate away to become significant swell in locations within the Gulf well away from their origins. This produces an extreme case in which Stokes drift as estimated from the local wind speed can be especially inadequate as a means of accounting for particle displacement.

During the four months of this study, two tropical cyclones passed through the Gulf of Mexico. Hurricane Alex occurred in late June, while Tropical Depression Bonnie (previously a tropical storm) occurred in late July. Bonnie was not considered for this study, due to being below tropical storm-force for its entire presence in the Gulf.

4.1 Hurricane Alex

Hurricane Alex formed in the Caribbean Sea on June 24, 2010 as a tropical depression, then strengthened into a tropical storm, crossing the Yucatan Peninsula and entering the southwestern Gulf of Mexico on June 27 with maximum sustained wind speeds of 35 kt. The storm then moved northwest across the western Gulf, strengthening into a category 2 hurricane with maximum sustained wind speeds of 95 kt, before making a second landfall on the northern Mexico coast on July 1 [Pasch 2010]. This resulted in a period of approximately 72 h during which large-height waves were being generated by increasingly strong winds across the southwestern Gulf of Mexico. These waves were of sufficient size and energy that they could propagate throughout the Gulf of Mexico as swell before dissipation.

To examine how Hurricane Alex affected Stokes drift magnitudes across the Gulf, two regions within the Gulf are compared before, during, and after the storm. The first of these regions is the southwestern Gulf, where the storm had a direct impact on wave heights, while the second region is the northeastern Gulf, where the oil spill was occurring and distant from the hurricane's winds (Figure 9). For each region, Stokes drift magnitudes are compared during three seven-day periods: one before the storm entered the Gulf, one encompassing the entire time any part of the storm's circulation was over the Gulf, and one following the storm's landfall (see Table 3). Seven-day periods are intended to be short enough to prevent the effects of the hurricane on Stokes drift from being lost as noise, while being long enough to not be affected by daily and day-to-day random weather events.

4.2 Stokes Drift During Hurricane Alex

During the week before Alex entered the Gulf of Mexico, Stokes drift magnitudes in the southwestern Gulf study region averaged 2.69 km/day, which was below the region's four-month average of 3.03 km/day, with a standard deviation of 1.47 (Figure 10 red line, and Table 4). Similarly, Stokes drift magnitudes in the northeastern Gulf averaged 1.89 km/day with a standard deviation of 1.82, which was also below that region's four-month average of 3.22 km/day (Figure 11, red line, and Table 5). As Alex traversed the southwestern Gulf of Mexico, its winds generated large waves. This resulted in that week's average Stokes drift magnitude in the region rising sharply to 7.64 km/day, which lies at the 88th percentile of the four-month period (Figure 10, blue line, and Table 4). The distribution of magnitudes during that time period also increased drastically, with the standard deviation rising to 5.16. In the northeastern Gulf, the mean Stokes drift magnitude also rose, but only to 2.82 km/day, which was still below the area's four-month average. However, the variability of the magnitudes also increased to 2.41 (Figure 11, blue line, and Table 5). It is likely that most (but not all) of the storm-produced wave energy during this period was still remaining in the southwestern Gulf, with only a small amount having propagated away into the northeastern Gulf to boost Stokes drift values there.

Once Alex made landfall in northeastern Mexico, its winds were no longer influencing wave development in the Gulf of Mexico. In the southwestern Gulf, this resulted in average Stokes drift magnitudes dropping to 3.80 km/day, or just under half of their during-storm values. The overall distribution of Stokes drift magnitudes in this region during this time was still more spread out compared to the week before the storm, with a standard deviation of 2.58, indicating a residual effect from the storm itself (Figure 10, green line, and Table 4). In the northeastern Gulf, Stokes drift magnitudes were even higher than they were during the storm, averaging 3.99 km/day, with a similarly larger standard deviation of 3.01 (Figure 11, green line, and Table 5). This is due to propagating swell from the storm more readily influencing Stokes drift in this region.

Hurricane Alex presents an extreme example of swell impacting Stokes drift magnitudes in an area distant from the storm. Large waves generated by the storm propagated northeastward as swell into the oil spill region, leading to larger Stokes drift magnitudes throughout the area even though there was no corresponding large increase in wind speeds. Estimating Stokes drift as a function of wind speed would have been especially inaccurate in this instance. Additionally, this case demonstrates the high variability of Stokes drift over a short time due to a single extreme weather event.

5. CONCLUSION

Stokes drift has been shown to be an important mechanism in the transport of surface oil, with an average magnitude of 3.99 km/day and an average 24-hour Lagrangian displacement of 3.84 km for any particle during the study period of 1 April 2010 to 31 July 2010 in the Gulf of Mexico. Although this study was limited to parts of the Gulf of Mexico over a relatively short period of time, the basic principle, that Stokes drift is an important surface transport mechanism and should be accounted for in models in the most precise manner available, is logically applicable for any body of water on which wind waves form.

When comparing Stokes drift for waves occurring in water of relatively shallow depth (the continental shelf, delineated as water of depth less than 100 m) against that for waves occurring in deeper water (depth greater than or equal to 100 m), no physically significant difference in magnitude was found during the study period. This is most likely because waves are primarily wind-driven, and there was little if any difference in wind speeds over waters of differing depths. It is possible that for areas of sufficiently shallow depth that waves interact with the ocean bottom, there may have been a more notable difference, but the Gulf of Mexico has relatively small waves when compared with other basins, due to lighter winds and scarcity of swell, especially during the spring and summer months included in this study. This means that the number of grid points and times wherein waves would be impacted by bottom interaction was small.

However, when comparing Stokes drift magnitudes to surface current magnitudes, there is a notable difference between shelf and deep water. Stokes drift is a larger relative component in overall surface transport compared to surface current in shelf water, approximately double the percentage of the local current magnitude, when compared to deep water. This is primarily due to weaker surface currents in shallower water. Therefore, if calculating Stokes drift in an oil spill model with limited computing resources, it is more important to do so for shallow/shelf water areas, as Stokes drift is a larger part of total surface transport there.

While Stokes drift is often approximated in surface transport models as a percentage of the wind speed at a specific angle from the wind direction, it is not the best way to account for

Stokes drift if the model includes a wave component. This is because Stokes drift has significant variation from the wind, due to the lag between changing wind speed and sea state response, as well as swell propagating into a region from elsewhere. This means that there are often waves (and with them, Stokes drift) occurring even when the local wind is calm. Thus, when designing a trajectory model which includes waves, it is preferable to calculate the Stokes drift component of transport directly from the wave parameters rather than using the wind speed approximation.

During weather events that involve high wind speeds over long time periods and large areas, such as hurricanes, waves (and with them, Stokes drift magnitudes) can grow very large. Swell propagating out from these areas into more distant areas can make a wind speed approximation of Stokes drift especially inaccurate. Additionally, Stokes drift can become a much more significant fraction of the total surface transport. This effectcan last for a few days after the storm has exited the basin, indicating that Stokes drift due to swell is an important consideration and that wave models should be used when estimating surface transport.

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TABLES:

Table 1: Stokes drift magnitudes, full Gulf of Mexico, April-July 2010

Parameter	Value (km/day)
Mean	3.99
9th percentile	0.76
25th percentile	1.79
Median (50th percentile)	3.40
75th percentile	5.63
91st percentile	8.13
Standard deviation	2.88

Table 2: Stokes drift magnitudes, deep vs. shelf water, Gulf of Mexico, April-July 2010

Parameter	Deep Water Value (km/day)	Shelf Water Value (km/day)
Mean	4.12	3.70
9th percentile	0.86	0.59
25th percentile	1.95	1.46
Median (50th percentile)	3.52	3.09
75th percentile	5.71	5.43
91st percentile	8.29	7.79
Standard Deviation	2.91	2.78

Table 3: Dates of weeks before, during and after Hurricane Alex for study consideration

Storm Location	Dates Considered
Before entering Gulf	6/19/2010 - 6/25/2010
Impacting Gulf	6/26/2010 - 7/2/2010
After exiting Gulf (Over land)	7/3/2010 - 7/9/2010

Table 4: Stokes drift magnitudes (km/day) of the weeks surrounding Hurricane Alex, in the area directly impacted by the storm.

Parameter	Before Alex	During Alex	After Alex
Mean	2.69	7.64	3.80
9th percentile	1.20	1.91	0.66
25th percentile	1.70	3.42	1.67
Median (50th percentile)	2.35	6.67	3.51
75th percentile	3.31	10.61	5.39
91st percentile	4.94	15.20	7.43
Standard Deviation	1.48	5.16	2.58

Table 5: Stokes drift magnitudes (km/day) of the weeks surrounding Hurricane Alex, in the area impacted by the oil spill.

Parameter	Before Alex	During Alex	After Alex
Mean	1.89	2.82	3.99
9th percentile	0.16	0.44	0.42
25th percentile	0.42	0.98	1.46
Median (50th percentile)	1.35	2.75	3.32
75th percentile	2.75	3.90	6.23
91st percentile	4.81	6.70	8.66
Standard Deviation	1.82	2.41	3.01

FIGURES:

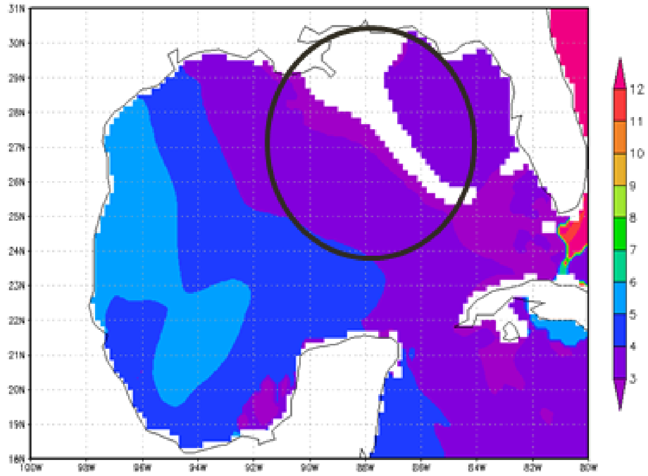

Figure 1: Example of NCEP peak wave period data (s), 1 May 2010 00Z. Problematic gap circled.

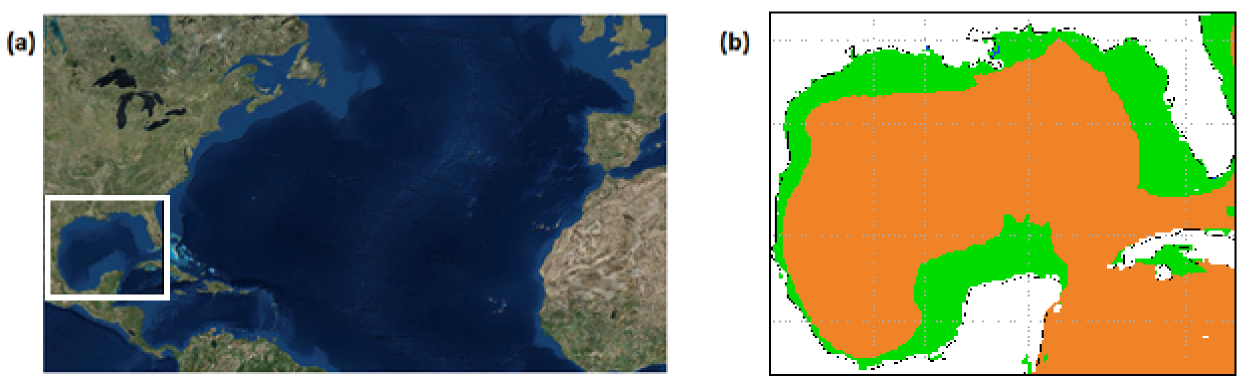

Figure 2: Maps showing extent of the model domains used for Wavewatch III. (a) 0.5° Atlantic Ocean grid with box indicating the location of the Gulf of Mexico grid. (b) 1/15° Gulf of Mexico grid with the green region indicating depths ≤ 100 m and the orange region indicating depths > 100 m

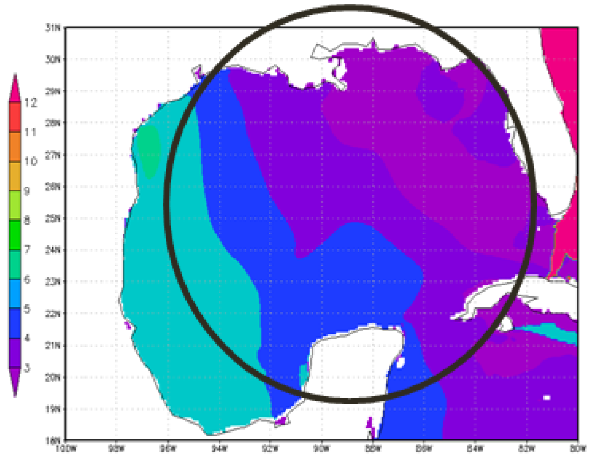

Figure 3: Example of WW3 modeled peak wave period data (s), 1 May 2010 00Z. The lack of a gap in this data is circled.

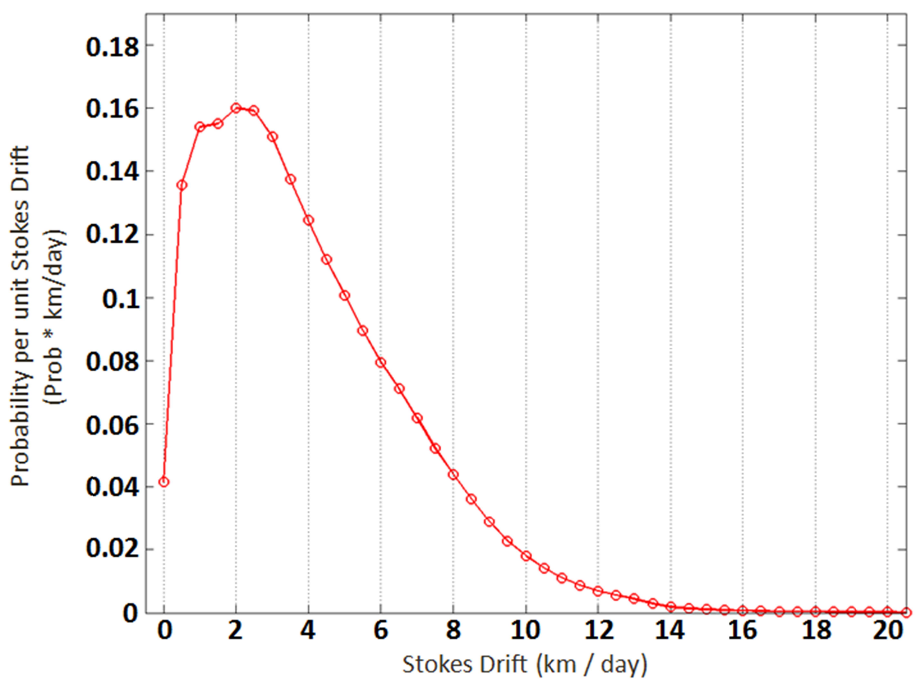

Figure 4: Probability density function of Stokes drift magnitude distributions in the Gulf of Mexico, April-July 2010.

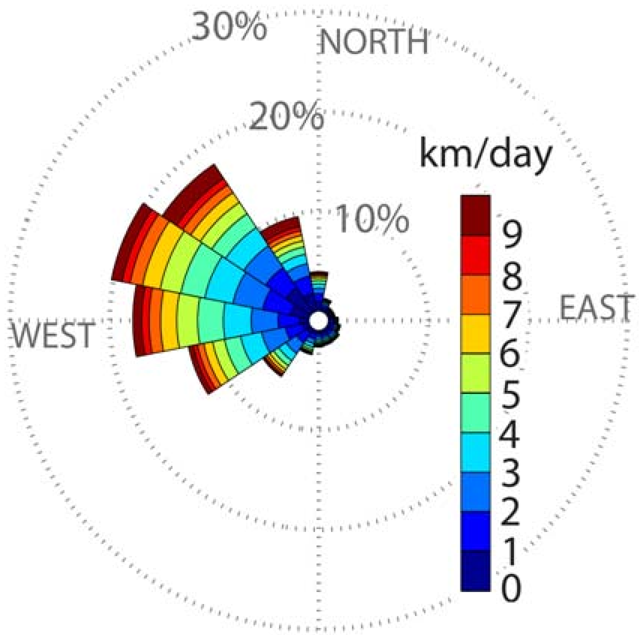

Figure 5: Directional rose plot of Stokes drift distributions in the Gulf of Mexico, April-July 2010. Directions are in oceanographic convention.

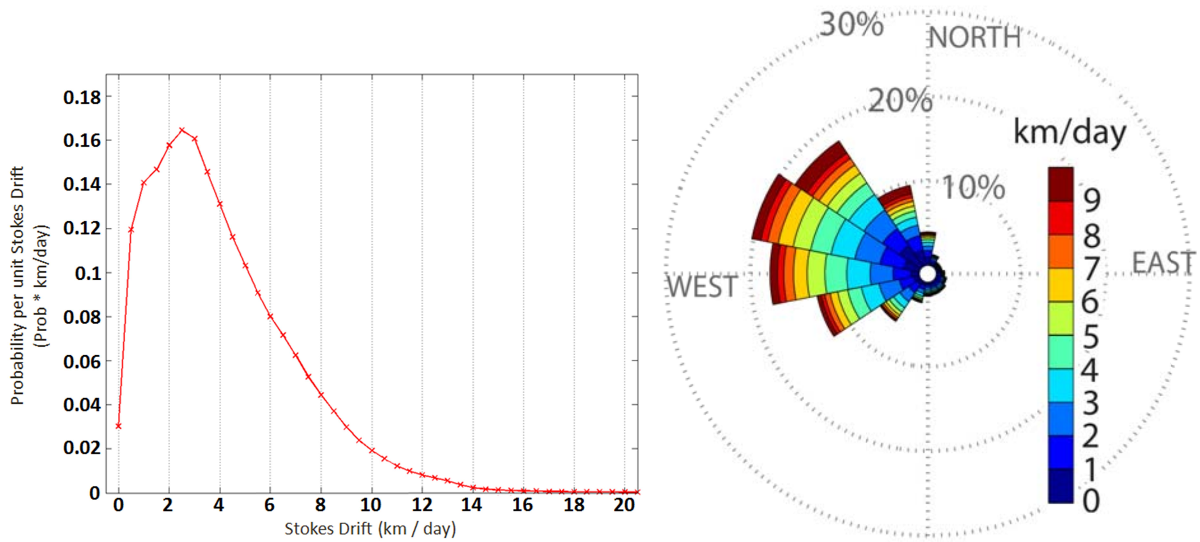

Figure 6: Probability distribution (left) and Directional rose plot (left) of Stokes drift distributions in the Gulf of Mexico, April-July 2010, for water with depths >100m. Directions are in oceanographic convention.

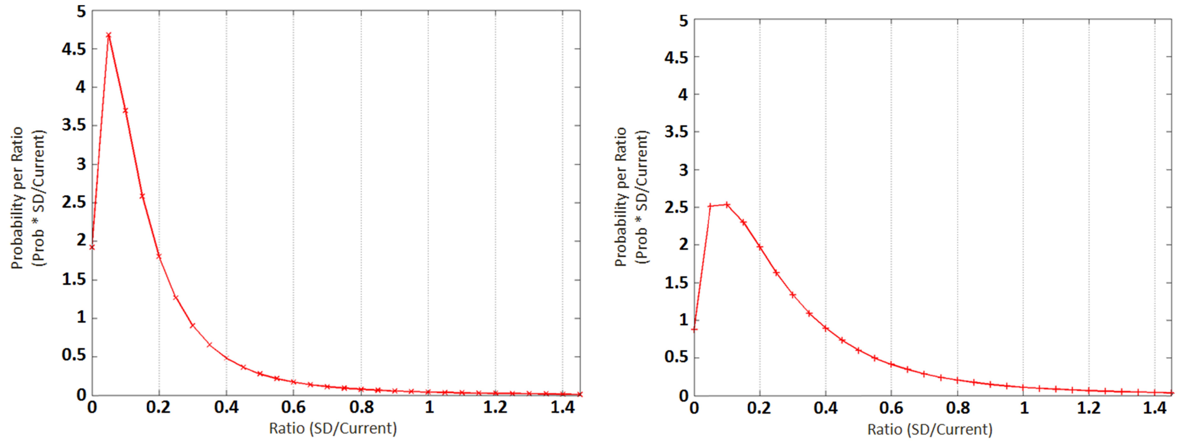

Figure 7: Probability density function of Stokes drift to surface current ratios in the Gulf Mexico, from April-July 2010, for (left) waters deeper than 100 m, and (right) waters ≤100 m depth.

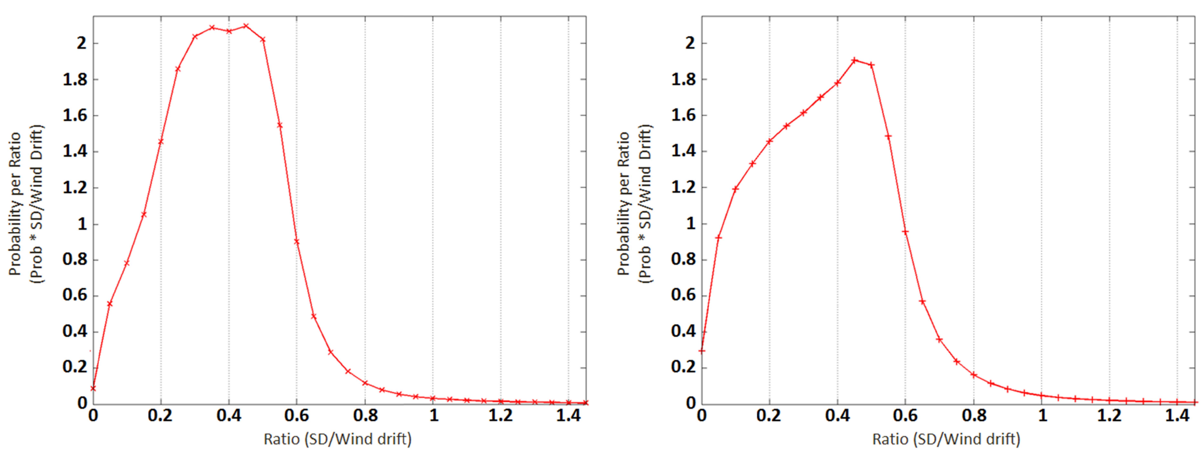

Figure 8: Probability density function of Stokes drift to wind drift ratios in the Gulf Mexico, April-July 2010 for (left)waters >100 m depth and (right) waters ≤100 m depth.. Wind drift is considered to be 2% of the 10 m wind speed.

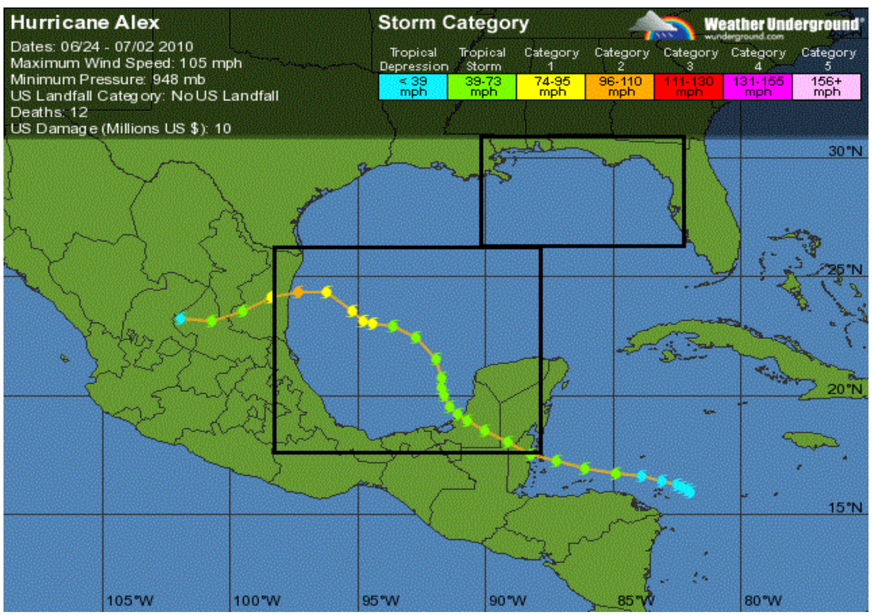

Figure 9: Map of Hurricane Alex storm track. Lower left box is area considered to be directly affected by storm. Upper right box is area considered to be affected by oil spill. From wunderground.com.

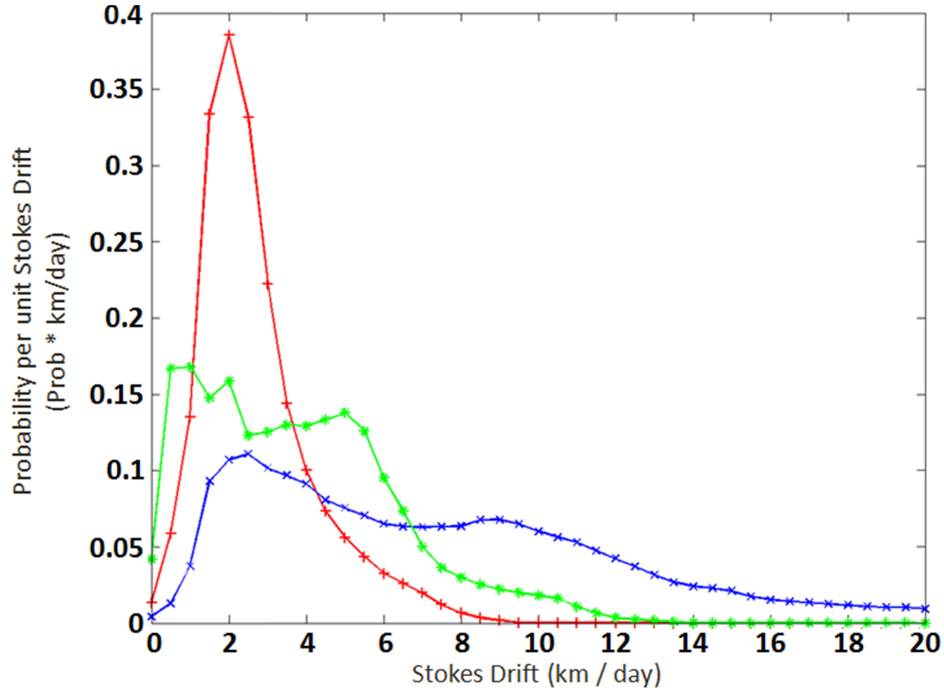

Figure 10: Probability density functions of Stokes drift magnitudes in the area of the Gulf of Mexico directly affected by Hurricane Alex. The red line with + marks is before the storm; the blue line with x marks is during the storm, and the green line with * marks is after the storm.

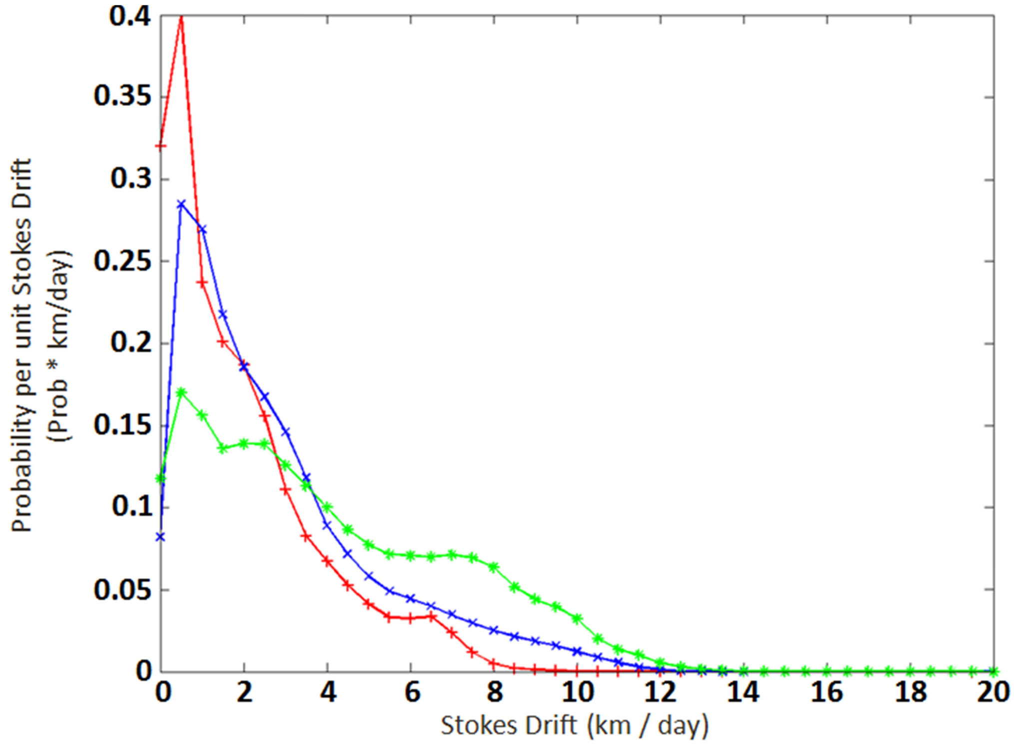

Figure 11: Probability density functions of Stokes drift magnitudes in the area of the Gulf of Mexico affected by the oil spill. The red line with + marks is before the storm; the blue line with x marks is during the storm, and the green line with * marks is after the storm.