2011

Determinig the Effects of Stokes Drift on the Movement of Oil in the Gulf of Mexico

Nicolas Heath

ABSTRACT

The impact of Stokes drift, a wave-driven mechanism of mass transport, is investigated for surface oil movement in the Gulf of Mexico. Stokes drift was neglected in trajectory forecasts in the Gulf during the Deepwater Horizon oil spill. The key considerations used in Gulf of Mexico trajectory forecasts were surface currents and wind drift. This study presents a physical argument for the importance of Stokes drift and questions the significance of wind drift over an oil slick. Furthermore, the magnitude and direction of the wind drift (2–5% of the wind speed and 20° to the right in the Northern Hemisphere) is very similar to that of the Stokes drift. For this reason, the differences between Stokes drift and the wind drift are examined using a vector comparison. The directional components of Stokes drift and the wind drift are found to be very similar although the magnitudes of the wind drift are found to be larger. When swell not associated with the local wind is present, however, the two drifts have significantly different directional components.

Horizontal surface trajectories are computed for different atmospheric and oceanic conditions. Trajectory results are compared to satellite-derived oil locations using a center of mass comparison method. Analysis of trajectory forecasts and observed oil locations suggests that Stokes drift might play an important role in the movement of oil at the surface and that the magnitude of the wind drift may not be as large as most models presume.

Key Words: oil spill, wave-driven transport, oil movement

THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

DETERMINING THE EFFECTS OF STOKES DRIFT ON THE MOVEMENT OF OIL IN THE GULF OF MEXICO

By

NICHOLAS HEATH

A Thesis submitted to the
Department of Earth, Ocean and Atmospheric Science
in partial fulfillment of the requirements for graduation with
Honors in the Major

Degree Awarded:
Spring Semester, 2011

The members of the Defense Committee approve the thesis of Nicholas Heath defended on 08 April 2011.

____

Dr. Mark Bourassa

Thesis Director

____

Dr. Dmitry Dukhovskoy

Outside Committee Member

____

Dr. Jon Ahlquist

Committee Member

ACKNOWLEDGEMENTS

I would like to acknowledge my major professor, Dr. Mark Bourassa, and my committee members, Dr. Jon Ahlquist and Dr. Dmitry Dukhovskoy, for all of their help and guidance throughout this research project. I would like to thank Dr. Steve Morey for providing the HYCOM currents data and Oscar Garcia for providing the satellite-derived oil spill locations. I would like to also acknowledge Dr. Robert Hart for providing assistance and guidance in GrADS. I would like to thank the COAPS writing coach, Kathy Fearon, for all of her help during the writing process. Lastly, I would like to thank everyone at COAPS for providing such a great environment to work in.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

On 20 April 2010, the BP Deepwater Horizon oil platform in the Gulf of Mexico suffered a catastrophic explosion that resulted in 11 deaths. This explosion created a leak in the Macondo oil well located approximately 1500 m below the sea surface. Oil from the leak gushed into the Gulf at an estimated rate of 58,000 barrels per day until it was finally capped on 15 July 2010 (MacDonald 2010). Approximately 4.8 million barrels (206 million gallons) of oil poured into the Gulf of Mexico over the leak's lifetime. Trajectory forecasts for the oil, especially at the surface, played a significant role in aiding cleanup crews with information on oil locations as well as in helping coastal regions prepare for oil beaching. Six different trajectory models using a variety of atmospheric and oceanic forcing to simulate oil particle trajectories were implemented for the Gulf of Mexico (Liu et al. 2011). Ensemble forecasts were then generated to determine the most likely path for the oil. Surprisingly, none of these models included a wave-driven mechanism of mass transport called Stokes drift (Stokes 1847), a net forward motion in the direction of surface wave propagation. Because of refraction, Stokes drift is usually directed toward shore, making it an important transport mechanism in coastal regions. The trajectory models that were used for the Deepwater Horizon spill included only an empirically derived wind drift (2–5% of the wind speed and 20° to the right of the wind direction) to describe surface movement apart from the ocean currents (ocean currents were the primary forcing in all six models). The purpose of this research is to look specifically at the effects of Stokes drift on the transport of oil in the Gulf of Mexico in hopes of better understanding all of the processes that contribute to oil movement and of helping increase the accuracy of trajectory models in the future. This paper first presents physical reasoning and evidence to support the argument that Stokes drift may be a more important factor than wind drift for oil covered sea surfaces and then looks at the numerical similarities between the two drifts. A model that parameterizes Stokes drift is then used to compare trajectory forecasts using Stokes drift and wind drift with satellite derived oil locations.

2 Background

2.1 Stokes Drift

As waves travel, the water particles that make up the waves do not travel in a straight line, but rather in orbital motions (Pond et al. 1978). While investigating oscillatory waves, G.G. Stokes (1847) discovered that water particles do not move over a closed orbital path. Instead, Stokes found that water particles have an additional movement in the direction of wave propagation. As the particles progress in an orbital motion, their movement is enhanced at the top of the orbit and slowed slightly at the bottom. The result is a net forward motion of water particles, referred to as Stokes drift. Stokes drift is graphically represented in Fig. 1.1.

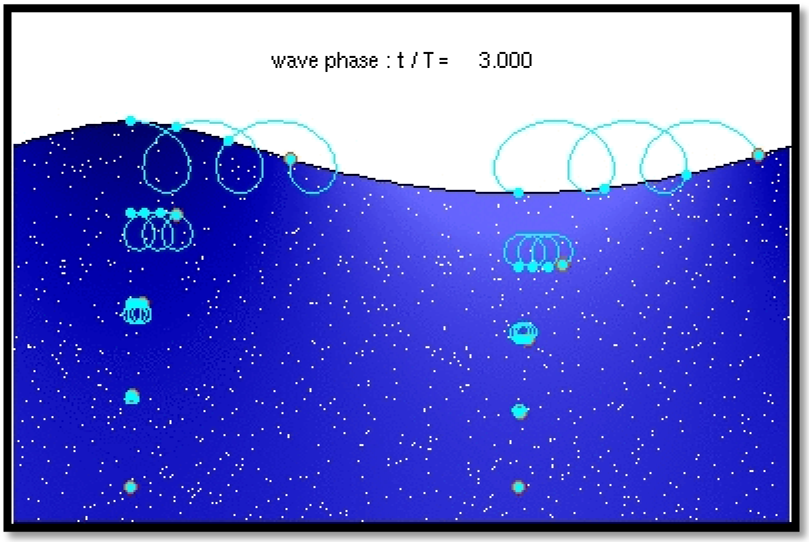

Fig. 1.1. A graphical, exaggerated display of Stokes drift. Shown is the path of a particle as it travels through a wave. Note that Stokes drift is greatest at the surface and diminishes quickly with depth. [Wikipedia cited 2010]

Stokes determined this additional movement in the direction of wave propagation when solving the equation of motion by which individual water particles move within waves. When Stokes approximated this equation out to a second order, he derived an extra term that numerically represents Stokes drift. For deep water, it was shown that Stokes drift can be mathematically represented as

Deep Water

$$U_{\text{Stoke}} = \frac{\pi^2 H^2}{L^2} c e^{-2\pi z/L}, \tag{1}$$

where *H* is wave height, *L* is wavelength, *c* is wave speed, and *z* is depth below the surface (Pond et al. 1978). Notice that Stokes drift decays exponentially with depth, which is also depicted in Fig. 1.1. For a finite depth, Stokes drift can be written as

Shallow Water

$$U_{\text{Stoke}} = \frac{\pi^2 H^2}{L^2} \mathrm{c} \frac{\cos h(2k(h-z))}{\sin h^2(kh)}, \tag{2}$$

where *k* is the wave number ($2\pi/L$) and *h* is the water depth. The equation for deep water applies when $h > L/2$ and the equation for shallow water applies when $h < L/20$. For the current study, the focus is on movement at the surface for which z=0 reducing (1) and (2) to

Deep Water

$$U_{Stoke} = \frac{\pi^2 H^2}{L^2} c \tag{3}$$

and

Shallow Water

$$U_{Stoke} = \frac{\pi^2 H^2}{L^2} c \frac{\cos h(2kh)}{\sin h^2(kh)} \tag{4}$$

respectively. Although Stokes' result was determined on the basis of a homogeneous, incompressible fluid that propagated at a constant velocity and did not change form, he realized that ocean waves do not differ too greatly from these conditions and thus this approximation would hold true for them as well (Stokes 1847).

The important feature of Stokes drift is that it is wave driven and consequently can persist through periods of calm wind and in oil slicks. In addition, the magnitude and direction of Stokes drift is very similar to that of the wind drift approximation for surface oil transport (Buranapratheprat et al. 1999). These similarities will be examined in section **3.5**. Further note that currents induced by wind stress will be different when the oil slick suppresses the wind-driven water waves. Under typical wind conditions in the area of the BP Deepwater Horizon oil spill, the reduced surface tension of the water due to the oil greatly inhibits the formation of wind-induced waves and currents, making Stokes drift caused by swell (waves moving into the region that are not associated with the local wind) a much more important player in surface transport.

2.2 Wave Damping: Physical Reasoning for the Importance of Stokes Drift

As described in the previous section, the presence of oil on the sea surface helps prevent the formation of wind-induced waves through a process known as wave damping. A surface active agent (surfactant), such as oil, can be thought of as an elastic surface that opposes compression and extension. Surfactants have been shown to reduce the surface tension of water up to 60% (Soloviev et al. 2006).

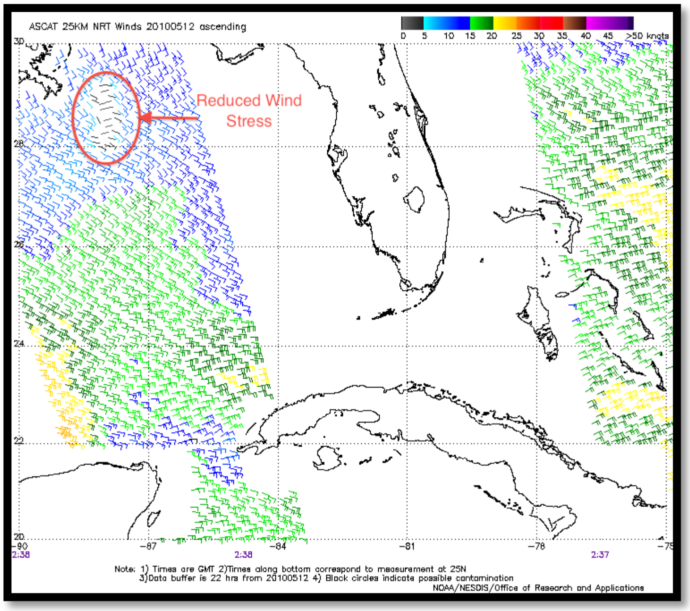

Fig. 2.1a.

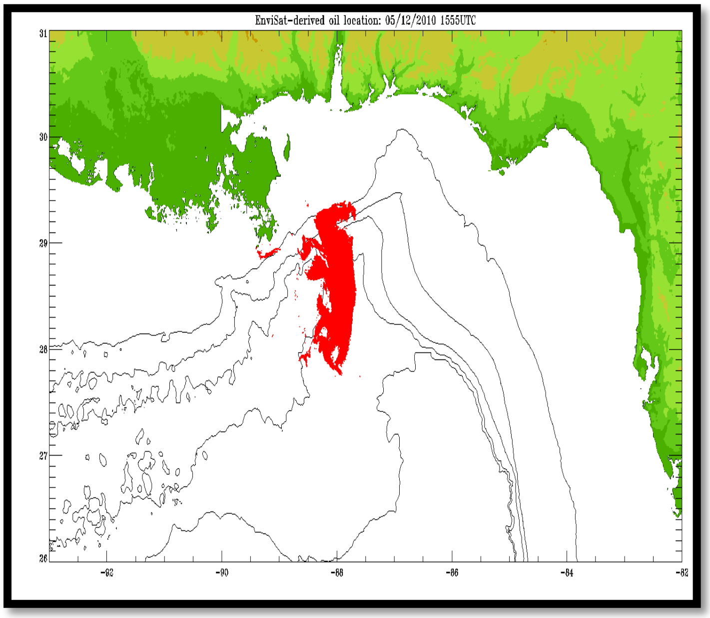

Fig. 2.1b.

Fig. 2.1. (a) Advanced Scatterometer (ASCAT) image showing reduced wind speeds, i.e., reduced wind stress, in a location covered by oil on 12 May 2010. Image courtesy of the National Environmental Satellite, Data, and Information Service (NESDIS) 2011. (b) Corresponding satellite-derived oil location for the same date. Image courtesy of S. Morey (COAPS FSU)

Consequently, surfactants help support tangential stress, i.e., wind stress, which hinders the growth of short-period wind waves (Scott 1999). Grodsky et al. (2000) showed that this repression of wind waves decreases the sea surface roughness, which decreases the coefficient of turbulent heat exchange and the coefficient of ocean surface resistance. Alpers et al. (1989) showed that this wave damping effect has less of an impact when winds reach 10–13 ms^{-1}. Over the region of the Deepwater Horizon oil spill, wind magnitudes are typically smaller than these values and the overall effect is a smoother sea surface in areas where oil resides

An outcome of wave damping is that oil slicks on the sea surface can be identified using scatterometers and other instruments that respond to sea surface roughness. Scatterometers aboard polar-orbiting satellites send out microwave pulses to the ocean surface and measure the backscattered electromagnetic radiation (EMR) received at the instrument's sensor (Naderi et al. 1991). The magnitude of the backscattered EMR power is a function of surface roughness, which is in turn a function of wind stress over the ocean surface. As wind velocities change, surface roughness changes, and thus the magnitude of the backscattered EMR changes, allowing surface wind vectors to be determined. But, as discussed above, oil on the sea surface reduces the impact of wind stress and hence reduces the surface roughness. Evidence of this effect can be seen on scatterometery images taken during the BP Deepwater Horizon oil spill, as displayed in Fig. 2.1. Note that in the area of the oil slick in Fig. 2.1, the winds are not actually slower; it is the wind stress and hence the surface roughness that is reduced. The wave damping that is depicted in the scatterometery image (Fig. 2.1b) is well known (see, e.g.,Girard-Ardhuin et al. 2003). But, surprisingly, there is very little literature linking the conclusions of studies (e.g., Grodsky et al. 2000), and scatterometery images (e.g., those shown in Fig. 2.1b), to the movement of surface oil. The reduction of wind stress over areas affected by oil, along with the reduction in the coefficient of turbulent heat exchange and sea surface resistance, implies that wind may not have a large effect on the movement of the surface oil directly over the spill. Instead, most wind-induced drift would have to occur at the boundaries where its momentum would still influence the water under the surface drift. As discussed above, trajectory models used in the Gulf of Mexico during the Deepwater Horizon event implemented the wind drift as the only secondary forcing for the advection of the surface oil. Furthermore, the magnitude and direction of the wind drift can be adjusted to fit observations. What's more, there is evidence of oil beaching during the Deepwater Horizon oil spill event. Since oil particles drift at an angle to the wind direction, small scale circulations (e.g., the sea breeze) do not explain this. Stokes drift, similar in magnitude and direction to wind drift, may be a more physically logical secondary transport mechanism that would also explain the movement of oil toward the coast.

2.3 Wave-Driven Surface Transport

Although Stokes drift was ignored in trajectory models during the Deepwater Horizon oil spill event, previous studies have shown its significance. Alofs and Reisbig (1972) experimentally observed Stokes drift in a wave tank. They used specific tank and temporal dimensions to avoid a backflow current that can be manifested in wave tank experiments. This, along with a sloping beach at one end, helped produce realistic oceanic conditions. Their experimental results showed that, when the predicted Stokes velocity was greater than 2 cm s^{-1}, the measured surface velocities due to waves were 35–150% greater than the predicted Stokes velocity. Sobey and Barker (1997), looking theoretically at the wave-driven transport of oil, showed that wave-driven transport may be accounted for in the "adjustment" of the wind drift to 3% or 4% of the wind speed. They then argued that this would account only for the local wind sea and could not account for incident swell not related to the local wind. They particularly stressed that movement associated with swell would be refracted toward shorelines, which is the most devastating outcome of an oil spill. They concluded that wave-induced drift, although small in magnitude (~cm s^{-1}), provides a mechanism for the beaching of oil and is therefore an important component of trajectory forecasts. Daniel et al. (2003) acknowledged Stokes drift as an important factor in determining the fate of floating pollutants, especially when swell is present and winds cease. They incorporated Stokes drift into their Modèle Océanique de Transport d'Hydrocarbures (MOTHY) pollutant drift model and found that Stokes drift was significant; however, their results were not consistent with observations. Near the coast, however, the Stokes solution did prove to be a valid approximation. Buranapratheprat et al. (1999) integrated Stokes drift (as well as wind drift, tidal currents, and background currents) into their hydrodynamic oil spill trajectory model. They employed their model for the Gulf of Thailand and used drift cards to represent an oil slick. Their findings suggested that Stokes drift, wind drift, tidal currents, and background currents each played a separate, but significant, role in the transport of the surface oil (drift cards). Their model produced reliable results for trajectory forecasts out to 15 hours. The implication of these studies is that Stokes drift is an important transport mechanism, especially in coastal regions, and should be included in surface oil trajectory forecasts.

3 Methodology and Results

3.1 Model Setup

Significant wave height, peak wave period, peak wave direction, and latitudinal and longitudinal wind components are obtained from the National Oceanic and Atmospheric Administration (NOAA) WAVEWATCH III regional Atlantic grid model reanalysis output at 10 minute (0.166667 degree) grid spacing and 3 hour time steps. WAVEWATCH III atmospheric forcing comes from the Global Forecast System (GFS) (NOAA 2009). WAVEWAATCH III uses shallow water physics, without the mean currents, and accounts for swells and short-period wind waves, although mesoscale wind wave events (e.g., from sea breezes) cannot be captured. A benefit of WAVEWATCH III is that it includes physical processes (e.g., refraction and wave growth and decay due to wind) that are critical for this research.

Using the variables from WAVEWATCH III, the magnitude of Stokes drift for the applicable regions and times is calculated using equations (3) and (4) in the Grid Analysis and Display System (GrADS). For shallow water (depth $\leq L/20$), equation (4) is used and for deep water (depth $> L/2$) equation (3) is used. Gulf of Mexico bathymetry data is obtained from the National Geophysical Data Center (NGDC) ETOPO2 on a 2x2 minute grid. Stokes drift vectors are then produced using the calculated magnitudes and the peak wave directions from WAVEWATCH III.

Wind drift vectors are represented as 2% of the wind speed and 20° to the right of the wind direction. Wind drift is usually represented as 2%–5% of the wind speed. Therefore, by choosing 2%, the “minimum” magnitude of the wind drift is being represented. Note that many models arbitrarily chose the magnitude of the wind drift to better fit the oil movement observations.

Ocean surface currents for the duration of the oil spill are obtained from the Hybrid Coordinate Ocean Model (HYCOM) 1/25° Gulf of Mexico analysis data at 1 hour output intervals. The Stokes and wind drift vectors are then interpolated into the HYCOM grid in GrADS. This allows for easy vector addition and subtraction of the currents with the Stokes and wind drifts. Therefore, the movement due to Stokes drift and the movement due to wind drift can each be isolated to examine their differences. The drifts can then be added to the surface currents to compute trajectories.

3.2 Satellite-Derived Oil Locations

Oil locations derived from the European Space Agency (ESA) Envisat satellite, available from Oscar Garcia in Dr. Ian MacDonald's lab at Florid State University, are used for each model run. The satellite images of the oil are given in GeoTiff format with an accompanying world file that allows for georeferencing the oil locations. Oil data files are then created and interpolated into the HYCOM grid in GrADS. The latitude and longitude of every pixel of oil are saved into a text file for each date, and trajectories for each oil particle are calculated for different time periods and oil locations.

One limitation to this research is the sparse number of satellite derived oil locations that are available. Only eight images derived over the two-and-a-half month period of the spill are practical for use in comparing the model trajectories to the observed oil movement. This limited number of images is a result of many factors. The satellite swath can cut through the middle of the oil slick (see Fig. 3.1) or completely miss the affected area. Also, clouds and rain can obstruct images from instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), which are essential in the identification of oil locations. Furthermore, recognizing oil from satellite images is not an exact practice, so mistakes in oil identification (e.g., images producing oil over land, see Fig. 3.1) can occur.

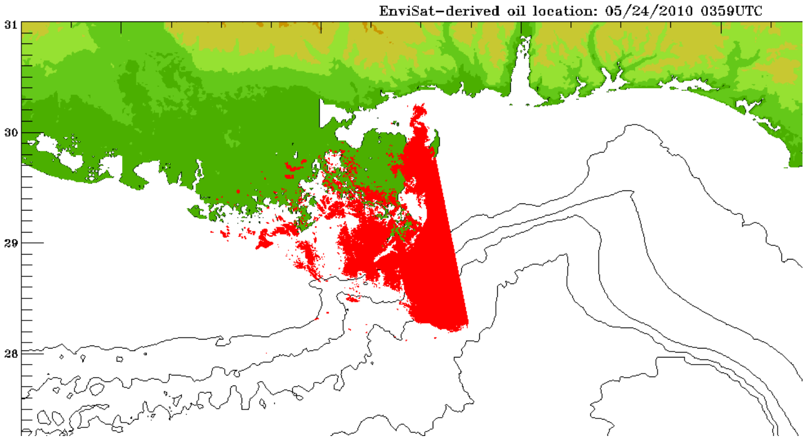

Fig. 3.1. Example of an unusable satellite-derived oil location. The swath can be seen going directly through the oil and there is also oil too far inland to be considered valid. Image courtesy of S. Morey (COAPS FSU)

3.3 Trajectories

This research looks specifically at Stokes drift and its impact on oil movement in the Gulf of Mexico. For this reason, many important processes (e.g., evaporation, emulsification, dispersion, sedimentation, etc.) that affect trajectory forecasts of oil are ignored. The only factors contributing to trajectories in this study are Stokes drift, wind drift, and ocean currents. Also note that new oil particles were not being created to account for the oil reaching the surface from the leak during the model runs. For each case, trajectories are calculated using only Stokes drift, only wind drift, Stokes drift plus currents, and wind drift plus currents.

Horizontal Lagrangian trajectories are calculated in GrADS using a code originally developed by Bernat Codina at the University of Barcelona. No vertical component of transport is accounted for and all trajectories are made at the sea surface. Modifications are made to the code to accompany the specific needs of this research. For each oil particle, the latitudinal and longitudinal components of the drift (e.g., Stokes or wind; represented as *u* below) are averaged over one time step (one hour for this study) and the corresponding distance traveled (*dx*) is found by multiplying by the time step (*dt*) in seconds:

$$\frac{dx}{dt} = u, \text{ averaging } u \text{ over one time step } (dt),\ dx \approx u \cdot dt.$$

The curvature of the Earth is accounted for to find the corresponding latitude and longitude of a point located the above calculated distance away in the direction of the drift. The particle is moved to this position, the time step is increased by one, and the process is repeated. This is done for every particle of oil individually for each case. The advantage of calculating the trajectory of each particle individually is that it displays the change in shape of the oil slick without explicitly accounting for the spreading and dispersion terms.

3.4 Vector Comparison

A method of vector comparison is used to analyze the similarities and differences between the Stokes and wind drifts. A graphical representation of this method is shown in Fig. 3.2. This method is used to account for directional differences (a critical component of the comparison) without invoking the need of angles. The use of angle comparisons presents problems when angles are close to 0° and 360° (e.g., a Stokes drift from 358° and a wind drift from 1° are very similar physically, but very dissimilar numerically). The vector method of comparison avoids this problem. First, a vector subtraction of the Stokes vector (**s**) from the wind drift vector (**w**) is calculated (**d** = **w** – **s**). A natural coordinates approach is taken by aligning the tangential axis (t) to the wind drift vector **w**, where the unit vector in the

^ ^

tangential direction is given by **t** = $(w_x,w_y)/|\mathbf{w}|$. The unit vector in the normal (n) direction is given by **n** = **k** × **t**, where **k** × rotates **t** 90° to the left, leaving $n_x=-t_y$ and $n_y=t_x$.

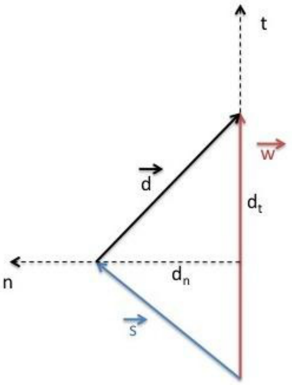

Fig. 3.2. Graphical representation of vector comparisons. For this example, the Stokes drift vector is to the left of the wind drift and smaller in magnitude, corresponding to a positive t-component and a negative n-component.

Dot products are then taken to find the projection of **d** onto the t and n axes, where $d_t = \mathbf{d} \cdot \mathbf{t}$ and $d_n = \mathbf{d} \cdot \mathbf{n}$. A positive t-component (d_t) indicates that the magnitude of the wind drift is larger than the Stokes drift. A positive n-component (d_n) indicates that the Stokes drift is directed to the right of the wind drift. In Fig. 3.2, the t-component is positive and the n-component is negative.

3.5 Results for Vector Comparisons

The first analysis uses the technique described in section **3.4** to compare the Stokes and wind drifts. Over the region of the spill (27°–29.5°N and 88.5°–87°W), the average difference vector (**d**=**w**-**s**) is calculated and the t- and n-components (d_t and d_n) are found for every hour from 21 April 2010 to 01 July 2010. These results are then averaged over the aforementioned time frame. The average t-component is found to be 0.07 m/s (7 cm/s) indicating that the wind drift has a higher magnitude, on average, than the Stokes drift. Over the course of 1 day, the wind drift would carry the oil approximately 6 km farther than the Stokes drift, and over the course of 3 days (the common time period between satellite oil observations), approximately 19 km farther. The average n-component is found to be -0.008 m/s (-0.8 cm/s). This indicates that, on average, the transport due to Stokes drift would be to the left of the wind drift approximately 0.7 km over the course of 1 day and approximately 2.2 km over the course of 3 days.

The relatively small n-component implies that, on average, the directions of the Stokes and wind drifts are fairly similar. In addition, the Gulf of Mexico is a relatively small body of water and therefore swell is rarely present. Shorter period wind-waves usually dominate the wave regime in coastal regions of the Gulf that may not be accurately resolved in WAVEWATCH III. Consequently, on average in the Gulf, the direction of the Stokes drift will correspond to the direction of the local wind-waves. This has two implications. First, the wind-generated waves that move into the oil spill, not the wind itself, may be responsible for the movement of the oil. With similar directions and relatively small magnitudes, the two drifts may be indistinguishable. Second, if swell were present, the outcome would change significantly. To demonstrate this, the n-component (d_n) is found for a 24-hour period (09Z 28 June – 09Z 29 June 2010) when swell from Hurricane Alex moved into the oil spill region. The resulting n-component is found to be 0.03 m/s (3 cm/s), which is to the right of the wind drift and approximately 3 times larger than the average. This would result in a Stokes drift forecast that is 2.4 km to the right of a wind drift forecast for this time frame. Unfortunately, no valid satellite-derived oil spill images were available for this time period to evaluate the observed movement compared with that predicted by the Stokes and wind drifts.

3.6 Center of Mass Comparison

The center of mass comparison method is used to calculate the distance between the average position of the forecasted oil and the average position of the observed oil. The general concept is displayed in Fig. 3.3. Using this method, the distance traveled because of each force (e.g., Stokes + currents or wind + currents) is determined and an average movement vector for each drift is created to analyze the different forecasts. The strengths of this method are also its weaknesses. If the size of the spill increases substantially over the forecasted time period but the shape does not change, the average position will still be valid. But, in some cases, the shape of the oil slick changes dramatically because of processes that are neglected for this study (e.g., new oil reaching the surface, other biological and chemical processes) which affects the center of mass location considerably. As a result, the validity of the center of mass approach has to be determined on a case-by-case basis. Overall, the center of mass approach has proven to be the best method for comparing forecasted to observed oil locations for this study.

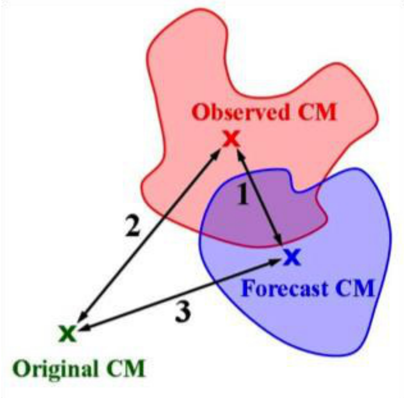

Fig. 3.3. Illustration of the center of mass (CM) approach. Distance 1 represents the distance between the forecasted and observed centers of mass. Distance 2 represents the distance the observed oil traveled and distance 3 represents the distance the forecasted oil traveled. Image courtesy of Perrine Rayet (COAPS)

3.7 Results for Center of Mass Comparisons

For the following results, HYCOM surface currents are the primary forcing for all trajectory forecasts. A trajectory forecast made using Stokes drift as the secondary forcing is denoted as a "Stokes trajectory" and a forecast using wind as the secondary forcing is denoted as a "wind trajectory."

16Z 24 April 2010 – 16Z 25 April 2010

For this case, the waves in the region of the oil spill were on average 2.5 m with a 7–8 second period, corresponding to relatively short period wind-waves. The winds were generally out of the south at 10–15 m/s, but switched more from the west near the end of the time frame. The results of the 24 hour Stokes and wind trajectories are displayed in Table 1 and Fig. 3.4.

It can be seen that, for this case, the directions of the Stokes and wind trajectories are very similar, although the wind is slightly closer (directionally) to the observed movement. What is interesting is the strength of the wind trajectory, which forecasted the oil to move almost twice as far as the observed movement (see Table 1). Note that the wind drift used for these results takes the magnitude to be 2% of the wind speed, the minimum value used in most oil trajectory models, and it still strongly over predicts the movement of the oil. The Stokes trajectory, on the other hand, matches closely with the observed distance traveled and is closer to the final position of the oil (see Table 1).

Table 3.1: Results for 24 April – 25 April 2010

Secondary Forcing	**Distance Traveled**	**Distance From Observed**
Observed	13.6 km	N/A
Stokes drift	15.6 km	5.8 km
Wind drift	24.7 km	12.4 km

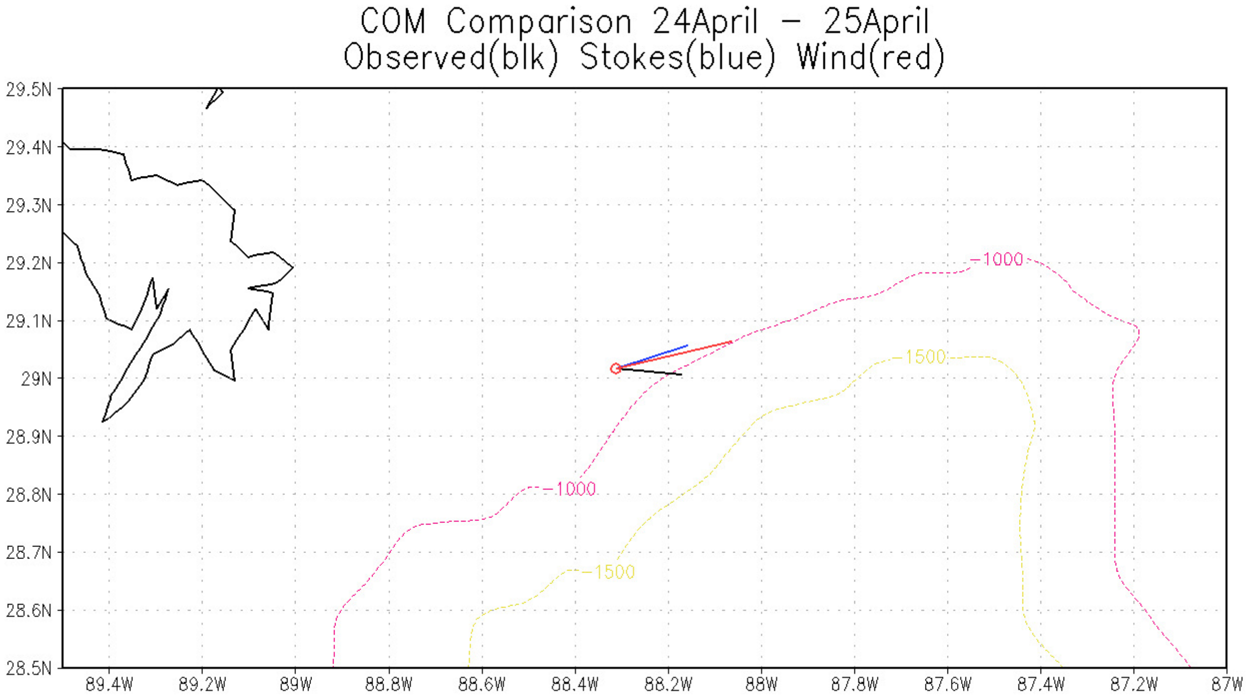

Fig. 3.4. Results of trajectory forecasts. The red, hollow circle is the initial center of mass location. The black line represents the observed center of mass movement, the red represents the wind trajectory, and the blue represents the Stokes trajectory.

16Z 25 April 2010 – 16Z 26 April 2010

In this 24-hour period, there were 1–2 m waves with only a 4–7 second peak wave period in the region of the oil spill. The winds were generally out of the northwest at around 8–12 m/s. The results of the wind and Stokes trajectories are displayed in Table 2 and Fig. 3.5.

For this case, the direction of the Stokes trajectory matches very well with the observed movement. The Stokes trajectory under predicts the distance traveled whereas the wind trajectory is much closer to the observed (see Table 2). Overall, the Stokes trajectory is closer to the observed oil than the wind trajectory is.

<u>Table 3.2</u>: Results for 25 April – 26 April 2010

Secondary Forcing	**Distance Traveled**	**Distance From Observed**
Observed	20.2 km	N/A
Stokes Drift	13.4 km	7 km
Wind Drift	22.4 km	8.8 km

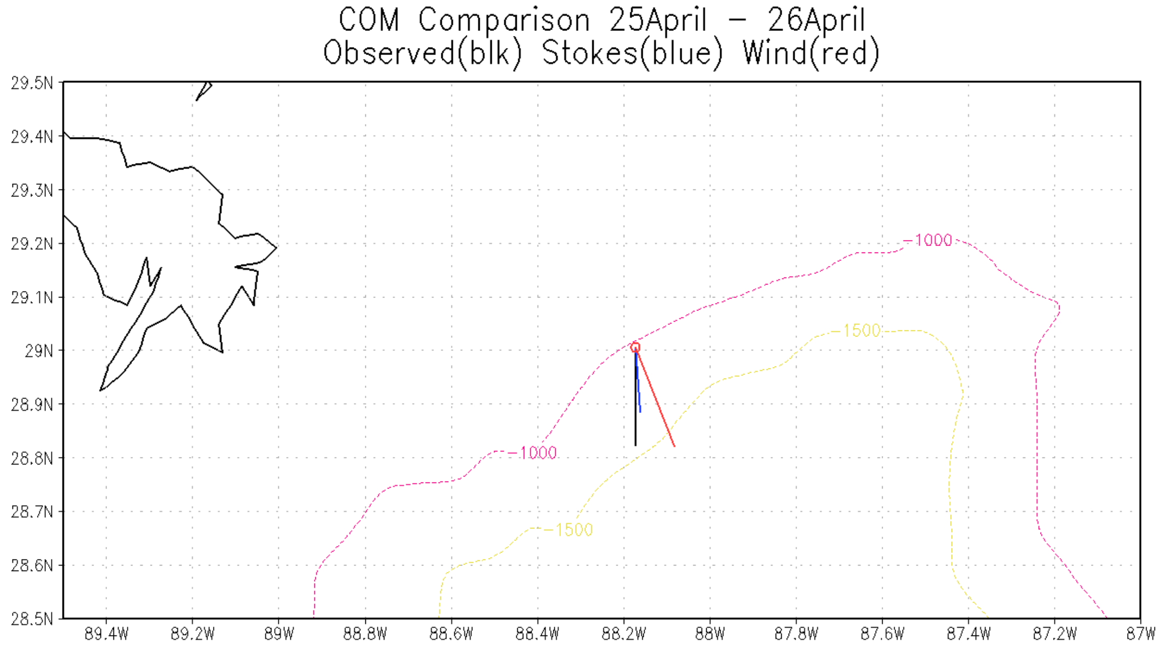

Fig. 3.5. Results of the trajectory forecasts for 25 April – 26 April 2010. The hollow red circle represents the initial, observed center of mass. The black line displays the observed movement, the red line represents the wind trajectory, and the blue line represents the Stokes trajectory.

<u>16Z 02 May 2010 – 16Z 05 May 2010</u>

During this time frame, the waves started out around 3–5 m and resided to around 1 m by the end of the 3-day period. The initial, larger waves had a period of around 10 seconds which decreased with the decreasing swell to around 6–7 seconds by 05 May. Due to the size and period of the wave field, this time frame represented the best swell event available with valid satellite-derived oil spill images. The winds were out of the south/south southeast for the first 48 hours before rotating out of the northeast for the last 24 hours. The results of the Stokes and wind trajectories are shown in Table 3 and Fig. 3.6.

For this case, the direction of the Stokes trajectory matches the observed better than the wind trajectory. In addition, the center of mass of the Stokes trajectory is again closer to the observed center of mass than the wind trajectory is. As in the previous case, the distance traveled according to the wind trajectory is closer to the observed distance traveled than the Stokes trajectory is. Note that the direction of the observed oil movement is more shoreward than either drift predicted. This could be the result of the refraction of waves toward coasts, indicating that wave-driven transport may be important in this case. Unfortunately, the resolution and model physics of WAVEWATCH III becomes less reliable very close to the coast, so the full effect of Stokes drift may not be accurately represented.

Table 3.3: Results for 02 May – 05 May 2010

Secondary Forcing	**Distance Traveled**	**Distance From Observed**
Observed	28.7 km	N/A
Stokes Drift	19.9 km	13.7 km
Wind Drift	27.3 km	21.3 km

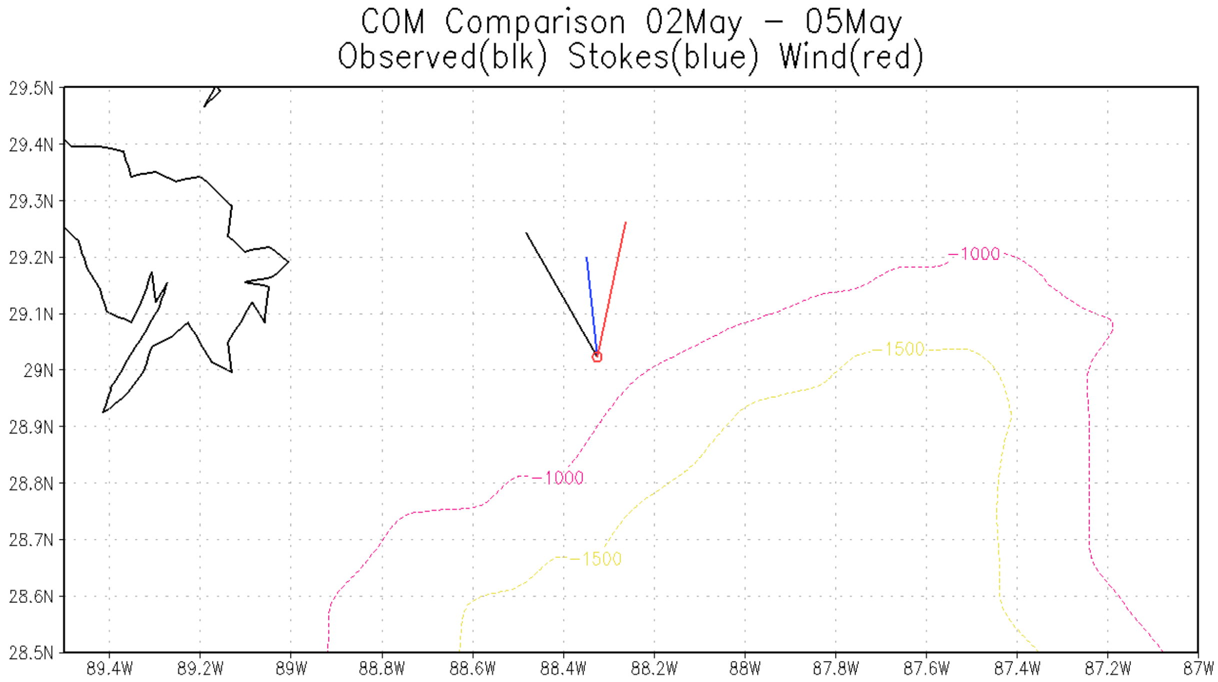

Fig. 3.6. Results of trajectory forecasts for 02 May – 05 May 2010. The red, hollow circle represents the initial center of mass. The black line represents the observed movement, the red line represents the wind trajectory, and the blue line represents the Stokes trajectory.

4 Discussion

These results indicate that Stokes drift may be an important factor in the transport of oil at the sea surface. Unfortunately, there were not enough valid satellite-derived oil locations to test a wider variety of cases. That being said, for the available cases, the Stokes trajectory does match the observed oil locations better than the wind trajectory does when using the center of mass comparison method. Furthermore, the directional component of the Stokes trajectory looks to be more accurate than that of the wind trajectory when compared to observations.

These results also suggest that the effect of the wind drift still does need to be accounted for, though it may not be as strong as most models predict. For two of the three cases, the distance traveled according to the wind trajectory is closer to the observed than the Stokes trajectory is. But, this is also using 2% of the wind speed, the minimum used in models. If a higher value were to be used (e.g., 3.5% or 4%), which is more common in oil trajectory models, the wind drift would have over predicted the distance traveled in every case. These results also show evidence to support the claim made in section **2.2** that wind may not have as strong an influence on surface drift when an oil slick is present.

5 Conclusion

Ocean waves have a net forward mass transport in the direction of wave propagation known as Stokes drift. This paper examined Stokes drift and its effect on surface oil transport during the Deepwater Horizon oil spill event in the Gulf of Mexico. Comparisons were made between Stokes drift and the empirically derived wind drift. Physical reasoning and evidence were provided that indicate that the wind drift may not be as strong as usually assumed. A model was then used to compare the results of trajectories using Stokes drift and trajectories using wind drift to satellite-derived oil locations. Encouraging results were found, but more satellite observations of the oil slick are needed to fully determine the significance of Stokes drift.

REFERENCES

Achenbach, J., and D.A. Fahrenthold, cited 2010: Oil spill dumped 4.9 million barrels into the Gulf of Mexico, latest measure shows. [Available online at http://www.washingtonpost.com/wp-dyn/ content/article/2010/08/02/AR2010080204695.html.]

Alpers, W., and Huhnerfuss, H., 1989: The damping of ocean waves by surface films: A new look at an old problem. *J. Geophys. Res.,* **94**, 6251–6265.

Alofs, D.J., and R.L. Reisbig, 1972: An experimental evaluation of oil slick movement caused by waves. *J. Phys. Oceanogr.*, **2**, 439–443.

Buranapratheprat, A., and S. Tangjaitrong, 1999: Hydrodynamic model for oil spill trajectory prediction. 2nd Workshop on Ocean Models for the APEC Region, 6D-1 – 6D-8.

Daniel, P., F. Marty, P. Josse, C. Skandrani, and R. Benshila, 2003: Improvement of drift calculation in MOTHY operational oil spill prediction system. *Proc. 2003 Int. Oil Spill Conf.,* Washington, DC, American Petroleum Institute, CD-ROM, 6 pp.

Girard-Ardhuin, F., G. Mercier, and R. Garello,2003: Oil slick detection by SAR imagery: Potential and limitation. *Oceans.* **1**, 164–169.

Grodsky, S.A., V.N. Kudryavtsev and V.K. Makin, 2000: Thermohydrodynamics of the ocean. *Phys. Oceanogr.,* **11**, 495–508.

Liu, Y., R.H. Weisberg, C. Hu, and L. Zheng, 2011: Tracking the Deepwater Horizon oil spill: A modeling perspective. *Eos, Trans. Amer. Geophys. Union.*, **92**, 45–46.

MacDonald, I., 2010: Deepwater disaster: How the oil spill estimates got it wrong. *Significance* 7(4): 149–154.

Naderi, F.M., M.H. Freilich, and D.G. Long, 1991: Spaceborne radar measurement of wind velocity over the ocean–An overview of the NSCAT scatterometer system. *Proc. IEEE.*, **79,** 850–866.

NOAA, cited 2009: NWW3 implementations. [Available online at http://polar.ncep.noaa.gov/waves/ implementations.shtml.]

Pond, S., and G. L. Pickard, 1978: *Introductory Dynamic Oceanography.* British Library Cataloguing in Publication Data, 241pp.

Scott, J.C., 1999: Ocean surface slicks – pollution, productivity, climate and life-saving. 1463–1468.

Sobey, R.J., and C.H. Barker, 1997: Wave-driven transport of surface oil. *J. Coas. Res.* **13**, 490–496.

Soloviev, A. and R. Lukas, 2006: *The Near-Surface Layer of the Ocean*. Springer, 572pp.

Stokes, G. G., 1847: On the theory of oscillatory waves. *Trans. Cambridge Phil. Soc.,* **8**, 441–455.

Wikipedia, cited 2010: Stokes drift. [Available online http://en.wikipedia.com/wiki/ Stokes_drift.]