Evaluation of an Oil Spill Trajectory Model Using Satellite-tracked, Oil-spill-simulating Drifters

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Abstract - We deployed ninety-seven oil-spill-simulating drifters over the continental shelf of the northeastern Gulf of Mexico during five hydrographic surveys conducted from 1997 through 1999. Earlier, side-by-side comparisons with spilled crude petroleum on the ocean surface had demonstrated that these drifters moved on the ocean surface like consolidated oil slicks under light to moderate winds. (Under high winds, a surface oil spill tends to be entrained into the mixed layer and Ekman transported, unlike the drifters, which remain on the sea surface and move mostly downwind.) The drifters were then deployed in the Gulf of Mexico as nonpolluting oil-spill proxies to compare their movements against results from an oil-spill trajectory model.

The drifter trajectories were compared statistically to trajectories generated by the Oil-Spill Risk Analysis (OSRA) model. The model uses a variation of the 3.5-percent rule to compute the drift due to local wind forcing and superposes the prevailing ocean current on this wind-induced drift to obtain the total velocity of an oil spill on the ocean surface. The input fields are the European Center for Medium Range Weather Forecasting (ECMWF) winds and a data-assimilating hindcast of the ocean currents over the time the drifters were deployed.

Scatter plots and linear regressions of the speeds and directions of simulated vs. modeled oil-spill drift show the extent to which they are different. Underlying these differences are the expected differences between the ocean current input field and the trajectories of satellite-tracked, "water-following" drifters deployed simultaneously with the oil-spill-simulating drifters. An earlier evaluation of the ECMWF winds showed better, but of course not perfect, agreement with meteorological buoys in the Gulf. The integrated effect of the errors in the input fields results in average discrepancies between the terminal ends of the simulated and modeled spill trajectories of 78, 229, 416, and 483 km after 3, 10, 20, and 30 days of drift, respectively.

These results are the consequence of integrating wind and ocean current fields, which are not perfect, and comparing the resultant trajectories against those of the oil-spill-simulating drifters, which themselves contain location errors and which are not considered to be perfect simulators of real oil spills. However, the results are useful to practical oils spill risk analysis through ongoing improvement of the model.

I. INTRODUCTION

The Minerals Management Service (MMS), an agency of the United States government, developed the "Oil-Spill Risk Analysis" (OSRA) model in 1975 [1]. The model produces statistical estimates of hypothetical oil-spill occurrence and contact by generating an ensemble of sea surface oil-spill trajectories. It initiates thousands of oil-spill simulations at hundreds to thousands of hypothetical spill locations over large ocean areas to statistically characterize the likelihood of oil-spill contact to designated geographic areas.

The hypothetical spills in the OSRA model are initiated every 1 to 4 model days over the time interval of the input wind and ocean current fields. The velocity of a spill is the vector sum of the surface ocean current at that location plus an empirical wind-induced drift. The magnitude of the wind-induced drift is 3.5 percent of the local wind speed, and its orientation angle relative to the wind is wind-speed-dependent according to [2]. For a given hypothetical oil-spill source and a given geographic area of interest, the model estimates the probability that the oil-spill will contact the area of interest as simply the number of contacts to the area

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divided by the total number of spills initiated from the source.

The interpretation of the probability estimates is aided by knowing how well the model trajectories replicate actual oil spills under given wind and sea conditions. Previously, model hindcasts were compared against the trajectories of large, accidental oil-spills in relevant areas. Although the comparisons gave reasonable qualitative agreement, they were few in numbers. This paper compares model-generated trajectories against the trajectories of 97 “oil-spill-simulating” drifters deployed over the continental shelf of the northeastern Gulf of Mexico during five hydrographic surveys conducted from 1997 through 1999 by several investigators from Texas A&M University. The hydrographic cruises constituted drifter deployment opportunities and contributed valuable, concurrent, ancillary oceanographic information to this project.

References [3], [4], and [5] demonstrated that these drifters replicate the motion of an oil spill on the ocean surface by making side-by-side comparisons against intentionally spilled crude petroleum during government-approved experiments. The drifters moved on the ocean surface like consolidated oil slicks under light to moderate winds during 3 to 4 days of continuous observation. Under high winds, however, a surface oil spill tends to be entrained into the mixed layer and Ekman transported, unlike the drifters, which would remain on the sea surface and move mostly downwind.

The work described herein is an initial statistical comparison between the trajectories of drifter-simulated oil-spills and OSRA model spills without consideration of the different oceanographic and wind situations occurring during the five different hydrographic cruises. Specifically, we have not differentiated situations when energetic Loop Current eddies moved onto the continental shelf from situations when the local winds dominated over the surface currents. Also, the OSRA model applied to the Gulf of Mexico does not include the tides, since they are of minimal influence to long-term risk assessment. Our objective in this study was to obtain an initial evaluation of how model-generated trajectories compared to the drifter trajectories. Subsequent analyses will attempt to determine when, where, and how the model differed from the observations. Hopefully, with that information, we can improve the model.

The following sections describe the drifters used in this study, the information derived from them including error estimates, the OSRA model and its ocean current and wind input fields, the statistical comparisons of simulated oil-spill trajectories and model-generated trajectories, and our concluding remarks.

II. OIL-SPILL-SIMULATING AND WATER-FOLLOWING DRIFTERS

In their efforts to develop nonpolluting proxies for oil spills persisting on the ocean surface, [3], [4], and [5] showed that two types of drifters would move on the sea surface like consolidated oil spills under light to moderate wind conditions during 3 to 4 days of continuous observation. One of these was a 30-cm diameter sphere with added ballast such that its waterline was at its “equator” (hereafter referred to as the “Sphere”). The other was a 36-cm diameter disc of about 15-cm thickness also with added ballast to make its waterline halfway between the top and bottom of the disc (hereafter called the “LCD”, in reference to its prototype, the “Low Cost Drifter” originally designed by Draper Labs). With this combination of above- and below-the-sea-surface profiles, the drifters moved under the influence of the prevailing local winds and ocean currents. The net effect of the winds and ocean currents on the drifters was a motion similar to that manifested by small, experimental oil spills next to which the drifters were placed.

References [3], [4], and [5] followed several, government-sanctioned, experimental oil spills and concurrently deployed drifters over a few days from ships in the experimental areas. They also used patrol aircraft flying overhead with remote sensing equipment to obtain infrared, ultraviolet, and microwave images of the slicks. The images from the various aircraft over-flights produced accurate maps of the slicks even after they were much dispersed horizontally. Polar orbiting weather satellites operated by the U. S. National Oceanographic and Atmospheric Administration (NOAA) continuously tracked the drifters. The satellites carry special receivers operated by Service ARGOS to locate the radio transmitters installed inside the drifters.

Under high wind and sea conditions, however, the experimental oil spills were entrained into the water column and Ekman transported below the sea surface. (Their locations were apparent from the small amount of oil returning to the surface under the wind-induced vertical mixing and the buoyancy of the oil.) The drifters, under these conditions, remained on the ocean surface and ran predominantly downwind.

Oil spills with higher wax and asphaltene content tend to persist on the sea surface as a consolidated mass more than the oils with lower concentrations of wax and asphaltene. The drifters replicate the motion of oil spills persisting as consolidated masses at the ocean surface, at least for 3 to 4 days. They do not replicate the motion of entrained oil mixed below the sea surface nor highly dispersed spills on the surface spread over a large area, although the drifters might move like the center of mass of a highly dispersed surface oil slick or like one of its component oil streaks.

In addition to the oil-spill-simulating drifters, we concurrently deployed "water-following" drifters. These "CODE" drifters moved with the upper 1-m of the surface ocean currents using four pieces of 1-m by 1/2-m sail cloth arranged symmetrically around a central plastic tube of 10 cm in diameter and were also tracked by the Service ARGOS system. Four flotation balls attached to the upper sail cloth support arms by flexible cord act to dampen the drifter's reaction to wave motion and, thereby, reduce the wave-induced "Stokes" drift for better tracking of the mean currents. In this investigation, we regarded the motion of the CODE drifters as a measure of the surface ocean currents, which partially drive the oil-spill-simulating drifters.

The name CODE derives from the Coastal Ocean Dynamics Experiment, wherein [6] used an earlier version of the drifter off the California coast employing line-of-sight VHF radio transmitters in the drifters and VHF radio direction finders to locate them. The CODE drifter used in this investigation is a later version of Davis' design, employing satellite tracking, more symmetrical flotation balls (spheres instead of rectangular solids), flexible attachment cords, and a self-erecting capability allowing for aircraft deployment. From tank tests and dye patch comparisons, [7] determined the slippage of the CODE drifters to be 3 cm/s in its current configuration.

Niiler directed two successful aircraft deployment experiments releasing more than 800 CODE drifters over the continental shelf of the northern Gulf of Mexico with only four failures. The first of the experiments, using about 400 drifters, yielded bin-averaged drifter velocities that correlated fairly well with modeled ocean currents derived from an application of the Princeton Ocean Model to the Gulf of Mexico [8]. Daily averaged currents within ¼-degree by ¼-degree latitude-longitude bins exhibited linear correlation coefficients of 0.50 and 0.71 regressing drifter on model velocities and model on drifter velocities respectively. These results encouraged us to use the CODE drifters in this study to observe the ocean currents in the deployment areas of the oil-spill-simulating drifters.

III. DRIFTER OIL-SPILL SIMULATIONS

Assuming that the "oil-spill-simulating" drifters represent persistent, consolidated oil spills on the ocean surface, we designed a modest oil-spill simulation study to be conducted in the northeastern Gulf of Mexico. The drifters are nonpolluting proxies for oil spills and, therefore, could be deployed in comparatively large numbers, giving a modest amount of statistical significance to the model verification studies we wanted to perform on the OSRA model. Under contract to the MMS, Texas A & M University investigators performed nine hydrographic surveys of the northeastern Gulf from November 1997 through July/August 2000. We deployed drifters during five of them: November 1997, May 1998, August 1998, November 1998, and November 1999.

Fig. 1 shows, as representative examples, the trajectories of the water-following and oil-spill-simulating drifters during the May 1998 deployments. In May, the water-following drifters remained predominantly on the continental shelf, with some moving southward with the Loop Current, and one of those leaving the Gulf through the Florida Strait. Circular fine structure in the trajectories appears to be inertial waves, and some larger eddies just south of the shelf are probably eddies shed from the Loop Current. The oil-spill-simulating drifters did much the same thing but without as far an excursion southward. Again, some eddy motion south of the shelf was exhibited. The drifters from the other deployments behaved roughly in a similar fashion.

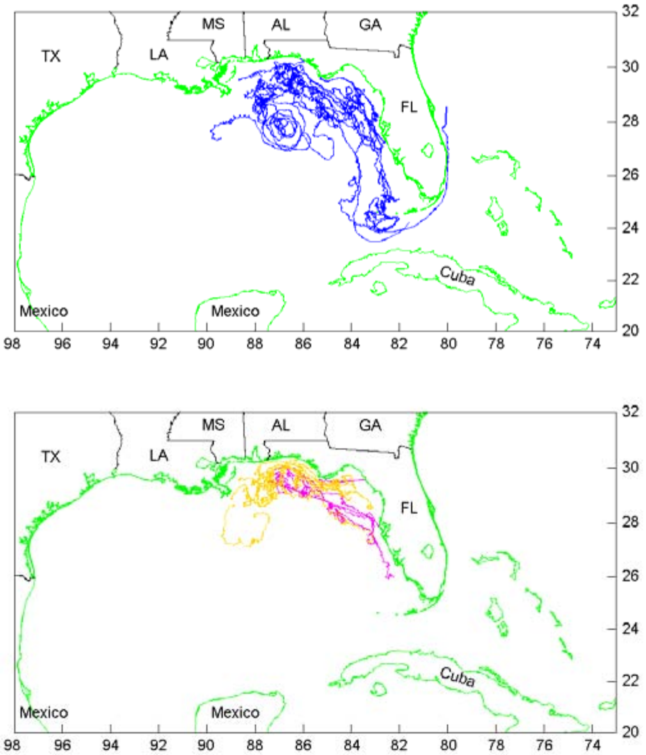

Fig. 1 Water-following drifter tracks (top) and oil-spill-simulating drifter tracks (bottom) from the May 1998 deployment. (LCD tracks are in red. Sphere tracks are in yellow.)

IV. DERIVED QUANTITIES FROM OBSERVATIONS

From the numerous drifter trajectories, we extracted several numerical quantities useful for a model-drifter comparison. They are as follows.

(1) Trajectories of 3, 10, 20, and 30 Days Duration We dissected the trajectories of the oil-spill-simulating drifters into segments of equal time intervals, regarding the beginning of each segment of a given trajectory as

a new oil spill originating at that location. We thereby constructed many trajectories of simulated oil spills of 3, 10, 20, and 30 days duration.

(2) Net Separations over Intervals of 3 Hours Duration or Less The Service ARGOS tracking system provides drifter locations at irregular times. Most of the time intervals are 3 hours or less, so we regard a drifter displacement over 3 hours or less as one realization of the process of wind and ocean currents acting on the drifters. The separation (drifter displacement) is simply the geographic distance between two successive locations after 3 hours or less elapsed time provided that the two locations are statistically distinct given the reported Service ARGOS location errors (discussed below).

(3) Speeds and Directions of Drifter Velocities Dividing the drifter separations by the corresponding elapsed times yields the drifter speeds, and the angular orientations of the separation vectors relative to geographic North, measured eastward from North, are the directions of the velocity vectors. Under the constraint of statistically distinct locations in the determination of the separations, the lower speeds are filtered out. The minimum speed considered in this analysis is about 0.09 m/s.

V. ERROR ESTIMATES

In this study, we quantitatively compared the drifter separations (displacements) and velocities against those derived from the OSRA model. Towards this end, we needed to consider the associated errors. Consider first the accuracy of the drifter locations, from which drifter separations and velocities are derived.

The accuracy of the satellite-determined locations depends upon the frequency stability of the transmitters in the drifters, the orbital stability of the receiving satellites, and the elevation above the horizon of the satellites at the time of measurement. Service ARGOS assigns a location class to every location determined by the system. The location errors have been determined to be circular in distribution with a Gaussian dependence on the distance from the center of the circle and independent of the azimuth within the circle. Location classes 1, 2, and 3 have radial standard deviations of 1500 m, 500 m, and 250 m respectively. These numbers are comparable to or moderately larger than those independently observed by [9] and [10].

It should also be noted that sunspot activity affects ARGOS location accuracy. We made no determination of the affects the sunspot activity had on the drifter locations determined by Service ARGOS. We used only the reported standard deviations of the ARGOS location classes throughout this study.

In addition, a single GPS (Global Positioning System) receiver with no differential or other corrections determined the initial deployment locations. Such GPS locations have standard deviations of 100 m, and we also assumed them to be Gaussian distributed in the radial direction and independent of azimuth, as with the ARGOS locations.

The radii of the "error circles" corresponding to a 95 percent probability are 3672 m, 1224 m, and 612 m when the location classes are 1, 2, or 3 respectively, and 245 m with a GPS-determined, initial deployment location. There is a 95 percent probability that the actual location is on or inside the error circle centered on the reported ARGOS location.

Since we were interested in drifter separations and velocities, we constructed error circles of probability equal to the square root of 95 percent = 97.48 percent so that the joint probability that the actual drifter locations are inside their respective error circles is 95 percent, assuming statistical independence of the individual location determinations. At 97.48 percent probability, the radii of the error circles are 4067 m, 1356 m, and 678 m when the location classes are 1, 2, or 3 respectively, and 271 m with a GPS-determined, initial deployment location. When the separation between successive locations is such that the two 97.48 percent probability error circles contact or overlap, we regarded the locations as not distinct and do not use them in our comparative analysis. This rejection criterion has the effect of filtering-out the slower drifter speeds. With 3-hour or less time intervals, the slowest speed considered is the smallest acceptable separation divided by the longest time interval. Two successive class 3 locations give a minimum acceptable separation of just over 678 m + 678 m = 1356 m. Dividing that by the longest time interval, 3 hours, gives us a minimum observable speed of about 0.13 m/s.

Computing the standard deviations of the separations and speeds is straightforward, since these quantities are simply the differences between statistically independent, Gaussian random variables. However, the direct computation of the standard deviation of the angular orientation of these vectors, is considerably more complicated due to the complexity of the functional relation. These were determined by considering the geometry of the error circles and using numerical integration.

We used the standard deviations as weights in weighted linear regressions of drifter versus model quantities to determine the error bars of the various linear regression parameters computed.

VI. THE OSRA MODEL

The OSRA model [1], adapted to the Gulf of Mexico, time-integrates the superposition of surface current velocities and an empirical (3.5-percent rule) wind-induced drift using an ocean current field and a wind field provided to the model as inputs. The integration is performed over specified time intervals, typically 3, 10, 20, and 30 days, to generate oil-spill trajectories for estimating the probabilities of oil-spill contact. We use them here for comparisons against the trajectories of oil-spill-simulating drifters.

The surface ocean current field was produced by the Princeton Regional Ocean Forecast System (PROFS) (http://www.aos.princeton.edu/WWWPUBLIC/PROFS/) applied to the Gulf of Mexico. The system is based on a version of the Princeton Ocean Model (POM) (http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/), driven by synoptic winds, heat flux, and river flows. The synoptic winds are the analyzed ECMWF 6-hourly surface winds. Drs. Leo Oey and Tal Ezer of Princeton University (Princeton, New Jersey, U. S. A.) generated the fields.

In order to more accurately represent the location of mesoscale oceanic eddies appearing in the generated model fields, the model employs data assimilation of the sea surface height, derived from ERS-2 and TOPEX satellite altimetry.

The OSRA model used in this study is driven by the PROFS-generated surface ocean currents and the ECMWF wind field. Both fields were mapped to the PROFS grid at 3-hour intervals over the 3 years, 1997 through 1999.

VII. DERIVED QUANTITIES FROM THE OSRA MODEL

Using the OSRA model, we reproduced all of the quantities derived from the drifter trajectories – (1) through (3) below. In addition, we constructed along-the-trajectories, time-averaged wind and ocean current fields, and three observation-model hybrid quantities – the "residual velocities", drift angles relative to the wind, and the "trajectory discrepancies" described below.

(1) Trajectories of 3, 10, 20, and 30 Days Duration At the starting location of each segment of the drifter trajectories, we initiated a concurrent model trajectory running for the same time interval.

(2) Net Separations over Intervals of 3 Hours Duration or Less At the starting location of each 3-hour or shorter drifter displacements, we initiated a concurrent model trajectory running for the 3 hours or shorter interval between successive drifter locations. These are the "model separations".

(3) Speeds and Directions of Drifter Velocities Dividing the model separations by the corresponding elapsed times yields the "model speeds", and the angular orientations of the model separation vectors relative to geographic North, measured eastward from North, are the directions of the model velocity vectors.

(4) Integral-averaged Wind Speeds and Directions Since the drifter separations and velocities are effectively averages over the 3-hour or shorter drift intervals, we averaged the concurrent wind velocity over the same time interval. We integrated the wind velocity components over time assuming that the components vary linearly over half the drift intervals. Then, we computed the wind speed and direction from the averaged components.

(5) Integral-averaged Ocean Current Speed and Direction (same procedure as item (4), but applied to the model ocean currents)

(6) Residual Velocities (Wind-induced Drift) To examine the 3.5-percent rule, wind-induced drift employed by the OSRA model, we constructed "residual velocities" by subtracting the integral-averaged ocean currents from the velocities of the oil-spill-simulating drifters.

(7) Drift Angles (Relative to the Wind) Also for the examination of the 3.5-percent rule, we subtracted the compass heading of the wind vectors from that of the residual velocities to get the drift angles – positive when drift is to the right of the wind, looking downwind.

(8) Lagrangian Discrepancies The distances between the terminal ends of the trajectories of the oil-spill-simulating drifters and the corresponding model trajectories in the 3-, 10-, 20-, and 30-day cases are called the "Lagrangian discrepancies".

VIII. STATISTICAL COMPARISONS

The accuracy of the model-generated trajectories depend upon the accuracy of the wind and ocean current fields integrated by the model. The CODE, water-following, drifters in this study allowed us to assess the accuracy of the modeled ocean current field on a point-by-point basis. Fig. 2 compares CODE drifter speeds and directions against the integral-averaged ocean current speeds and directions with the error bars of the drifter quantities. (It is practically impossible to construct error bars for the model-generated ocean current and wind fields.)

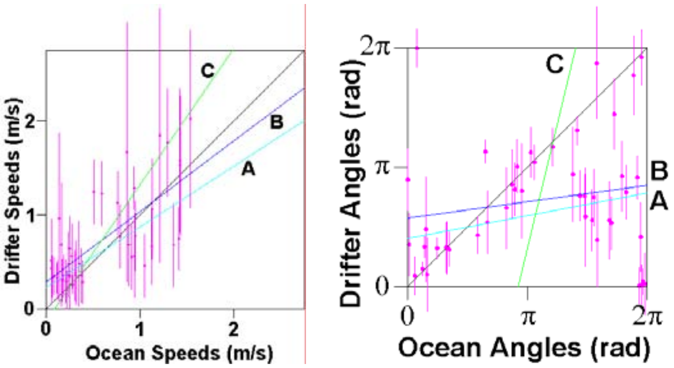

Fig. 2 Scatter plots of Nov. 1997 CODE drifter Velocities vs. Integral-averaged Ocean Currents with linear regression lines: weighted, drifter-dependent (A); non-weighted, drifter-dependent (B); and non-weighted, model dependent (C). Also shown: 45-degree lines and 95-percent confidence intervals on the drifter speeds and directions.

Table 1 (All tables are in the appendix.) presents the linear correlation coefficients of the various comparisons made. With the exception of the small, 45-point November 1997 set, the correlation coefficients are less than 0.50 and sometimes much less, and a few are not significant at the 95-percent confidence level. The correlations with "model speeds" are a little worse but comparable to the correlations with the integral-averaged ocean current field. Curiously, the correlations between the model and drifter separations are the largest. Overall, the ocean current field is in some discrepancy with the observed ocean currents.

The accuracy of the ECMWF wind field used to generate the ocean currents as well as the oil-spill trajectories in the OSRA model was assessed by [11] via comparisons against many moored meteorological buoys in the Gulf of Mexico. They found linear correlations as high as 0.8 and ECMWF model skill in excess of 80 percent over the time periods of this study. Thus, the OSRA input wind is somewhat more accurate than the ocean current field on a temporal point-by-point basis at many geographic locations in the Gulf.

Moving on to the oil-spill drifters, we see scatter in the drifter-model comparisons similar to that with the CODE drifters with comparably low linear correlation coefficients (Table 2). Again, the November 1997 set shows the highest values, 0.64 in speed and separation and 0.48 in angle in the drifter-model comparisons, but the other cases, including the composite of all the deployments, show again very low correlation. The "residual velocities" correlate less well with the wind speeds and directions than do the drifter trajectories alone (Table 2 and Fig. 3). This is not surprising, given the inaccuracies of the ocean current field.

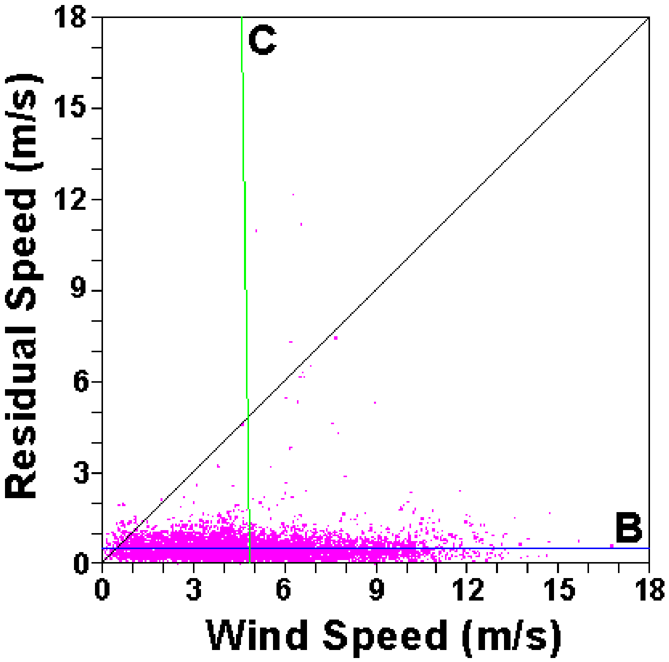

Fig. 3 Scatter plot of All Residual Speeds vs. Wind Speeds with linear regression lines: non-weighted, drifter-dependent (B); non-weighted, model-dependent (C). The plots also show the 45-degree line.

The least well correlated quantities in Table 2 are the drift angles A_D and the empirically determined drift angle A_E [2], which is used in the OSRA model. ($A_E = 25^o\exp(-w^3/1184.75)$, where w = wind speed in m/s.) Plotting A_D and A_E against wind speed, we see the considerable disagreement. As many relative wind directions are to the left of the wind looking downwind (negative A_D) as to the right (positive A_D).

The linear regression coefficients derived from the speeds of the residual velocities compared against the integral-averaged wind speeds are presented in Table 3. In the ideal case, the 3.5-percent rule, also employed in the OSRA model, would be revealed by coefficients A and B equating to 0.0 and 0.035 respectively. None of the coefficients A were 0.0 ; they were in the neighborhood of 0.5 m/s. The closest B to 0.035 came from the November 1997 set, which was less than half of the commonly accepted empirical value. The May 1998 set produced a slope nearly equal to 0.035 in magnitude but with a negative sign, implying decreasing drift speed with increasing wind speed – not a plausible result. That case revealed the highest correlation coefficient too, but again the sign was negative. These results are not surprising, given the inaccuracies of the ocean current field, the somewhat better, but not perfect, wind field, and the drifter locations. This comparison was highly ambitious but worth performing anyway.

Finally, Table 4 summarizes the extent of the Lagrangian discrepancies over selected time intervals with the assumption that the terminal ends of the trajectories of the oil-spill-simulating drifters are the "true locations". The values in Table 4 are derived from the composite of all five deployments. One must consider that two drifters deployed side-by-side in a highly dispersive wind and ocean current regime could separate by comparable amounts in the same time intervals.

IX. CONCLUSIONS AND DISCUSSION

We would like to emphasize that this study was a preliminary, first-look analysis of the drifter data presented and that we are making no conclusions at this time about the accuracy of the OSRA model or any other oil-spill trajectory model. Much more work needs to be done to fully assess the accuracy of the OSRA model, to understand the reasons for the differences between the model and the observations, and to determine ways in which the OSRA model and the use of the model can be improved.

In this study, we assumed that the water-following (CODE) and the oil-spill-simulating drifters are true representations of the ocean currents and the movements of consolidated oil spills on the sea surface. In our comparisons between the trajectories of the drifters and those generated by the OSRA model, we have observed differences of some magnitude.

The differences are the consequence of integrating wind and ocean current fields that are not perfect. The ECMWF winds and the data-assimilated ocean current field are products of state-of-the-art modeling, but of course do not exactly represent the real world conditions. Since the modeled oil-spill trajectories are integrals of the input fields, their terminal locations bear an accumulation of the errors in those fields. Adding to that are the location errors in the oil-spill-simulating drifters, which are not perfect representations of oil spills. All things considered, the low correlations found in this investigation are neither surprising nor disappointing. They do not negate the utility of the OSRA model or, by implication, other oil-spill models, but merely provide information which may lead to quantitative error bars on the model results. They also give us some clues as to the sources of the errors and how the model might be improved in the future.

In addition, one must consider that a point-by-point comparison between observed ocean currents and model ocean currents is the most severely demanding test one can make of an ocean current model. In a less severe comparison between CODE drifters and model ocean currents in the Gulf, produced without benefit of data assimilation, [8] found correlation coefficients of 0.50 (drifters on model) and 0.71 (model on drifters) in daily averaged velocities grouped in 0.25^{o} X 0.25^{o} latitude-longitude boxes. However, the OSRA model integrates the ocean current and wind fields on a point-by-point basis, with no averaging of the input fields in space and time. It was necessary, therefore, to make our assessment of the model in the same way that the model generates its trajectories – comparing the drifters against the model on a point-by-point basis. An even more demanding test was the comparison of the residual velocities against the integral-averaged wind (Figs. 3 and 4). Here, the combined errors in the drifter locations, model ocean currents, and model-generated ECMWF winds combine to produce negligible or no significant correlations and the implausible result of decreasing wind drift speeds with increasing wind speed. But again, the OSRA model employs a wind drift formula at each time step to produce the model trajectories, so we needed to assess its accuracy, given the input wind and ocean current fields. We hasten to add that this comparison is not a repudiation of the 3.5-percent rule, which has been derived empirically.

An additional important consideration is the case of high wind speeds. We know from observational studies cited earlier that the motion of oil-spill-simulating drifters deviates substantially from actual oil spill trajectories under wind speeds exceeding about 10 m/s. At these wind speeds, surface spills are entrained into the mixed layer and Ekman transported, while the oil-spill-simulating drifters remain on the ocean surface and run downwind. The OSRA model makes no provision for the entrainment and subsequent Ekman transport. Instead, it merely extends the 3.5-percent rule [2] into the higher wind cases. We need to consider this fact in the next steps of our analysis.

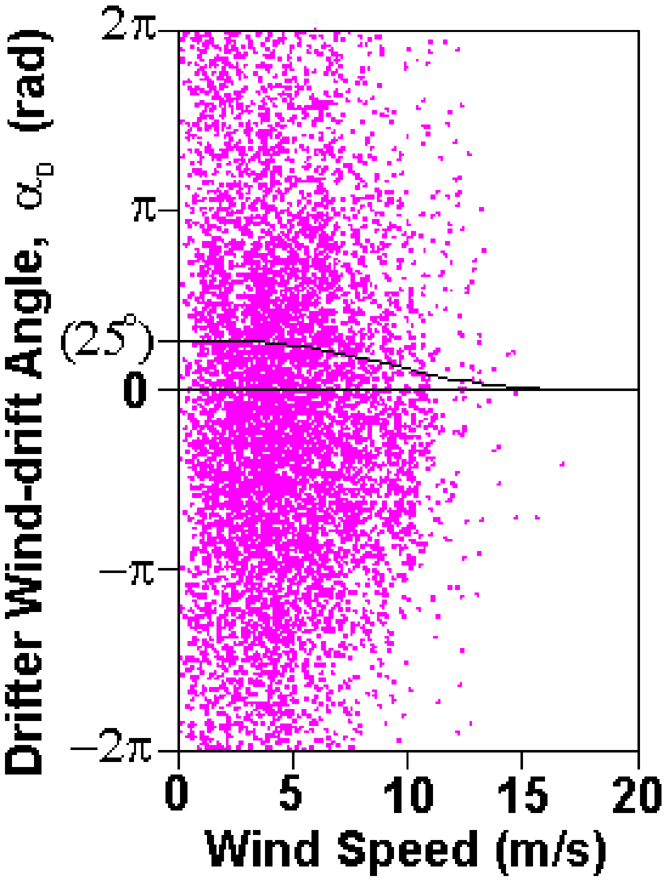

Fig. 4 Scatter plot of All Drift Angles A_D vs. Wind Speeds. The plotted curve is the empirical relationship used in the OSRA model, relating drift angle A_E and wind speed [2]: $A_E = 25^{o}\exp(-w^3/1184.75)$, where w = wind speed (m/s). Positive angles are to the right of the wind looking downwind, i.e. they are cum sole deflection angles.

In the next steps, we will look closely at the different oceanographic and meteorological conditions at the times the drifters were in the water. It could be that different conditions produce different model errors. For example, the model ocean currents, derived from sea surface height assimilation, may be more accurate when the mesoscale eddies dominate the field than when smaller scale currents dominate. The scatter plots of observed angles vs. model angles (not shown) reveal two groupings

One group is roughly coincident with the 45-degree line, indicating agreement between the model and observations, and the other is centered in the lower-right quadrant of the plot. This may be a consequence of two different wind and ocean current regimes – one reproduced accurately in the OSRA input fields and the other did not. Possibly, the accurate case occurs when mesoscale eddies dominate the area, because those eddies can be resolved well in the ocean current model and are accurately geographically located with the data assimilation that went into the ocean current model. When the mesoscale eddies are not dominant, smaller-scale processes not well resolved by the ocean current model nor manifest in the ECMWF winds will produce model trajectories that have little or no correlation with the drifter trajectories. But the wind-dominated situations could also be the positive-correlation case if the ocean currents and current gradients were small enough and random-like and therefore much less important to the net surface transport than the prevailing winds, accurately determined. And finally, the case with large eddy structures in the flow, with their large velocities and large velocity shear, could be the negative correlation case if the shape and magnitude of the eddies were not sufficiently well determined by the ocean current modeling. We will look at these and other possibilities in the next round of our analysis.

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Appendix

TABLE 1

Linear Correlation Coefficients of (from left to right) "water-following" drifter speed against model speed (model separation divided by elapsed time), the angular orientation of the drifter separation vector against that of the model separation vector, drifter separation against model separation, drifter speed against the integral-averaged speed of the input ocean current field, and the angular orientation of the drifter velocity against the angular orientation of the integral-averaged ocean current vector. An * denotes a correlation coefficient that is not significant at the 95-percent confidence level. All other coefficients are significant at the 95-percent confidence level.

Drifter Release Dates	Speed Drifter-Model	Angle Drifter-Model	Separation Drifter-Model	Speed Drifter-Ocean	Angle Drifter-Ocean	Number Points Compared
Nov. 1997	0.73	0.14 *	0.76	0.72	0.18 *	45
May 1998	0.22	0.12	0.30	0.25	0.14	3213
Aug. 1998	0.18	0.09	0.28	0.20	0.06 *	1022
Nov. 1998	0.10 *	0.12	0.20	0.09 *	0.21	602
Nov. 1999	0.49	-0.01 *	0.49	0.49	0.00 *	266
(all)	0.24	0.10	0.31	0.26	0.13	5148

TABLE 2

Linear Correlation Coefficients of (from left to right) "oil-spill-simulating" drifter speed against model speed (model separation divided by elapsed time), the angular orientation of the drifter separation vector against that of the model separation vector, drifter separation against model separation, drifter speed against the integral-averaged wind speed, and the angular orientation of the drifter separation vector against the angular orientation of the integral-averaged wind vector, the residual drifter speed (the magnitude of the drifter velocity minus the input ocean current velocity) against wind speed, the angular orientation of the residual drifter velocity and the angular orientation of the integral-averaged wind vector, and the drifter wind-drift angle (the angle between the residual velocity and the wind velocity, A_D) and the speed-dependent wind-drift angles as in [2], $A_E = 25^o \exp(-w^3/1184.75)$, where w = wind speed (m/s). An * denotes a correlation coefficient that is not significant at the 95-percent confidence level. All other coefficients are significant at the 95-percent confidence level.

Drifter Release Dates	Speed Drifter-Model	Angle Drifter-Model	Separation Drifter-Model	Speed Drifter-Wind	Angle Drifter-Wind	Speed Residual-Wind	Angle Residual-Wind	A_D versus A_E	Number Points Compared
Nov. 1997	0.64	0.48	0.64	0.19	0.23	0.11	0.17	-0.03 *	433
May 1998	0.07	0.09	0.21	-0.02 *	0.17	-0.21	0.18	-0.06 *	799
Aug. 1998	0.25	0.26	0.34	0.31	0.39	-0.02 *	0.28	-0.06	2143
Nov. 1998	0.20	0.23	0.37	0.09	0.26	0.03 *	0.18	-0.02 *	3271
Nov. 1999	0.11	0.33	0.36	0.10	0.43	0.02 *	0.19	0.06 *	692
(all)	0.25	0.27	0.39	0.13	0.33	0.00 *	0.22	0.00 *	7338

TABLE 3

Linear Regression Coefficients A and B of the residual speed of the oil-spill-simulating drifters, V_R , against the integral-averaged wind speed, W. The derived, least-squares best fit line is $V_R = A + BW$. Also shown are the correlation coefficients (repeated from Table 2) of the residual speed of the oil-sill-simulating drifters against the integral-averaged wind speed. No error bars can be assigned to A or B, because there are no error bars associated with the ocean current field, which was subtracted from the drifter velocities to get the residual velocities. An * denotes a correlation coefficient that is not significant at the 95-percent confidence level. The other two correlation coefficients are significant at the 95-percent confidence level.

Drifter Release Dates	Linear Regression Coefficient A	Linear Regression Coefficient B	Speed Residual-Wind	Number Points Compared
Nov. 1997	0.475 m/s	0.015	0.11	433
May 1998	0.660 m/s	-0.033	-0.21	799
Aug. 1998	0.547 m/s	-0.002	-0.02 *	2143
Nov. 1998	0.475 m/s	0.005	0.03 *	3271
Nov. 1999	0.471 m/s	0.004	0.02 *	692
(all)	0.523 m/s	0.000	0.00 *	7338

TABLE 4

Lagrangian Discrepancies The distance between the terminal ends of the model trajectories and those of the oil-spill-simulating drifters of 3, 10, 20, and 30 days duration. All trajectories from all 5 deployments were used to compute these statistics.

	03 days	10 days	20 days	30 days
mean	78 km	229 km	416 km	483 km
standard dev.	53 km	144 km	234 km	281 km
minimum	1 km	10 km	16 km	25 km
maximum	416 km	670 km	951 km	1134 km