The Effect of Wind and Surface Currents on Drifters[1]

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ABSTRACT

The problem analyzed here is the motion of a drifter acted on by wind, surface and subsurface currents. From the condition of static equilibrium of all drag forces acting on the drifter, the effects of wind and surface current of arbitrary direction and magnitude and drogue characteristics are examined parametrically. Specific application is made to a recently developed drifter with 9.2 and 11.85 m parachute drogues and a window shade drogue. The calculations show that for some environmental conditions the deviation between the magnitudes of the drifter velocity and the water parcel velocity may exceed 50%. Furthermore, the direction of velocity vectors may differ by as much as 45°. Drifter data from an experiment conducted by the Atlantic Oceanographic and Meteorological Laboratories and the NOAA Data Buoy Office in the Gulf of Mexico Loop Current are examined in light of the theoretical results. The wind effects predicted by the theory were observed in the field. Thus wind corrections to the drifter velocity records which are based on the theory can significantly improve the velocity records.

1. Introduction

Preliminary plans for the First GARP Global Experiment (FGGE) call for a large number of free drifting platforms observing oceanic and atmospheric conditions. The data would be collected by a Random Access Measurement System (RAMS) aboard the TIROS N satellite. Because of the large deployment this component of FGGE has great potential for studying horizontal scales of ocean dynamics provided these vehicles can be effectively attached to representative water parcels by drogues.

Because of the need for an antenna, there must be a surface buoy. This, however, introduces some serious technical problems. Accelerations on the buoy due to waves, wind, and vertical shears between the buoy and drogue are different than those on the water parcel. In addition, the drogue may fishtail and kite. Unless accounted for all of these factors can lead to serious errors in interpretation of observations of drifter motion.

This report is restricted to one of the above questions; namely, how much can wind and surface drag affect a drifter system composed of a surface buoy with antenna and an attached drogue. Our results are preliminary and apply to a simplified situation, yet they do provide some quantitative design criteria. If FGGE drifters are to be utilized for studying ocean currents, this study must be followed up by more detailed theoretical analysis and field tests of all of the technical problems mentioned above.

2. Formulation of problem

The following assumptions are made in this analysis:

(i) The wind, surface and subsurface currents are steady.

(ii) The "V^2" drag law with a constant drag coefficient applies.

(iii) Drag on the cable connecting the drag body at depth z to the surface vehicle is neglected. Thus our results apply only to drifters drogued to shallow depths. Beyond 500 m the drag on the cable may well be the most significant effect.

From assumptions (i) and (iii) the equations of motion for the drifter system reduce to

$$\mathbf{F}_z+\mathbf{F}_s+\mathbf{F}_a=0. \qquad (1)$$

In order, these terms are the drag acting at depth z on the drogue, the surface current drag acting on the wetted portion of the surface vehicle, and the wind drag exerted on the dry portion. Assumption (ii) asserts that each of the drag forces is given by

$$\mathbf{F}_i=\rho_i C_{Di} A_i |\mathbf{V}_i-\mathbf{V}| (\mathbf{V}_i-\mathbf{V}), \qquad (2)$$

where ρ_i is the fluid density (air and water) enveloping the ith component of the drifter system, C_{Di} the drag

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[1] Dedicated to W. Richardson and W. Hill and the crew of the R. V. *Gulfstream*, lost at sea 4 January 1975.

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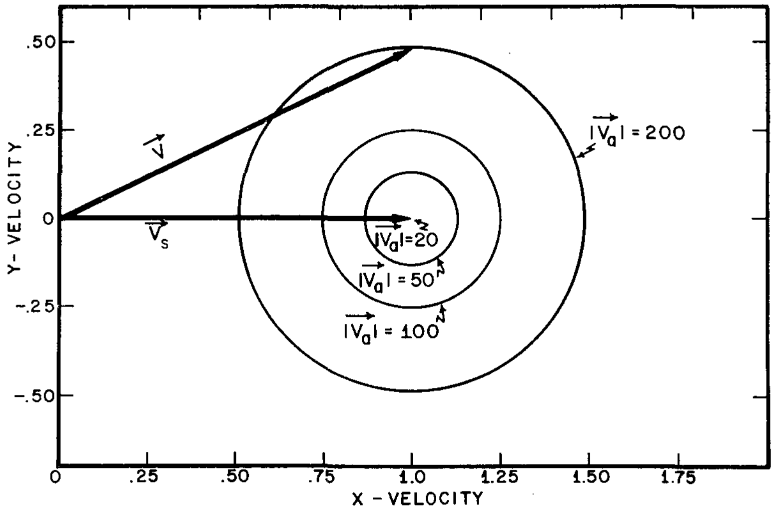

FIG. 1. The effect of wind on a Nova drifter drogued with a 9.2 m parachute at the surface. The locus for the drifter velocity for a given wind magnitude occurs on the appropriate circle.

coefficient for the ith component, A_i the area of the ith component as seen by the fluid streaming past it, $\mathbf{V}_i$ the velocity of the fluid at the ith part of the system with x and y components U_i and V_i, and $\mathbf{V}$ the velocity of the drifter system whose components are U and V.

Inserting (2) into (1) we obtain

$$\rho_z C_{Dz} A_z |\mathbf{V}_z - \mathbf{V}| (\mathbf{V}_z - \mathbf{V}) + \rho_s C_{Ds} A_s |\mathbf{V}_s - \mathbf{V}| (\mathbf{V}_s - \mathbf{V}) + \rho_a C_{Da} A_a |\mathbf{V}_a - \mathbf{V}| (\mathbf{V}_a - \mathbf{V}) = 0. \quad (3)$$

The effect of the wind and surface current can be investigated with (3) by regarding $\mathbf{V}_s$, $\mathbf{V}_a$ and $\mathbf{V}_z$ as parameters of a solution for $\mathbf{V}$. The other quantities ρ_i, C_{Di} and A_i are known *a priori*. Note the formal similarity of this problem with the theory of the statics of structures. In the latter case the condition of equilibrium of forces provides a system of equations which is solved for the displacement vector in terms of prescribed loadings. In our case the equilibrium of forces determines the velocity.

The inversion of (3) for $\mathbf{V}$ is readily accomplished numerically once $\mathbf{V}_z$, $\mathbf{V}_s$ and $\mathbf{V}_a$ have been specified. We found a simple interation technique using complex arithmetic to be very efficient for the parameter ranges of interest.

An important special case is when the drifter is drogued at the surface. In this case (3) can be inverted analytically to obtain

$$\mathbf{V} = (\mathbf{V}_s + K^{\frac{1}{2}} \mathbf{V}_a)/(1 + K^{\frac{1}{2}}), \quad (4)$$

where

$$K = \rho_a C_{Da} A_a / (\rho_s C_{Ds} A_s).$$

Thus for a wind of magnitude of $|\mathbf{V}_a|$ but of arbitrary direction the system velocity is given by a circle centered at $\mathbf{V}_s/(1+K^{\frac{1}{2}})$ with a radius of $K^{\frac{1}{2}}|\mathbf{V}_a|/(1+K^{\frac{1}{2}})$. The center of the circle is the system velocity for no wind.

Eq. (4) indicates that the relative velocity error, $(\mathbf{V}-\mathbf{V}_s)$, depends upon the magnitude (and not the magnitude squared) of the air velocity even though the V^2 drag law is applied. The effect of the increased drag when the wind is increased is compensated by an increase in the drag at the ocean surface.

Calculations are performed for a drifter developed at Nova University, Fort Lauderdale, Fla., for the NOAA Data Buoy Office (NDBO). This drifter has been proposed as the surface platform for many of the FGGE experiments.

Fig. 1 shows the effect of wind of various magnitudes and arbitrary directions on the Nova University drifter with a 9.2 m parachute drogue at the surface. (In this case A_s and C_{Ds} for the drifter are effectively that of the 9.2 m parachute; see Table 1.) The coordinate system is oriented in the direction of the surface current. Also the calculations have been normalized by the current magnitude. This graph demonstrates that the percentage error,

$$[|\mathbf{V}-\mathbf{V}_s|/|\mathbf{V}|]\times 10^2,$$

between the drifter velocity and the surface current may be of the order of 50% for a wind speed 200 times greater than the surface current. Note also that the drifter velocity vector may deviate as much as 30° from the surface current vector.

For high winds the percent error is approximately

$$[K^{\frac{1}{2}}|V_a|/|V|(1+K^{\frac{1}{2}})]\times 10^2.$$

Thus for a wind of magnitude 200 times the surface current the percentage error is reduced to only 45% by changing from a 9.2 to an 11.85 m parachute. On

TABLE 1. Hydrodynamic characteristics of Nova University Drifter and drogues.

	Drifter		
	$A_a = 5.76 \times 10^{-1}$ m², $C_{Da} = 1.2$ $A_s = 2.973 \times 10^{-1}$ m², $C_{Ds} = 1.2$		
	Drogues		
	9.2 m parachute	11.85 m parachute	Window shade
A_z	5.723×10 m²	9.448×10 m²	2.787×10 m²
C_{Dz}	1.35	1.35	1.9

the other hand, if the drifter loses its drogue, A_s and C_{Ds} become that of the buoy (see Table 1). The percentage error then exceeds 100% for a wind speed of only 50 times the surface current.

3. Three-drag body problem

When the drifter is drogued at depth z, there are three drag bodies to consider and it is necessary to invert (3) numerically. Some examples of these calculations are given in Figs. 2–4.

These calculations are most conveniently depicted in a coordinate system oriented in the direction of the subsurface current $\mathbf{V}_z$. Also, the magnitude of this current is fixed at unity.

The inputs for the calculation are the areas and drag coefficients for the three drag bodies (Table 1) and the magnitudes of the surface current and wind vector relative to $|\mathbf{V}_z|$. The calculation is started with the wind and surface current aligned in the direction of the subsurface current. The numerical inversion of (3) for $\mathbf{V}$, the drifter velocity, is then readily accomplished. The wind direction is varied in 30° increments for 360° with the solution for $\mathbf{V}$ being performed at each increment. Then the surface

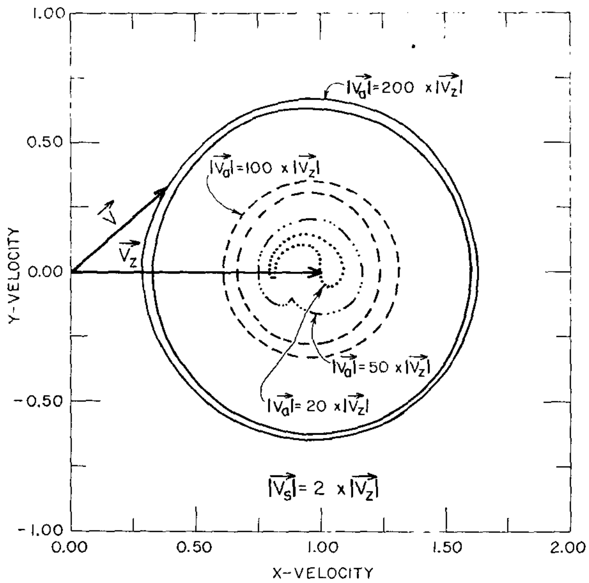

FIG. 3. The effect of wind with a constant surface current magnitude on a Nova drifter drogued at some subsurface depth by a 9.2 m parachute. The locus for the drifter velocity for a given wind speed occurs within the indicated enclosed region.

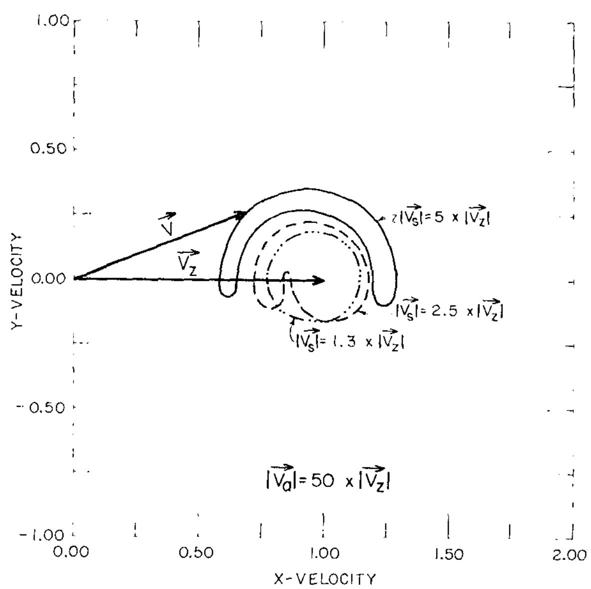

FIG. 2. The effect of surface current with a constant wind magnitude on a Nova drifter drogued at some subsurface depth by a 9.2 m parachute. The locus for the drifter velocity for a given surface current magnitude occurs within the indicated enclosed region.

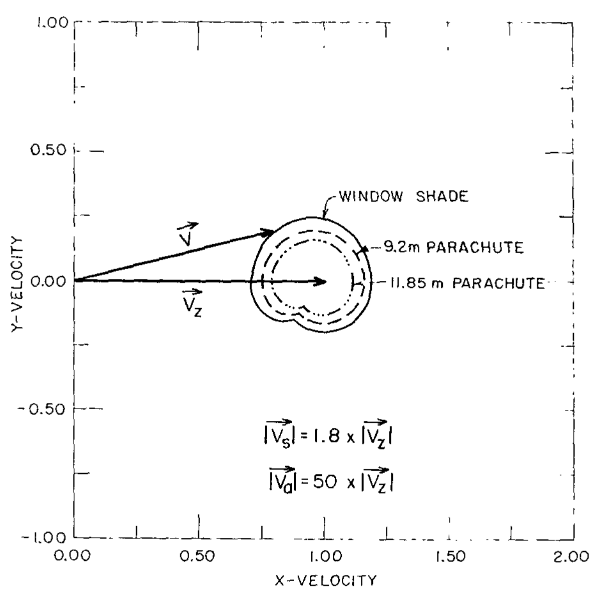

FIG. 4. The effect of various drogue sizes at constant wind and current magnitudes for a Nova drifter. The locus for the drifter velocity for a given drogue occurs within the indicated enclosed region.

TABLE 2. Hydrodynamic characteristics of drifters used in loop current study.

Drifter no.	Type	A_a(m²)	A_s(m²)
1, 2	1	Cylinder* 9.755×10⁻¹	Parachute 8.938×10
3	2	Cylinder 1.366×10	Cylinder 1.343×10
4	3	Cylinder 3.581×10	Cylinder 1.375×10 Rectangular pole 4.297.10⁻¹
5	4	Cylinder 3.581×10	Cylinder 1.375×10 Vane 4.262×10

* C_D for cylinder is 1.2

current is changed by 30° increments for 180°. For each angle increment of current, the wind direction is varied 360° as before. This procedure produces an envelope containing 84 solutions for the drifter velocity for each set of parameters.

Fig. 2 shows the effect of surface current magnitude with a constant wind speed on the drifter velocity for a Nova University drifter with a 9.2 m parachute drogue. From this we see that if the wind and surface current are opposed to the subsurface current, the drifter velocity could deviate by more than 50% in the case of a surface speed five times the subsurface speed. Under the same conditions, except that the wind and surface current are aligned with the subsurface current, the percentage error is of the order of 20%. For a shear ratio of 1.3 to 1, the velocity errors may still be in excess of 25%.

The results of calculations examining the effect of wind magnitude with a constant surface current magnitude on the drifter velocity are shown in Fig. 3. As before, the calculations apply to the Nova University drifter with a 9.2 m parachute drogue. For the most stringent case considered, the velocity error is of the order of 75%. Moreover, the direction of motion of the drifter in this case can be inclined 45° to that of the subsurface current.

The effect of varying the drogue type while holding the wind and current magnitude fixed is shown in Fig. 4. The calculations were performed for the Nova University drifter with a window shade drogue, a 9.2 m parachute drogue, and an 11.85 m parachute drogue. It is seen from this that the window shade with a cross-sectional area of only 29.9 m² is not as efficient as a drag body as either of the parachute drogues. In fact, it alone can cause an incremental increase of over 10% in the error in the velocity measurement when compared with measurements from the large parachute drogue.

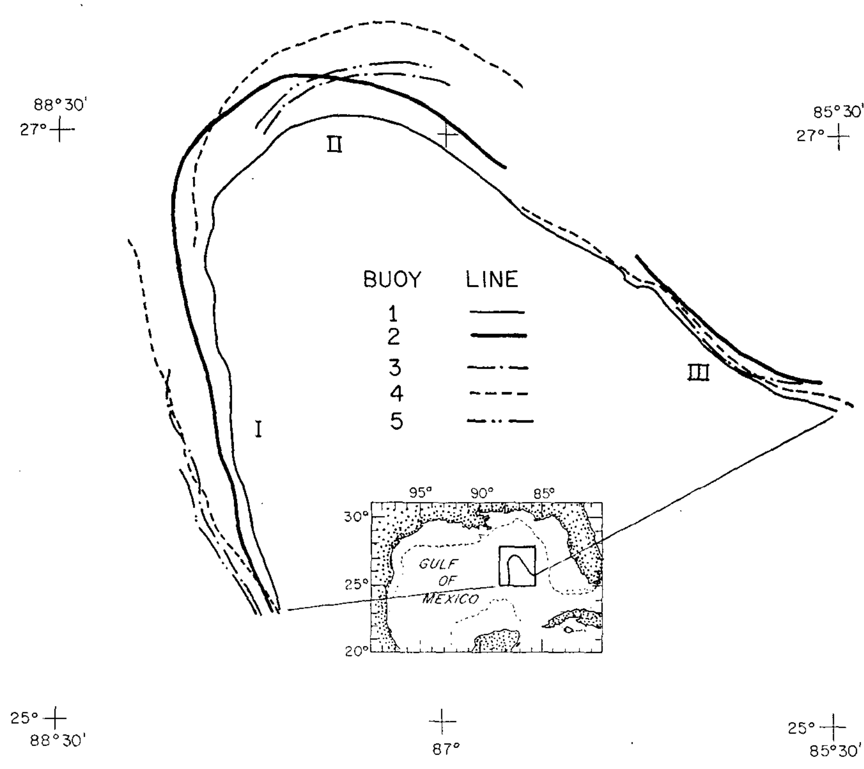

FIG. 5. Trajectories for comparison test in Gulf of Mexico. The three different legs are indicated by Roman numerals.

4. Experimental data

An experiment that sheds some light on the utility of the analytical and numerical results was conducted by the Atlantic Oceanographic and Meteorological Laboratories (AOML) for NDBO. The objective of this study was to evaluate the effect of wind and surface current on certain NDBO buoys by comparing their drift to the drift of a "calibration" drifter. The experiment was conducted in the eastern Gulf of Mexico Loop Current. Hydrodynamic data for the drifters used in this experiment are given in Table 2.

The navigational and positioning capability of the tracking ship (R/V *Virginia Key*) along with the rapid dispersion of the drifters made it necessary to smooth the half-hourly positions. Successive groups of 13 fixes (6 h) were smoothed by fitting second-degree polynomial functions to the latitude-vs-time and longitude-vs-time values. Coordinate speeds were calculated by differentiating these functions. Finally, the velocity and position records were smoothed by a three-point running average to obtain hourly readings. The raw wind data observed on the *Virginia Key* were reduced in a similar manner.

The height that the wind observations were made

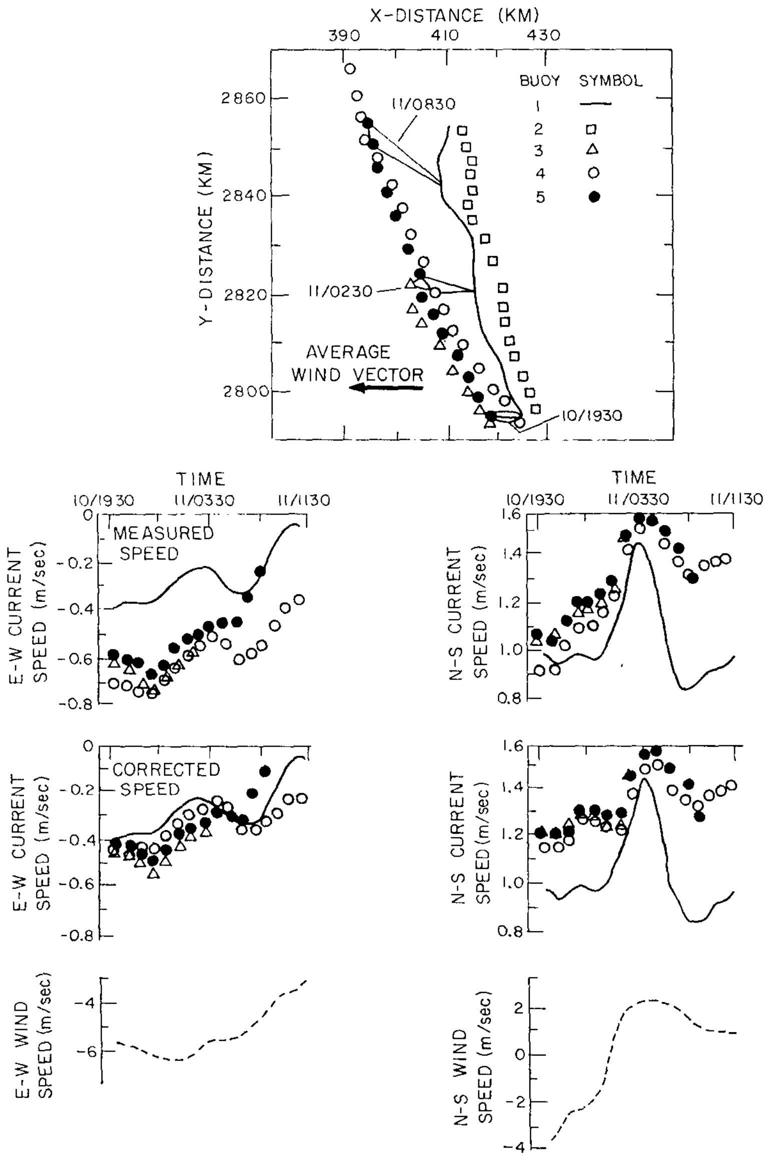

Fig. 6. Trajectories, currents and wind records for leg 1. The top panel shows trajectories of the five drifters. The bottom panels show the measured current components as well as the current components corrected in accordance with (4). Also shown are the components of the wind.

X-DISTANCE (KM)

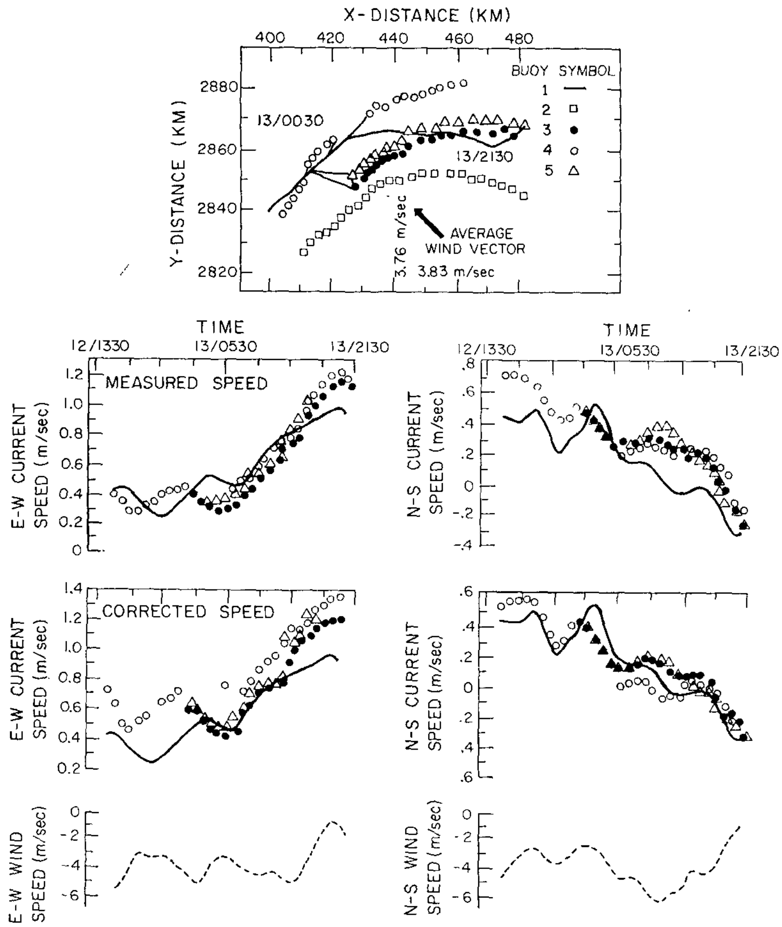

FIG. 7. As in Fig. 6 except for leg 2.

differed by about 5 m from the height of the buoys. Assuming a logarithmic velocity profile one finds that the velocity at the buoy is within 90% of that observed. Because the *Virginia Key* frequently was 10–20 km from some of the drifters and because the logarithmic profile indicated such a small difference, we elected not to make a height correction to the wind records.

Fig. 5 gives the smoothed trajectories determined from the analysis. The rapid separation of the drogued and non-drogued drifters is evident in this figure. As expected, the non-drogued drifters had a larger downwind displacement than did the drogued drifters. The separation between the two drogued drifters also varies but to a lesser degree. The cause of this separation could be due to small-scale diffusive processes, horizontal inhomogeneity of the currents (discussed below), or the result of the dynamics of turning currents (Chew, 1974).

Drifter type 1 has been used by AOML in a number of previous experiments. Here this type was drogued at 30 m by a 11.85 m parachute while the other types were not drogued. This disparity in coupling depths required a special assumption for analysis of the data, namely, that there was no vertical current shear between the surface and 30 m.

Note from Table 2 that the type 1 drifters have a much smaller K than the other types. For the wind speeds encountered in this experiment, the maximum wind effect for type 1, as computed from (4), was only 4% of the drifter velocity. Thus the velocity records for type 1 are regarded as the "true" surface current. For each of the other drifters listed in Table 2, a surface current is also computed from (4).

These computed surface currents are compared to the observed currents in Figs. 6, 7 and 8. Downstream and cross-stream current components are relative to the direction of the drogued drifters for that particular trajectory interval. Thus for leg 1 the downstream direction is N–S while for legs 2 and 3, it is E–W.

These figures show that the corrected cross-stream speed records are very similar for all of the drifters. This is true even though the uncorrected cross-stream speeds of drifter 4 during legs 1 and 2 are in some cases a factor of 2 greater than the velocities of drifter 1. After correction the speeds are within 15% over most of the trajectories. Drifter 4 was drogued during leg 3, and Fig. 7 indicates that the effect of wind on this drifter is greatly reduced as it tracks closely with the other drogued drifters.

The wind correction for the downstream components increases the velocity difference between drifters for legs 1 and 2. However, for all legs this was the weakest wind component. Vertical and horizontal shears in the intense Loop Current, rather than the wind, probably were the most dominant causes of the deviation of the velocity records. It was not possible to make a quantitative correction for this effect. However, a qualitative assessment shows that a horizontal shear correction would reduce the error.

5. Discussion

1) The theoretical calculations show that steady winds and surface currents can substantially bias velocity records obtained from drifter trajectories. The magnitudes of the parcel and drifter velocities can differ by 75% and the direction by 45% when there is a 200 to 1 ratio of wind speed to parcel velocity.

The theoretical results are substantiated by the field tests even though different drifters and K's were used in the latter. During leg 1 it is seen that $K^{\frac{1}{2}}|\mathbf{V}_a|/[|\mathbf{V}|(1+K^{\frac{1}{2}})]$ for the field tests was the same as that used in the calculations which produced the errors indicated above.

2) The calculations also showed that the effect on a drifter of wind and/or surface currents depended upon direction. For a fixed magnitude the percent velocity error was larger when the surface current and/or wind opposed the subsurface current. The reason for this is that in opposed cases the relative velocity past the drifter system is greatest. Thus the drag is greater.

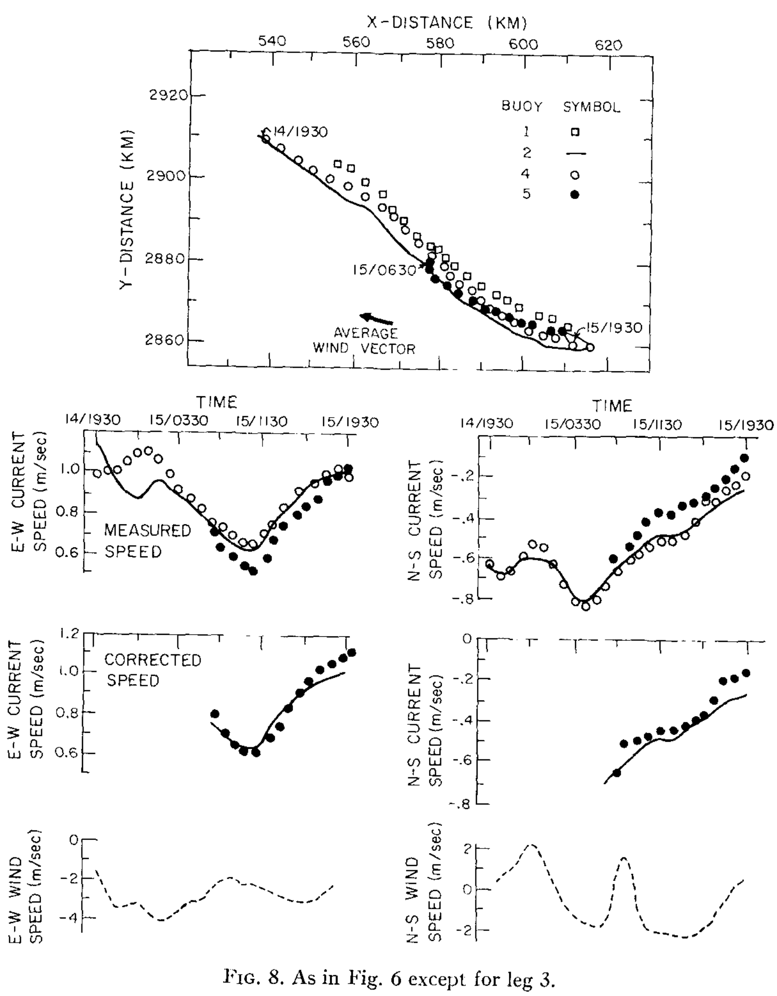

FIG. 8. As in Fig. 6 except for leg 3.

Also, for either a surface current or wind large with respect to the other, the theoretical solution approaches the two-body case.

3) The experimental data show that even for large differences in parcel and drifter velocities, wind corrections based on (4) can improve the results.

4) The experimental data also demonstrate that where there are large horizontal velocity gradients, another effect is observed. A very small wind can move the drifter into a completely different current regime. This horizontal shear effect enhances the turbulent dispersive processes.

The separation of the drifters during leg 1 (Fig. 6) exemplifies this type of effect. Here the northward motion of drifter 2 relative to 1 indicates that the current axis is to the west. Thus the east wind component caused the non-drogued drifters to move toward the axis. Although the east-west separation of the drogued and non-drogued drifters is a function of wind-induced motion, the north-south separation is caused by this horizontal current shear.

Because of this last type of effect, it is virtually impossible to correct a trajectory to obtain the true path of the water parcel originally tagged. Eq. (4) requires as input the observed drifter velocity and wind speed to obtain the corrected speed. After the first time step the observed velocity at the "corrected" position is not known, and particularly in the case of large shears, the task of estimating this velocity is not trivial. In essence, a drifter integrates its instantaneous velocity to obtain its trajectory. Thus velocity errors accumulate in the trajectory.

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