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Measurements of the water-following capability of holey-sock and TRISTAR drifters

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Abstract—Since 1985, a number of measurements have been made in deep water to determine the water-following characteristics of mixed layer drifters with both holey-sock and TRISTAR drogues at 15 m depth. The measurements were done by attaching two neutrally buoyant vector measuring current meters (VMCMs) to the top and the bottom of the drogues and deploying the drifters in different wind and upper ocean shear conditions for periods of 2–4 h. The average velocity of the VMCM records was taken to be a quantitative measure of the slip of the drogue through the water, observed to be 0.5–3.5 cm s^{-1}. The most important hydrodynamic design parameter which influenced the slip of the drogue was the ratio of the drag area of the drogue to the sum of the drag areas of the tether and surface floats: the drag area ratio R. The most important environmental parameters which affected the slip were the wind and the measured velocity difference across the vertical extent of the drogue. A model of the vector slip as a function of R, vector wind and velocity difference across the drogue was developed and a least squares fit accounts for 85% of the variance of the slip measurements. These measurements indicated that to reduce the wind produced slip below 1 cm s^{-1} in 10 m s^{-1} wind speed, $R > 40$. Conversely, if the daily average wind is known to 5 m s^{-1} accuracy, the displacement of the $R = 40$ drifter can be corrected to an accuracy of 0.5 km day^{-1}.

1. INTRODUCTION

In the past few years, there has been an increased effort and need to understand the detailed behavior of Lagrangian drifters in the upper ocean (Dahlen, 1986; Niiler *et al.*, 1987; Geyer, 1989; Chereskin *et al.*, 1989; Krauss *et al.*, 1989; Poulain and Niiler, 1990; WCRP-26, 1989). Through satellite ranging with ARGOS, transmitters can be located globally within a 1 km radius, and if these are attached to drogues at some depth, the daily average motion of the water at the drogue level potentially can be determined to about 1 cm s^{-1} accuracy. Thus, to make full use of the ARGOS capability for obtaining accurate measurements of upper ocean currents, drifters would have to be constructed with characteristics that would not allow an unknown slippage through water in excess of 1 cm s^{-1}. Mechanical current meters can be calibrated to about 1 cm s^{-1} accuracy, and this is a report on using vector measuring current meters (VMCMs; Weller and Davis, 1980) to measure how fast water slips past the drogues deployed in the open ocean.

All devices which use lift or drag forces for measuring upper ocean currents incur errors due to the non-linear and non-periodic forces created by surface gravity waves (Weller and

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Davis, 1980; Niiler *et al.*, 1987). Examples of the wave-produced, hydrodynamically complex phenomena observed in this study were the breaking of surface waves around and over the surface float and the formation of three-dimensional loops in the tether which join the drogue and the surface float. Wind blowing directly on a surface float causes a slip-producing force on the drogue in the direction of the wind. An additional slip-producing force on the drogue is caused by the time-average, mean relative currents between its various surface and subsurface elements; e.g., wind waves cause a surface intensified Stokes drift that is a component of this differential mean current. Because the combined effect of these forces is difficult to model realistically and accurately for a flexible drifter in a wind-blown, breaking sea, field measurements of the slip are needed.

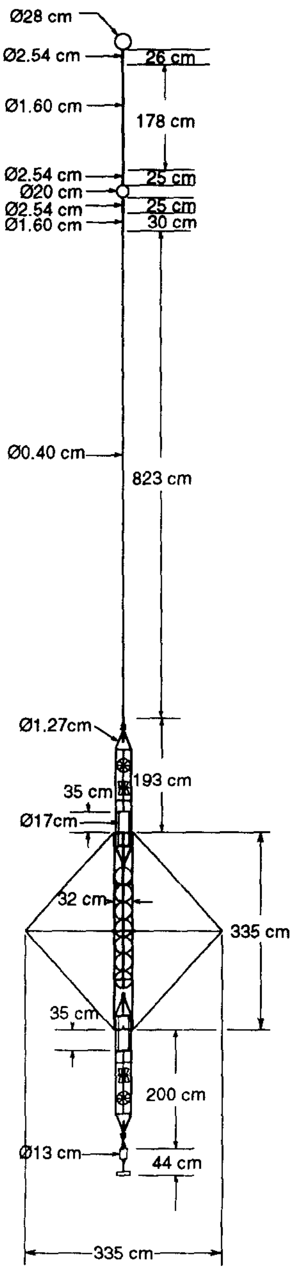
In this paper, we present the results of several studies of the water-following capability of drifters that have a float on the ocean surface for housing an ARGOS transmitter and batteries and a large subsurface drogue tethered with a thin wire cable to 15 m depth. The objective of these studies was to quantitatively discriminate between the effects of design parameters and environmental conditions on the slip of the drogue through the water by direct measurements. Since the wind (and waves), upper ocean shear, internal tension between the float and drogue and the hydrodynamic shapes of the drogue, tether and surface float all have been suggested theoretically as being important (Chhabra, 1985; Chereskin *et al.*, 1989), a large number of slip measurements were needed to sort out the effects of each parameter. This study is focused on drifters that are designed for measuring mixed layer currents averaged over the vertical extent of the drogue, centered at 15 m depth. These drifters are now in use in large numbers in global ocean research projects such as the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean and Global Atmosphere (TOGA) Programme (WCRP-26, 1989).

2. METHOD

Calibration studies were done in the California Current in September 1985 and May 1986, in the tropical Pacific in May 1988 and in the northeastern Pacific (near OWS PAPA) in October 1989. In each case, drifter drogues were outfitted with two neutrally buoyant VMCMs and the data were obtained from the instrumented drifter for periods of 2–4 h (Fig. 1; Bitterman *et al.*, 1990). In 1988, depth of the current meter was measured by a quartz digital pressure gauge to an accuracy of 1 cm in 10 m of water. The objective of the pressure measurement was to provide data on the possible tilting or kiting of the drogue in strong upper ocean shears which occur in the tropics. The drogues were designed to remain vertical in the known vertical shear fields of the tropical mixed layer by introducing an internal tension (of 4–5 kg) between the bottom of the drogue and a subsurface float at 3 m depth. The 1985 data have been discussed by Niiler *et al.* (1987), who found wind to be the most important slip-producing force. The 1988 data have been summarized in a data report by Bitterman *et al.* (1990). This presentation brings together unified interpretation of all the data.

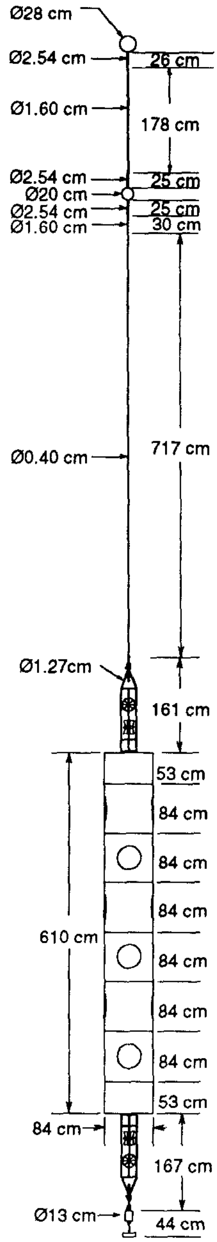
Fig. 1. The configuration of drifters and VMCMs used in the 1989 field study near OWS PAPA. The tables beside each of the figure panels document the computation of the drag area of each segment of the drifter; the configurations on panels (a) and (b) were also used in the 1988 equatorial experiment, when different floats were interchanges between the drifters in the middle of each deployment.

Drag Ratio of Calibration Drifters



A	C_d	C_dA
615	0.5	308
66	1.0	66
285	1.4	399
64	1.0	64
314	0.5	157
64	1.0	64
48	1.0	48
287	1.4	402
	Σ_S	1508
980	1.0	980
595	1.0	595
61640	1.2	73968
595	1.0	595
1016	1.0	1016
572	1.0	572
	Σ_D	77726

$$R = \Sigma_D / \Sigma_S = 49.6$$



A	C_d	C_dA
615	0.5	308
66	1.0	66
285	1.4	399
64	1.0	64
314	0.5	157
64	1.0	64
48	1.0	48
287	1.4	402
	Σ_S	1508
818	1.0	818
51240	1.4	71736
818	1.0	818
572	1.0	572
	Σ_D	73944

$$R = \Sigma_D / \Sigma_S = 49.0$$

In 1988, the deployments were made from the R.V. *Oceanographer*, which carried a full contingent of scuba divers. During these tests, photographs and visual observations were obtained of the behavior of the drifter components under water (laboratory model observations and the description of the behavior of different kinds of surface floats in wind waves can be found in Niiler *et al.*, 1987). The divers reported that on all drifters, whether they had current meters or subsurface floats attached or not, the tether would become slack and, occasionally, a three-dimensional loop would form in the tether (Fig. 2). From these field observations, it is apparent that the time scale for the response of the vertical motion of the drogue to 1–4 kg of weight at its base is much lower than the time scale of response of the surface floats and tether to wind waves of 4–10 s period. The top portions of the holey-sock drogues also showed accordion-like motion, as these sections would also become slack, or partially collapse, along with the contorted shapes of the tethers (Fig. 3). On several drifters with holey-socks which had a weighted ring on the top (a design no longer used), the top part of the sock would collapse before the rest of the sock could respond to the passage of wind waves. It was apparent that the drifters, as well as the divers, moved vertically in concert with the swell of 12–18 s period, but the contorted behavior of the subsurface elements of the drifters was caused by short period waves, some of which were breaking on the surface and over the surface float.

The typical test, during which instrumented drifters were placed over the side, required about 4 h. Often an accompanying boat was launched to help in the recovery operations or, as in 1988, in exchanging surface floats and tethers so the drag area ratio of the drifter could be changed in the middle of a deployment. In 1985 and 1986, current meters were shackled to the top and bottom of drifters; in 1988 and 1989, special aluminium frames were built to house the current meters so that only the propellers protruded from the drifters (Fig. 1). In 1989, the instrumented drifters remained deployed for about 40 h without recovery.

Data records of currents, temperatures and differences of pressure revealed a pattern of 1–20 min time scale variability which was not coherent across the drogues. Variability with periods longer than 20 min (Fig. 4), on the other hand, was coherent. Record lengths of 2 h or greater were used for calculating "mean" conditions. Table 2 displays the summary of the total data set, together with several statistics of each record segment. In many deployments, the velocity difference across the drogue was larger than the average velocity, or slip, which indicates that even in strong shears these drifters are good water followers. The 1988 pressure data showed that the tilting of the drogues was less then 13° and that the kiting was less than 0.2 m. Thus, an internal tension of 4 kg between the subsurface float and the bottom of the drogue was sufficient to keep the drogue vertical and centered at its design center to within 0.2 m.

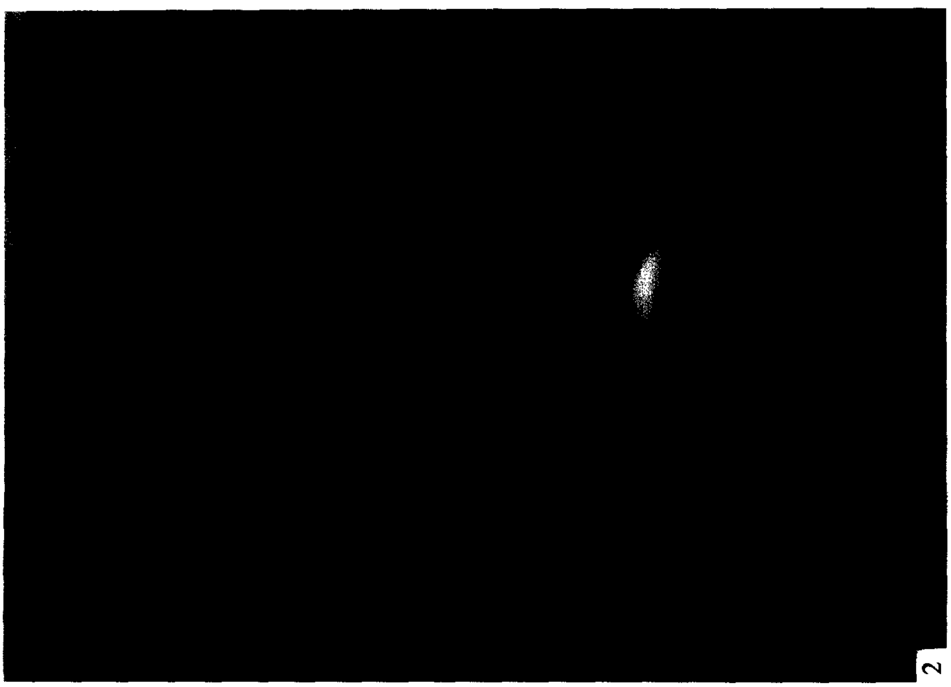
It should be noted that no data were obtained on the underwater behavior of the drifters at wind speeds greater than 10 m s^{-1}. This was because launch and recovery operations were judged to be unsafe when these high wind conditions prevailed.

In this work, the slip is taken to be the arithmetic average velocity of the water flow past the drogue of a vertical extent of 6–10 m, as measured by the two current measurements at

Fig. 2. An underwater photograph of the tether of a TRISTAR in the tropical Pacific in May 1988. Note the convoluted loop which has formed on the top of the subsurface float.

Fig. 3. An underwater photograph of the top of a holey-sock drifter in the tropical Pacific in May 1988. Note the partially collapsed form of the drogue material. The vertical excursions of the ribbons indicate that there is vertical motion past the top of the drogue, or as if the drogue is collapsing like an accordion.

3



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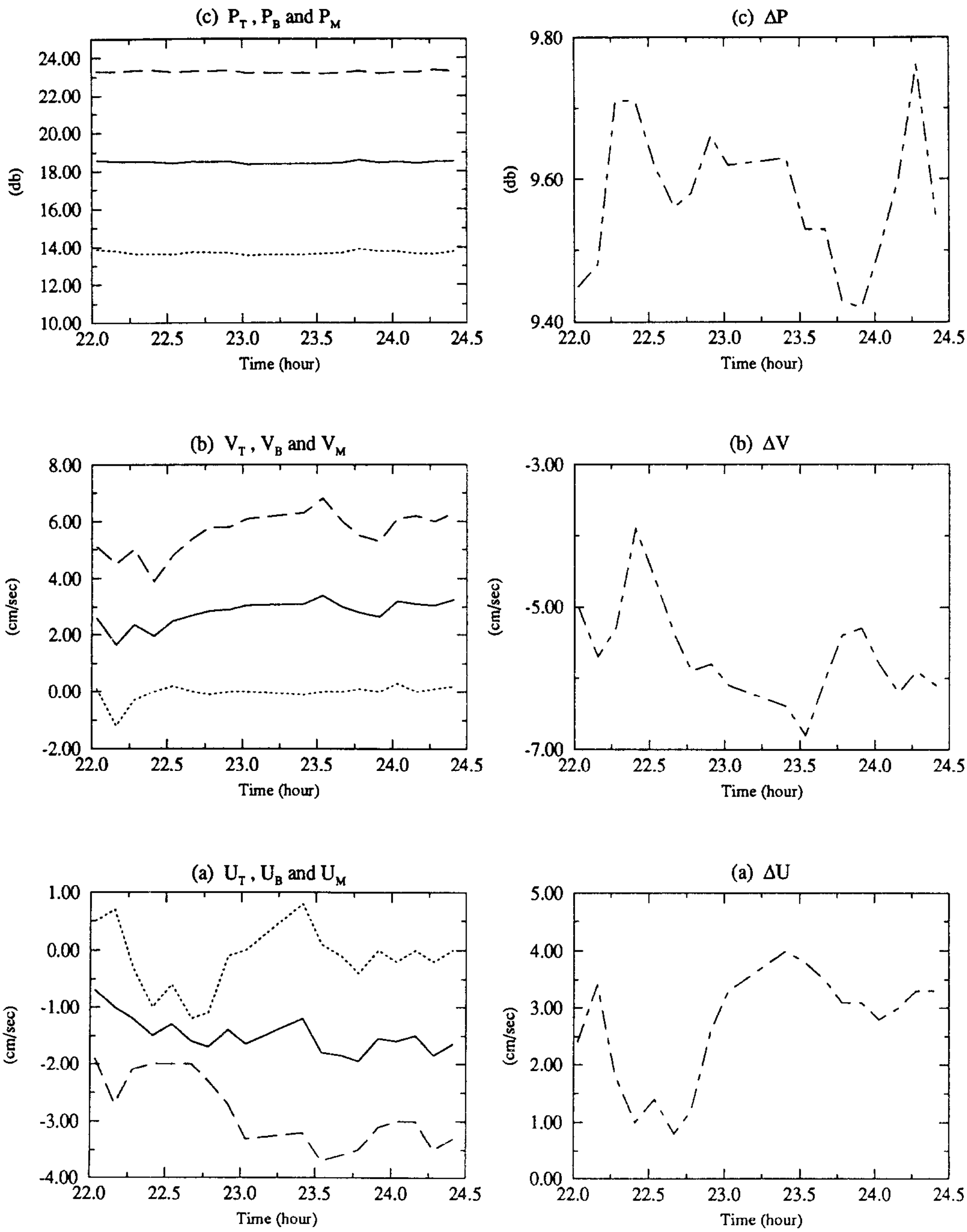

Fig. 4. The northward (a) and eastward (b) velocity components and pressure (c) records from the holey-sock, experiment 88.4 (Table 1). The dotted is the upper VMCM and the dashed is the lower VMCM record. Note the change of scale in the pressure records for the pressure difference.

Table 1A. *Estimated parameters for down and cross wind balance models* (± *indicates* 95% *confidence intervals*)

$$U_d = a\frac{W}{R} + b\frac{D_d}{R} \quad U_c = c\frac{D_c}{R}$$

Drogue	$a \times 10^2$	b	Variance counted	$c \times 10^2$	Variance counted
TRISTAR	3.54 ± 1.03	13.12 ± 5.21	77.6%	21.12 ± 4.59	76.7%
Sock	5.34 ± 1.03	5.57 ± 2.03	65.8%	14.43 ± 4.02	63.8%
Combined	4.63 ± 0.68	6.92 ± 1.93	68.0%	16.17 ± 2.98	64.2%

The parameters above are: U_d = slip in wind direction, W = wind speed, R = drag area ratio (defined in text), D_d = velocity difference across drogue in wind direction, D_c = velocity difference perpendicular to wind direction.

Table 1B. *Estimated parameters for vector balance model* (± *indicates* 95% *confidence intervals*)

$$U = c_1 e^{i\theta_1}\frac{W}{R} + c_2 e^{i\theta_1}\frac{D}{R}$$

Drogue	$c_1 \times 10^2$	θ_1	c_2	θ_2	Variance counted
TRISTAR	3.11 ± 0.85	−170 ± 16	17.37 ± 3.53	171 ± 12	84.2%
Sock	5.20 ± 1.02	−158 ± 11	10.04 ± 1.77	148 ± 10	85.2%
Combined	4.32 ± 0.67	−166 ± 9	11.04 ± 1.63	156 ± 8	81.4%

The parameters above are: $U = (u + iv)$, the average complex velocity recorded on drogue, W = wind speed, θ_1 = angle relative to the wind direction, D = magnitude of velocity difference across drogue, θ_2 = angle relative to the shear direction.

the top and bottom of the drogue. This is also the average velocity past the drogue, if the shear between the current meters is a constant. The time variable shear with periods smaller than 20 min was observed not to be constant in depth because the velocity variability for such short periods is not coherent across the 6–10 m vertical separation of the VMCMs. More complex situations than encountered here can occur directly under the surface. Geyer (1989) observed, in the upper 7 m near the surface of the shallow Buzzards Bay, that the vertical shear was not constant over a 20 min average. In this latter case, a vertical average velocity of a 5 m water column, centered at 5 m depth below the surface, could not be accurately represented by the arithmetic average of the records at 2 and 7 m. Measurements used in this study were from deeper levels in the mixed layer and were in a less severe shear environment than the shallow water environment encountered by Geyer (for observed profiles of currents above 10 m depth, see Price *et al.*, 1986).

3. RESULTS

Theoretical modeling of the slip of a two-dimensional, flexible drifter in shear flow with a concentrated horizontal force acting on the surface float was the starting point for selecting the functional parameter behavior with which to interpret the field measurements of slip. First, there should be a slip-producing force in the direction of wind and waves (Niiler *et al.*, 1987). Second, there should be a force in the direction of the velocity

Table 2A. *TRISTAR data set*

Test	R	W (m s^{-1})	θ_W (0_T)	U (cm s^{-1})	θ_U (0_T)	D (cm s^{-1})	θ_D (0_T)
87.2	77.0	9.30	300	0.97	281	6.63	216
88.1a	35.4	7.20	95	1.60	40	2.57	225
88.1b	97.9	8.20	95	0.84	55	1.83	241
88.2a	31.4	9.60	90	4.95	45	12.96	246
88.2b*	97.9*	9.60*	85*	3.52*	36*	12.25*	265*
88.3	31.4	7.50	102	3.21	62	10.30	245
88.4	31.4	4.30	122	3.16	118	5.54	295
88.5a	87.5	8.60	60	1.14	53	1.14	221
88.5b	31.4	8.60	59	1.94	55	3.29	249
88.6a	31.4	9.60	61	1.16	39	2.13	211
88.6b	97.6	8.90	56	1.25	34	1.31	236
89.1a	42.0	3.90	144	0.72	209	0.52	333
89.2a	42.0	4.80	178	1.03	216	0.34	16
89.3a	42.0	7.38	176	1.35	213	0.41	36
89.4a	42.0	7.16	166	1.25	212	0.45	31
89.5a	42.0	6.44	176	1.25	209	0.46	38
89.6a	42.0	7.06	181	1.15	204	0.50	116
89.7a	42.0	9.34	191	1.39	207	0.73	120
89.8a	42.0	8.79	188	1.73	211	0.62	105
89.9a	42.0	9.04	153	1.92	209	0.72	21
89.10a	42.0	5.82	179	1.24	201	0.47	50
89.11a	42.0	7.19	204	1.22	211	0.46	111
89.12a	42.0	6.69	199	1.45	216	0.36	97
89.13	42.0	6.78	198	1.34	213	0.40	120
89.1b	49.0	3.90	144	0.25	157	0.74	338
89.2b	49.0	4.80	178	0.49	198	0.97	17
89.3b	49.0	7.38	176	0.55	196	0.82	61
89.4b	49.0	7.16	166	0.67	207	1.06	26
89.5b	49.0	6.44	176	0.62	183	0.92	39
89.6b	49.0	7.06	181	0.48	188	0.57	77
89.7b	49.0	9.34	190	0.82	218	0.98	74
89.8b	49.0	8.79	188	1.46	221	2.11	38
89.9b	49.0	9.04	153	1.52	197	2.94	357
89.10b	49.0	5.82	179	0.80	196	1.12	52
89.11b	49.0	7.19	204	0.87	212	1.16	21
89.12b	49.0	6.69	199	1.16	209	1.20	25

R is the drag area ratio. The magnitudes and directions of the wind W, the slip U_s and the velocity difference ΔU across the drogue are represented by W and θ_W, U and θ_U, and D and θ_D. All directions are relative to the north. The relative directions θ_U–θ_W and θ_D–θ_W give the down-wind and cross-wind components of the slip and shear. Abnormal data not used in the model are indicated by an asterisk.

past the floats and tether relative to the drogue. Third, the larger the drogue area is compared to the size of the floats and tether, the smaller the slip should be. Chereskin *et al.* (1989) showed that in a planar, steady shear flow the slip is proportional to the inverse power of the drag area ratio of the drogue to the float and tethers combined, and directly proportional to the velocity difference across the top and the bottom of the drogue. The drag area was computed as the product of the drag coefficient and the total maximum frontal area of each element of the drifter (see Fig. 1). Furthermore, slip decreases as the inverse square of the internal tension in the drogue, due to the reduction of kiting and

Table 2B. Holey-sock data set

Test	R	W (m s^{-1})	θ_W (0_T)	U (cm s^{-1})	θ_U (0_T)	D (cm s^{-1})	θ_D (0_T)
85.3a*	28.0*	10.00*	290*	2.40*	253*	6.58*	130*
85.3b*	28.0*	10.00*	290*	2.90*	298*	9.68*	158*
85.4a	28.0	6.00	340	2.40	361	1.66	202
85.4b	28.0	6.00	340	2.70	355	1.87	194
85.4c	28.0	6.50	340	1.70	17	1.06	223
85.5	28.0	2.00	280	1.50	169	2.80	322
85.6	28.0	5.50	345	1.20	52	1.78	322
87.1	77.0	9.20	310	0.66	33	4.29	234
87.3	77.0	5.40	326	0.35	315	0.50	143
87.4	77.0	9.40	324	2.53	25	4.73	202
88.1a	50.5	7.20	95	1.02	59	0.62	237
88.1b	18.1	8.20	95	2.33	59	1.49	228
88.2a	50.5	9.60	90	2.23	59	4.82	250
88.2b	18.1	9.60	85	3.20	76	2.68	239
88.3	56.5	7.50	102	1.71	67	2.28	250
88.4	18.9	4.30	122	2.90	107	1.63	268
88.5	18.9	8.60	60	2.18	48	1.64	232
88.6a	50.5	9.60	61	0.89	65	0.46	236
88.6b	18.1	8.90	56	1.90	46	1.13	207
89.1	49.6	3.90	144	0.59	194	0.52	36
89.2	49.6	4.80	178	0.60	167	0.63	65
89.3	49.6	7.38	176	0.67	182	0.42	112
89.4	49.6	7.16	166	0.61	191	0.53	50
89.5	49.6	6.44	176	0.57	200	0.42	85
89.6	49.6	7.06	181	0.57	200	0.65	86
89.7	49.6	9.34	190	0.58	191	0.74	100
89.8	49.6	8.79	188	0.77	213	0.84	97
89.9	49.6	9.04	153	0.87	178	1.08	30
89.10	49.6	5.82	179	0.48	188	0.39	37
89.11	49.6	7.19	204	0.46	207	0.71	73
89.12	49.6	6.69	199	0.51	201	0.56	83

R is the drag area ratio. The magnitudes and directions of the wind W, the slip U_s and the velocity difference ΔU across the drogue are represented by W and θ_W, U and θ_U, and D and θ_D. All directions are relative to the north. The relative directions θ_U–θ_W and θ_D–θ_W give the down-wind and cross-wind components of the slip and shear. Abnormal data not used in the model are indicated by an asterisk.

tilting. Chhabra (1985), using a model which employed a two-dimensional, linear gravity wave velocity distribution with depth to produce time-dependent forces on the drifter, showed that wave-aliased slip can be reduced if the internal tension in the tether is reduced. Reducing the tether tension under the surface float reduces the aliasing of vertical forces into horizontal forces during the segment of the motion when the tether becomes slack. In the drifters used in this study, the mean negative buoyancy at the subsurface float was reduced to 1 kg, and that meant internal tension very effectively kept the subsurface float from coming to the surface. The internal tension in the drogue and tether below the subsurface float was increased to 4 kg, so the theoretical tilting would be less than a few degrees in the tropical shear fields we were expecting. Theoretically, the slip of drifters used here should depend on three parameters: wind (or waves), velocity difference across the drogue and drag area ratio (because the kiting and tilting were kept small by design and it was measured to be small).

Theoretical models for steady-state slip are non-linear and in general exhibit a complex behavior to the slip-producing forces. The computation of slip from these models can be considered a data set, and a parameter model can be fitted to this data set. This parameter dependence can then be used as a guide to interpreting the field data. We used Chhabra's (1985) steady-state model for flexible, steady-state, two-dimensional drogues with concentrated buoyancy elements and dimensions similar to the drogues used in this field study to generate numerical data in the 1–3 cm slip range. The parameter model, which accounts for 99% of the theoretically calculated slip was

$$|U_s|U_s = (a/R) + (b/R^2)|\Delta U|\Delta U. \tag{1}$$

Here U_s is the slip, F is the wind (or wave) force acting on the surface float, ΔU is the velocity difference across the drogue and R is the drag area ratio. For application to field measurements, F was set proportional to the square of the wind speed and assigned the direction of the wind. The coefficients a and b were determined for each tether and drogue length. This model, when used for interpretation of the field data, accounts for 72% of the observed slip, in the least squares sense.

The analytical model, which almost perfectly fits the complex numerical model of Chhabra in the range of the relative flow observed and is expressed in (1), shows the slip to be inversely proportional to R and directly proportional to both the wind and the velocity difference ΔU. This suggested a simpler model be tried out, with U_W the wind velocity

$$U_S = (a/R)U_W + (b/R)\Delta U. \tag{2}$$

The relationship expressed in equation (2) accounts for up to 77% of the variance of slip as a function of the three parameters and is the best three-parameter model we found for both drogue configurations when the regressions were done in the direction of the wind. In Table 1 are the best fit coefficients for data from TRISTARS and holey-socks and for the combined data set as well. This analysis was done first by regressing the downwind component of the lefthand side of (2) onto the righthand side. A separate estimate of b, called c, was obtained by regressing the slip perpendicular to the wind onto the shear perpendicular to the wind. We note that the shear perpendicular to the wind had the same effect on the slip as the shear parallel to the wind. The coefficient c was larger than b, except for the TRISTAR, where it was within the 95% confidence levels which determine each coefficient.

A second mode of analysis was used in which an amplitude and a rotation were fitted to the least squares' sense. In this case, the percent variance explained increased to 84%; the increase of variance was not more than that due to the artificial increase of adding two more degrees of freedom. The best fit to the data in the five-parameter model indicated that the combined drifters slipped 12° to the right of the wind. The TRISTAR drogue appeared less affected by the wind than the holey-sock, and the holey-sock was less affected by velocity difference than the TRISTAR. But note also that, since the holey-sock had a bigger velocity difference, the actual slip caused by the shear was not much different than in the TRISTAR. From the analysis of the uncertainty of our model fits, it is apparent that, at 95% confidence, the data set does not allow a clear differentiation between the water-following capabilities of the two drogue types.

Graphical presentation of the agreement of the data with the model is shown in Fig. 5, as a scatter diagram.

4. DISCUSSION AND CONCLUSIONS

This investigation is not the only effort to quantify how well drifters might follow water. Since the discovery of the Atlantic Equatorial Undercurrent by Buchanan in 1892 with a drifter, these devices have been used extensively to make discoveries about the upper ocean circulation (McPhaden, 1986). There are many calculations, previously cited, of what might be the effect of a wind force or wave force on a particular drifter; several comparisons with current meter data when drifters pass near a mooring site have been made (Richardson and Wooding, 1985; McPhaden *et al.*, 1991); and intercomparisons between drifters set loose for several hours from the same location (Mackas *et al.*, 1987) have also been made. The measurements reported here were similar to those made by Geyer (1989) and were unique because they were direct measurements of the slip, and they showed that if $R > 40$, a slip of less than 1 cm s^{-1} is expected in the climatological mean global wind of 8 m s^{-1}.

One of the limitations of this study was that we were not able to obtain slip measurements in wind speeds in excess of 10 m s^{-1}. The heaving of the ship and the difficulties of deploying and retrieving the heavy package of instrumented drifters and the accompanying small craft made the operations unsafe in stronger winds. It would be worthwhile to try to obtain slip data in heavy weather, but this would have to be done with current meters that are much smaller and lighter than the VMCMs. Secondly, we did not know what the profiles were of the several hour mean currents on vertical resolution of less than 6 m, so we could not estimate the uncertainty of considering the vertically averaged velocity past the drogue to be the average of the top and bottom relative velocities. In interpreting the velocity difference between the top and the bottom of the drogue as an index for the conditions of shear in the upper 20 m of the ocean, we do not wish to imply that the shear between 11 and 6 m depth is equal to and not modified between 6 m and the surface. It was a statistically and dynamically sensible parameter to use in the interpretation of the observations of the slip.

The most commonly used drifter before 1985 was usually constructed of a 2 m long, 10 cm diameter spar float, attached with a 1 cm diameter rope to a window-shape drogue of 2×6 m dimensions. Over 300 of these devices were released during FGGE. Our reconstruction of this FGGE-type drifter configuration reveal that these had $R = 10$–15 and would, according to equation (2), slip 4–6 cm s^{-1} in the direction of a 10 m s^{-1} wind. Many FGGE-type drifters were used in the description of strong equatorial currents of 30–40 cm s^{-1} and western boundary currents of 80–10 cm s^{-1}, so the wind-produced slips would not be transparent in what investigators expected to see or affect the conclusions drawn from the data. When drifters are used to measure the mixed layer currents of oceans on a more global basis, where in over 90% of the area mean velocities of 4–10 cm s^{-1} are expected (e.g., Poulain and Niiler, 1989; Paduan and Niiler, 1993), the rational design and selection of drifter components as implied by (2) becomes critical. "Wind driven" currents derived from the FGGE-type drifters are expected to have at least 50% error (Niiler and Paduan, 1995).

The principal conclusions of this study are that flexible drogued, mixed layer drifters can be designed on a rational basis to be excellent water followers over the depth interval of

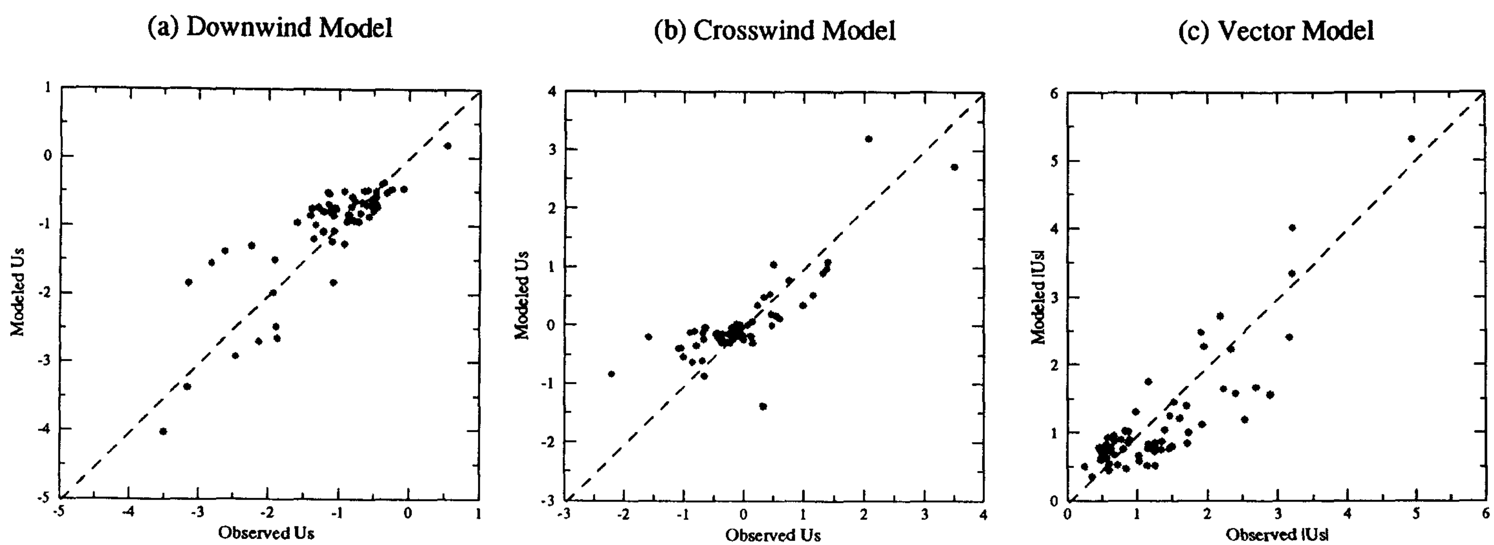

Fig. 5. The scatter diagram\ of the combined holey-sock and TRISTAR data sets for the predicted slip from equation (2) vs the observed slip for a downwind component (a) cross-wind component (b) and vector regression (c). See Table 2 for the values of the coefficients used. The units of U_s are cm s^{-1}.

drogues which are 4–7 m in length. Longer drogues would require additional measurements. Furthermore, for designs in which $R > 40$, the wind produced slip is < 1 cm s^{-1} in 10 m s^{-1} wind. Thus, if a global wind can be obtained to the accuracy of $\pm$ 5 m s^{-1}, the wind-produced slip of well-designed drifters can be simply subtracted from the observed current and the resulting current would have the wind produced bias removed to within $\pm 1/2$ cm s^{-1}. The engineering problems which remain are to understand drifter behavior in winds in excess of 10 m s^{-1}, for which conditions no data were acquired, and to produce mechanical designs which survive the rigors of the open sea for several years.

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