JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C4, PAGES 7249–7263, APRIL 15, 1991

Differences in Drift Behavior Between Drogued and Undrogued Satellite-Tracked Drifting Buoys

B. BRÜGGE AND J. DENGG

Institut für Meereskunde an der Universität Kiel, Germany

Drift behavior of drogued and undrogued Hermes-type buoys is studied. After drogue loss, an increase in drift speed and acceleration is observed as well as improved correlations between drift and wind in both speed and direction. With these criteria, a method for the separation of large data sets into a drogued and an undrogued part has been developed. In most areas of the North Atlantic this works very well; problems arise in regions with strong surface currents and/or light winds. A statistical analysis is performed in a selected area to demonstrate the errors that can be caused by indiscriminate use of drogued and undrogued drifters. Mean and rms velocities as well as kinetic energies change significantly when undrogued buoys are considered. Therefore caution is essential when using surface drifters without drogues.

1. INTRODUCTION

The last decade has seen quite a number of research programs that included satellite-tracked drifting buoys. Among these were the First GARP Global Experiment (FGGE) with over 300 buoys in the southern oceans [*Garrett*, 1980, 1983] and the NORPAX program with more than 130 buoys in the Pacific during the late 1970s [*McNally et al.*, 1983]. *Richardson* [1983] compiled a data set consisting of 110 drifters in the western North Atlantic. In the central North Atlantic the Institut für Meereskunde in Kiel launched over 200 buoys between 1981 and 1989.

It is difficult to obtain a consistent picture from the analysis of these data because there are fundamental differences between the types of drifters used by different investigators. The buoys had varying shapes and sizes, and the drogues attached to them were of different types and placed at different depths. Sometimes the buoys did not have any drogues at all.

As has been shown in several studies, the configuration of the drifter system greatly influences its drift behavior. *Niiler et al.* [1987] and *Krauss et al.* [1989] (hereinafter referred to as KDH) pointed out that the type of buoy and drogue determines the slippage of the system relative to the surrounding water. The surface area exposed to waves and vertical current shear depends very much on the shape of the drifter used. The resulting errors in drift speed can be of the order of 1–5 cm/s for drogued buoys.

This effect is small compared to the changes in drift performance caused by the loss of a drifter's drogue. The purpose of drogues is to allow the buoy to be moved around by the current at drogue depth rather than by surface currents. When the drogue is lost, the drifter is only affected by processes at the sea surface, and because drogues also act as additional ballast, the buoyancy of the drifter is changed. For the drifters used in KDH, speeds differed by up to 40 cm/s between a buoy with a drogue at 100-m depth and an undrogued one. This is almost an order of magnitude larger than the effect of slippage.

If differences in drift behavior are that large, it is to be expected that data sets that contain both drogued and undrogued buoys will give a distorted picture of the oceanic circulation. As yet, there is little information on how serious this effect can be.

For this reason, it is extremely important that the state of a drifter's drogue is known when the data are being analyzed. In the past, however, this was only possible in some cases [*McNally et al.*, 1983; *Poulain and Niiler*, 1989]. Even when the buoys were equipped with drogue sensors the data were not always reliable because tensiometers sometimes failed [*Kirwan et al.*, 1976; *Richardson*, 1981]. Many authors state that they had no information about the time of drogue loss [*Madelain and Kerut*, 1978; *Krauss and Böning*, 1987; *Maillard and Käse*, 1989; *Krauss et al.*, 1990*b*].

Large and van Loon [1989] give a summary of previous studies of wind influence on drifters. They conclude by saying that they will "resist the temptation to equate buoy motions with surface currents, and instead refer to buoy drift." It has also been urged by other authors that data sets without information on the state of the drogues should be treated with care [*Meincke*, 1980; *Krauss and Böning*, 1987], but preferably one would like to have some means of recognizing undrogued buoys in a data set.

In this paper we shall try to determine some typical differences in the drift behavior of drogued and undrogued buoys. These characteristics will then be used to distinguish between the two kinds of drifters and eliminate the "wind-contaminated" part of our data. In order to get an impression of how seriously data from mixed data sets can distort statistical results, we will perform a simple statistical analysis for a selected part of the North Atlantic.

We proceed by reviewing some results from experiments in the Baltic in section 2 in order to illustrate the differences in drift behavior between buoys that float directly at the sea surface and drifters that are partially submerged. These characteristic signals will be compared with data from the Atlantic. In section 3 we demonstrate, using these characteristics, how our data set of the North Atlantic has been divided into one part without and another with wind influence. Section 4 deals with problematic cases where our method does not give clear results. The systematic errors that arise from the neglect of windage effects in the analysis of drifter data will be examined in section 5. Finally, in

Paper number 90JC02667.
0148-0227/91/90JC-02667$05.00

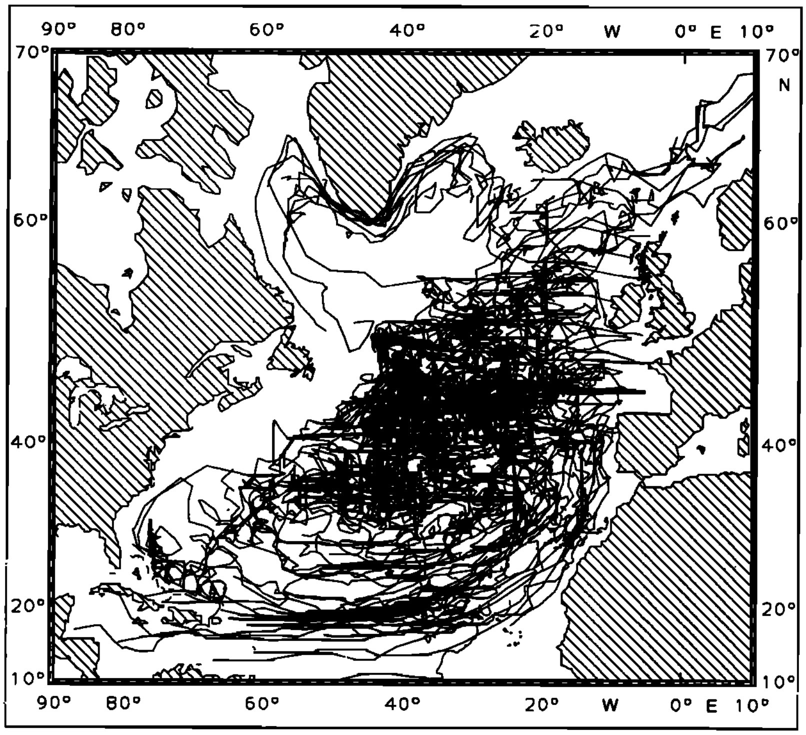

Fig. 1. Buoy trajectories in the North Atlantic from May 1981 to December 1989 (10-day averages are used).

section 6 we address the question why we found significant differences in the drift behavior of drogued and undrogued buoys when many other authors assume that there is none.

2. GENERAL DIFFERENCES IN DRIFT BEHAVIOR

Throughout this paper we shall be referring to the Hermes-type drift buoy as described in KDH. Although the quantitative results will be valid only for this type of drifter, the qualitative discussion should hold for any buoy that is greatly exposed to the wind after drogue loss.

The experiments in the Baltic (KDH) gave us an impression of the kind of behavior to look for when trying to identify undrogued buoys in a large data set. The main results can be summarized as follows.

The more surface area a drifter offers to the action of wind and waves, the greater its drift speed will be. Undrogued buoys that had a 50-kg weight attached, to simulate the load of a drogue, moved with a slip of up to 20 cm/s relative to a drogued surface drifter at wind speeds of 10 m/s. Buoys without additional ballast drifted with even greater speeds. A tentative correlation between drift and wind speed was found.

The more exposed a buoy is to the wind, the closer it aligns with it. The buoy without ballast drifted almost in the direction of the wind, whereas buoys that were more deeply submerged moved at a greater angle to the wind direction. (Quantitative statements were not possible at that time because the data base was too small.)

These results lead us to expect an increase in drift speed and an alignment of the drift direction with the wind direction when a buoy loses its drogue. However, conditions in the Baltic are much different from those in the North Atlantic, our main area of concern. In Kiel Bay we had only light winds, small waves, small water depths and therefore a large amount of topographic steering. To be able to draw more general conclusions, it was necessary to test our predictions in the Atlantic.

In the period from 1981 to 1989, 218 satellite-tracked drifting buoys have been deployed in the North Atlantic by the Institut für Meereskunde in Kiel. Of these, 179 were of the HERMES type and 39 of the CEIS type. With the exception of 19 buoys, all drifters had a window shade drogue at 100-m depth in order to measure the geostrophic flow. A detailed description of the buoy types and the buoy-drogue configuration is given in KDH (see their Figure 4 and Table 1). In this paper and in *Krauss et al.* [1990*a*] the slippage of this type of buoy is given as less than 2 cm s^{-1}. The drifters were monitored by the ARGOS system, providing typically 4–10 good locations per buoy per day. To produce equally spaced time series for each buoy, the raw data were subjected to a probability check and interpolated to 3-hour intervals using a three-point Lagrangian scheme. Figure 1 shows the 10-day averages of all trajectories obtained from May 1981 to December 1989. This data set comprises more than 67,000 buoy days and covers most of the North Atlantic. The largest concentration of data is in the North Atlantic Current and the Subtropical Gyre, with little information in the Gulf Stream region.

Parts of the data set were the basis for studies on the mean flow of the North Atlantic [*Krauss*, 1986] and its mesoscale variability [*Krauss and Käse*, 1984; *Krauss and Böning*, 1987].

None of the buoys used was equipped with a drogue sensor because when this series of drifters was designed, it was felt that the sensors available were not reliable enough to justify the additional costs [cf. *Kirwan et al.*, 1976;

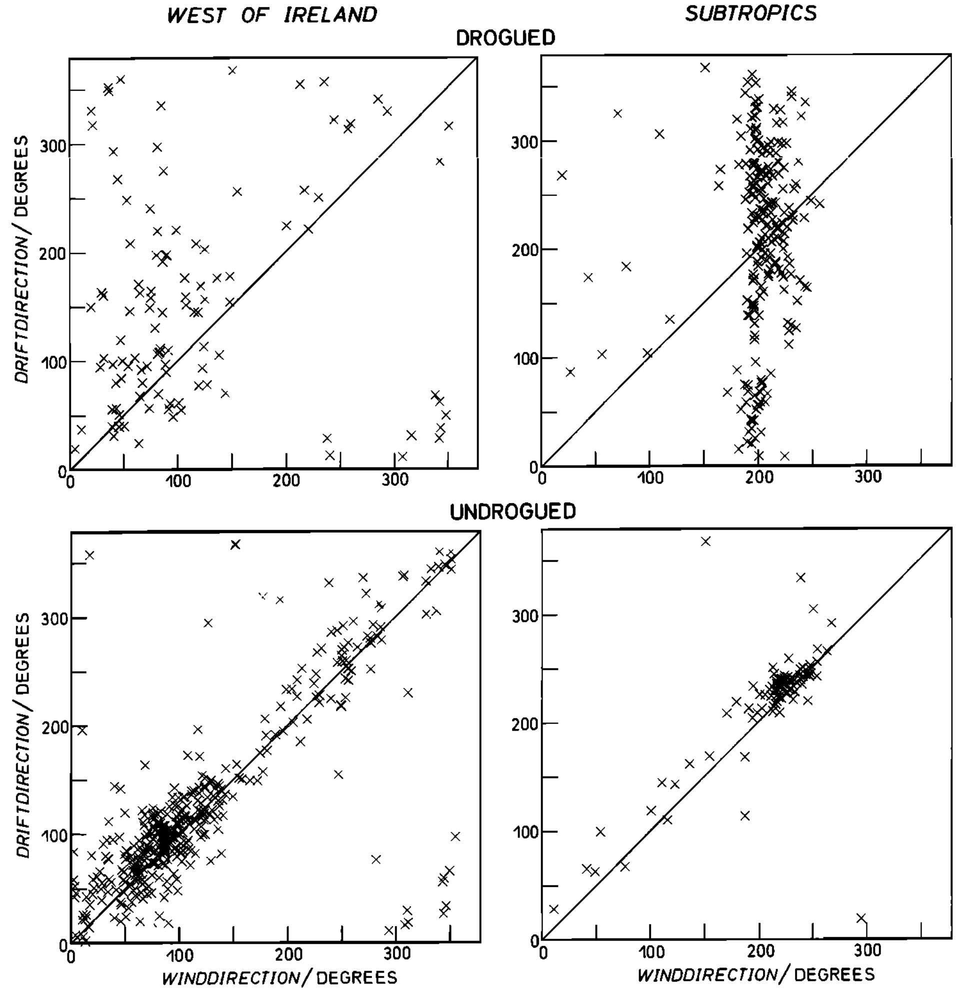

Fig. 2. Scatter plots of drift direction versus wind direction for data sets (left) west of Ireland and (right) in the subtropics [cf. *Krauss et al.*, 1989]. (Top) Drogued data and (bottom) undrogued data. Diagonal line marks $\phi_{\text{drift}} = \phi_{\text{wind}}$.

Richardson, 1981]. Consequently, we had no information about the times of drogue loss. Fortunately, however, there were some cases where the state of the drifter's drogue was known, either because it had been picked up at sea or because its drift behavior left no doubt about missing drogues.

With the help of these buoys, we were able to show in KDH that the results from the Baltic also hold for the Atlantic. The difference in drift speed between drogued and undrogued buoys as well as the correlation between drift and wind speed could be verified. Undrogued buoys drifted with about 2.5% of the wind speed, a figure that agrees well with the 3.4 ± 1.4% given by *Peterson* [1985]. Furthermore, it was found that drifter acceleration as well as the variance of the mean drift speed are also larger for undrogued buoys. (The term "acceleration" here refers to the absolute value of the difference in drift velocity between two successive 3-hour intervals. It is felt that, as long as a drifter follows only the water movement, its velocity should not change dramatically from one 3-hour interval to the next. If the buoy is strongly influenced by the wind, the time rate of change of velocity can be immense, because wind speed and direction may change on shorter time scales than ocean currents.)

Wind data from the European Center for Medium-Range Weather Forecasts (ECMWF) made it possible to analyze the effect of wind on drift direction as well. Wind fields for the North Atlantic were available once a day on a 1.875° × 1.875° grid. Daily means of position, velocity, and drift direction were calculated for each buoy in order to diminish the effect of inertial oscillations. Wind data were extrapolated to the buoy's position using bicubic splines.

With these data we were not only able to confirm our results from KDH but we could also compute correlations between wind and drift direction. (Direction here is defined in the common oceanographic sense, i.e., the direction a current flows to.)

In Figure 2 we show the directional correlations for the drifters used in KDH, i.e., the data sets west of Ireland and in the subtropics. In these plots, only data with wind speeds $|w| > 6$ m/s are used because, as shown in KDH, at low wind speeds, error bars between drogued and undrogued buoys overlap and we cannot expect to find a significant difference there. Another problem is that the data for wind direction at sea are less reliable at low wind speeds because it is more difficult to measure wind direction on board ships at light winds. In addition, the pressure gradients that give the direction of the geostrophic wind are smaller under these conditions, thus giving greater relative errors in the analyzed wind fields.

For drogued buoys (Figure 2, top) there is no correlation between wind and drift direction. In the period studied, wind direction west of Ireland was mainly toward the east and northeast, with occasional winds to other directions. In the subtropical region near the Azores, wind direction was almost exclusively to the southwest. The drogued drifters do not seem to have a direction of preference, probably because of the small-scale eddy field. Correlation coefficients are 0.11 in both cases.

For undrogued buoys (Figure 2, bottom) there is an obvious relationship between wind and drift, with the data grouping around the line $\phi_{\text{drift}} = \phi_{\text{wind}}$ in both regions of the Atlantic. Here the correlation coefficient is 0.73 west of Ireland and 0.78 in the subtropics.

Note that for undrogued buoys, drift directions are slightly to the right of the wind (on average about 10°), but the statistics are not reliable enough to give small standard deviations. (This may in part be due to the fact that we are comparing daily averages of buoy drift with synoptic observations of wind.) The deviation of the drift to the right of the wind direction is interpreted as influence of Ekman and Stokes drift. The angle depends on the submerged area of the drifter's surface. A deeply immersed drifter should comply better with Ekman theory than a buoy that floats on the surface and offers little resistance to the surrounding water. The experiments in the Baltic showed this to be true, and so the 10° deviation from wind direction is quite possible. The conclusion would be that the angle of deviation from wind direction gives us a way of judging the water-following qualities of undrogued drifters. *Peterson* [1985] gives an angle of 25.0° ± 12.0° for his buoys. *McNally and White* [1985] find a 20° angle for drifters with drogues in the mixed layer and an angle of about 30° when these data are corrected for windage. *Deniault and Ménard* [1985] get a mean angle of 17° for the FGGE buoys.

From these examples it is evident that the drift performance of our buoys changes drastically when they lose their drogues. It is therefore necessary to divide our data set into two parts: one part including all trajectories with drogues and the other part with the undrogued data.

3. THE SEPARATION METHOD

For the separation of the data the individual time series had to be examined in order to find a transition period between a first part resembling our data from drogued buoys and a second resembling the undrogued ones.

In order to determine the cutoff point reliably, we adopted the following method.

Time series of drift speed and acceleration were calculated from the positions at 3-hour intervals. These were then checked to see whether at some point in time there was a sudden jump to higher means and variances. If these persisted throughout the rest of the time series, we cross checked the "suspicious" date with the trajectory to make sure that the increase did not occur because the drifter moved into a strong current or entered an eddy.

Then monthly plots of wind speed versus drift speed and wind direction versus drift direction were prepared, and the correlation coefficients were computed. (Again, data pairs with wind speeds less than 6 m/s were omitted.) If correlations improved significantly after the time of increase in drift speed, the drogue was assumed to be lost and the trajectory divided into a drogued and an undrogued part.

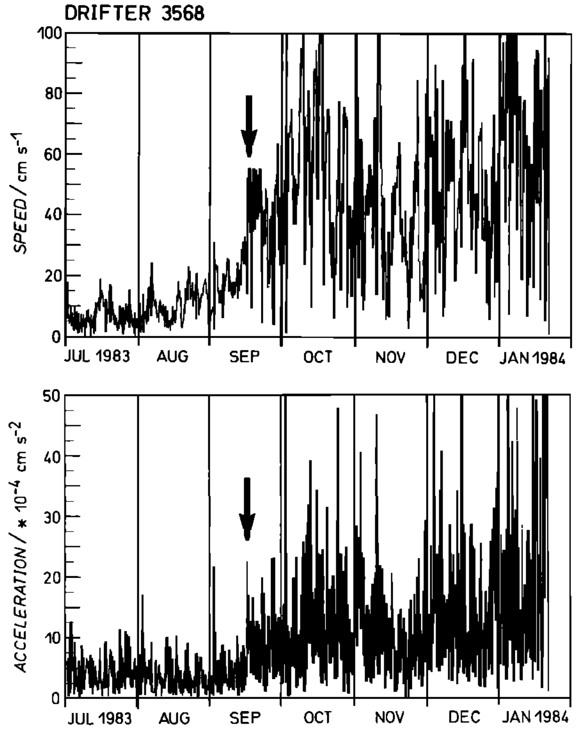

Fig. 3. (Top) Time series of drift speed in cm/s and (bottom) acceleration in 10^{-4} cm/s^2 for drifter 3568 from July 1983 to January 1984. (Arrows indicate the time of drogue loss as determined with the method described in the text.)

Drifter 3568 is a perfect example for the application of this method: the time series of drift speed and acceleration (Figure 3) show small values (about 8 cm/s, 4×10^{-4} cm/s^2) throughout July and August, a steady increase in September, and large values (45 cm/s, 12×10^{-4} cm/s^2) from October until the end of the series in January. Variance of speed and acceleration is small in the first 2 months and increases immensely in September. A look at the trajectory (Figure 4) assures us that in September the drifter did not move from a region of sluggish currents into an intensive stream, as the time series might lead to suspect. According to *Krauss* [1986] the buoy should follow the general direction of the North Atlantic Current toward the northeast, but instead it moves to the southeast after leaving the eddy in early September, changes its course all of a sudden at 34°W, 54.5°N and even continues toward the southwest for some time.

From Figure 3, one could guess that the drogue came off some time in September. This date is confirmed by the monthly plots of correlation between wind and buoy (Figure 5). In July and August there is no correlation between wind and drift, neither in speed nor in direction. In September the situation changes: speeds increase and directions gather around the diagonal, where drift and wind directions coincide. From October to December the picture is clear: high correlation between speeds and almost perfect coincidence in direction.

It could be argued that the deepening of the mixed layer due to autumnal storms might be responsible for the change

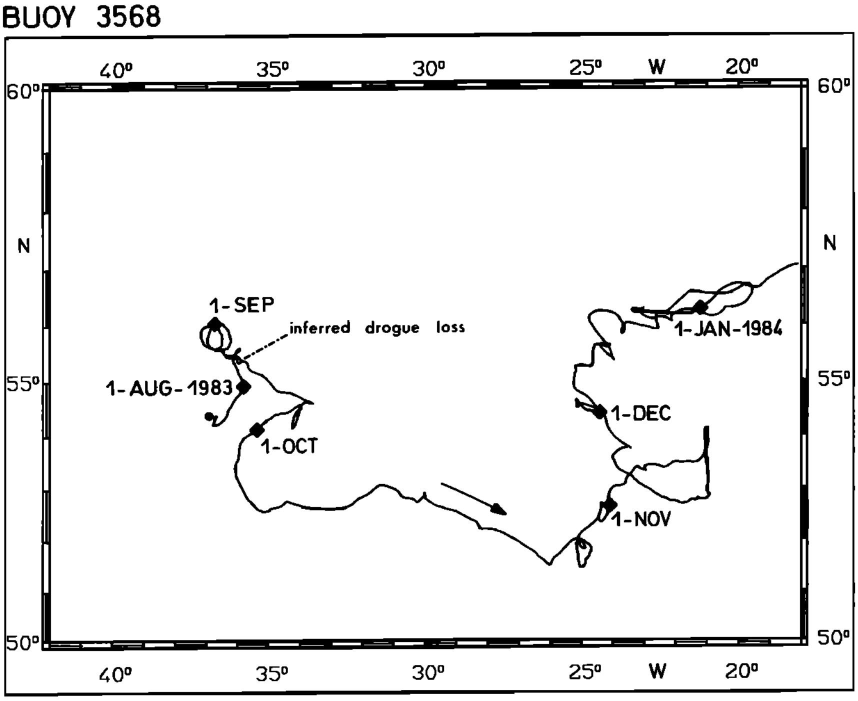

Fig. 4. Trajectory of drifter 3568 from July 1983 to January 1984.

in drift behavior, but the mean monthly charts of mixed layer depth given in *Robinson et al.* [1979] show that in September the top of the thermocline should be well above the drogue depth.

From these results it was concluded that the drifter lost its drogue during September 1983. Closer inspection revealed that the drogue came off on September 14, plus or minus 1 day.

If correlations for the period 1 month before and 1 month after that date are calculated, the low speeds and badly correlated directions of the September plot in Figure 5 fall into the time before September 14. With this information the time series was divided into a part with drogue from July to September 12, and a wind-contaminated part from September 16, to January. September 13–15 were omitted due to the uncertainty on the exact time.

In our example, both the correlation of speed and of direction give a clear picture. However, in general we found that the plots of drift direction versus wind direction are better suited for our purposes, and so we tended to concentrate on these.

With the method described above the whole data set was divided into a drogued part and an undrogued part (Figure 6). It turned out that of the buoy data collected between 1981 and 1989, only 52% came from drogued drifters. On the average the drogues lasted for 179 days. However, the standard deviation of ±82 days indicates that this number differs considerably between buoys, mainly due to changes

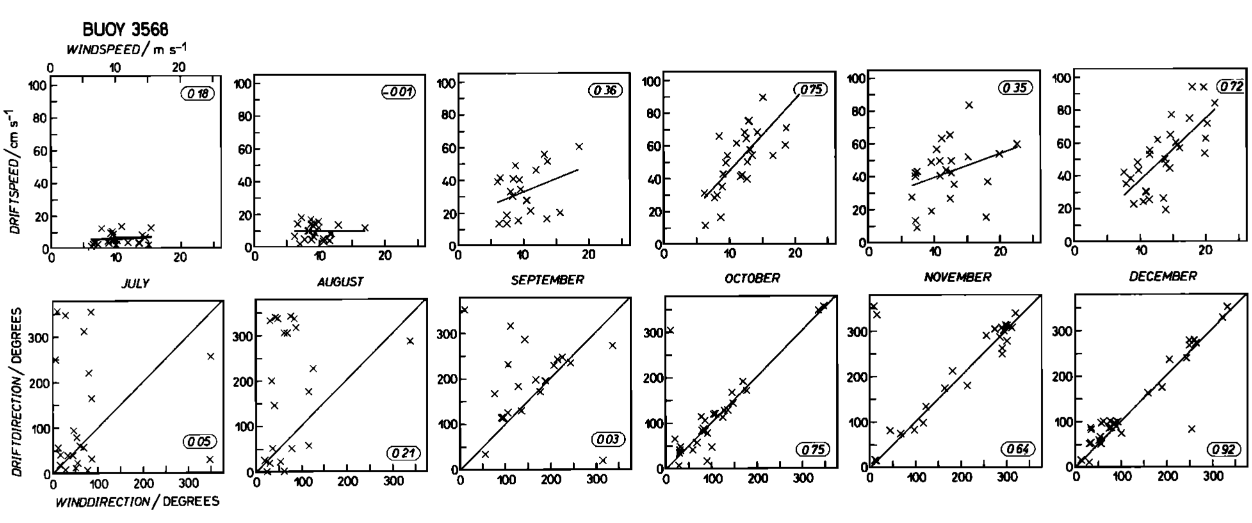

Fig. 5. Drifter 3568. (Top) Comparison of drift and wind speed and (bottom) drift direction versus wind direction for the months July to December 1983. (Correlation coefficients and regression lines are indicated in the plots).

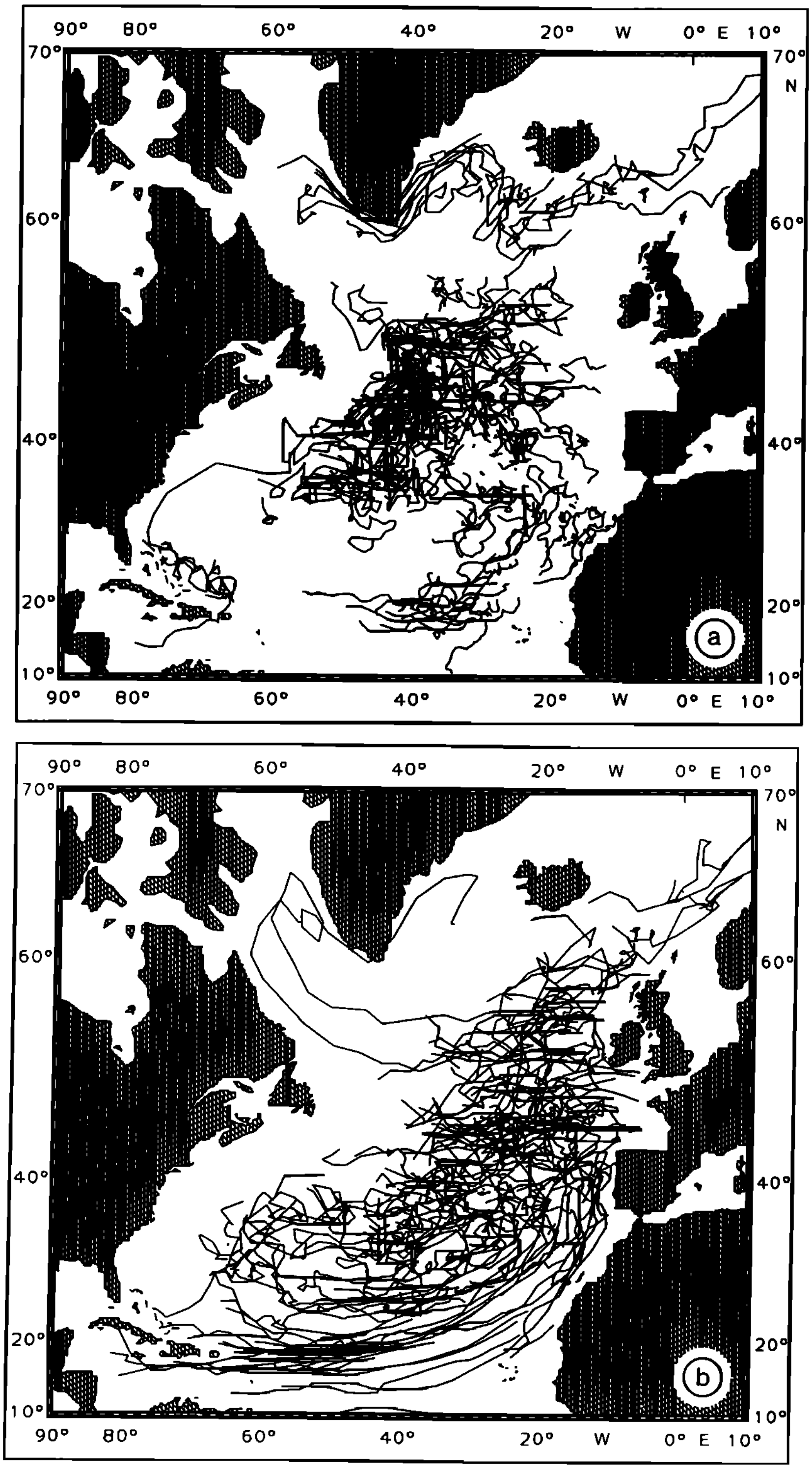

Fig. 6. Data set as in Figure 1, but divided into (*a*) data before inferred drogue loss and (*b*) data after inferred drogue loss.

in design and materials and because of different weather conditions. The earliest detachment was found 16 days after deployment, whereas the longest trajectory of a drogued drifting buoy was 758 days.

4. PROBLEMATIC CASES

Our example, drifter 3568, was one of the cases where we were able to determine the time of loss to 1 or 2 days, but in other cases we had to discard more than a month of drifter data because we could not fix the exact moment. This determination depends on the way the drogue comes off. If the line breaks, one would expect a clear signal because the state of the drifter changes very quickly. However, if the drogue is torn apart and pieces of it remain attached to the buoy for some time, there will not be a sudden jump in the time series.

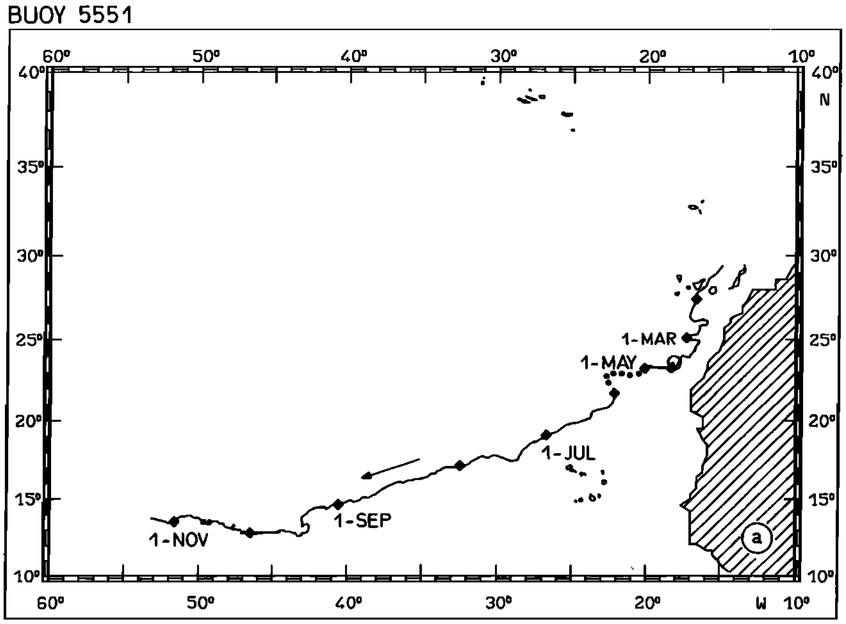

Fig. 7*a*. Trajectory of drifter 5551 off the west African coast. The buoy was deployed near the Canary Islands and moved to the southwest. Dots indicate the part of the trajectory where the drifter must have lost its drogue.

An example for this is drifter 5551 (Figure 7). The time series of drift speed shows the typical signal of a lost drogue in the last 3 months (August–October 1986), i.e., high speeds (mean around 40 cm/s, maxima > 80 cm/s) and large variance of speed. Comparison with buoys in the same area that are known to be drogued shows that typical speeds and variances in this region are smaller. However, from the time series it is not obvious when this abnormal behavior began. There is a slow but continuous increase in speed from about the beginning of May, but this might be a real oceanic signal. Fortunately, the comparison of wind and drift direction revealed that May was the month of drogue loss (Figure 8). If wind direction is plotted against drift direction for the periods January–April and June–October, there is large scatter before May (Figure 8*a*). At a main wind direction of about 230° the data occupy the whole range of drift directions. After May, the wind direction is still the same, but now the range of drift directions is reduced to a small cluster around the diagonal. Correlation coefficients are not very helpful in this case because of the small range of directions.

Our method breaks down when the influence of the wind on the undrogued buoy fails to dominate the effect of the surface current. This means that our tests for drogue loss will not give good results for drifter types that are little exposed to the wind in their undrogued state. It also means that we have problems in determining the time of drogue loss when the drogue comes off in a region or at a time of light winds and/or strong surface currents. *Richardson* [1983] anticipated this situation when he stated that "in swift currents and high eddy energy regions . . . local wind influence is difficult to detect."

Consequently, the signal of a drifter that loses its drogue in the Gulf Stream will still be strongly influenced by this current. To illustrate this point, drifters 6935 and 6946 are presented, both of which were carried into the Gulf Stream at almost the same time (Figure 9*a*). Wind comparison showed that the drogue of one buoy (6935) was still intact, whereas that of the other (6946) had come off by the time the drifter moved into the stream. If we compare the drift speeds in the region off Cape Hatteras (Figure 9*b*, shaded areas),

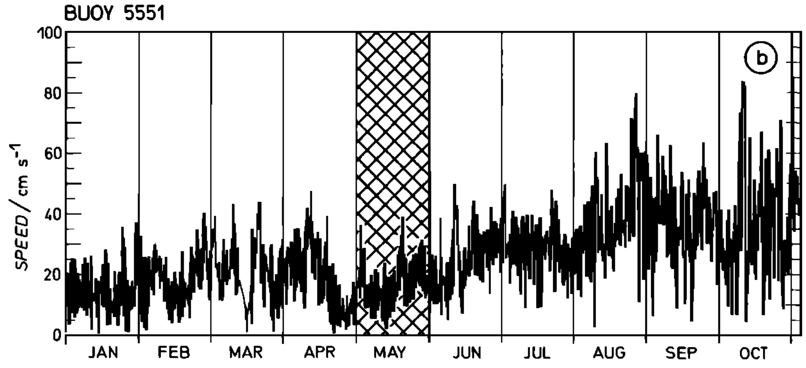

Fig. 7*b*. Time series of drift speed in cm/s. The cross-hatched period corresponds to the dotted trajectory in Figure 7*a*.

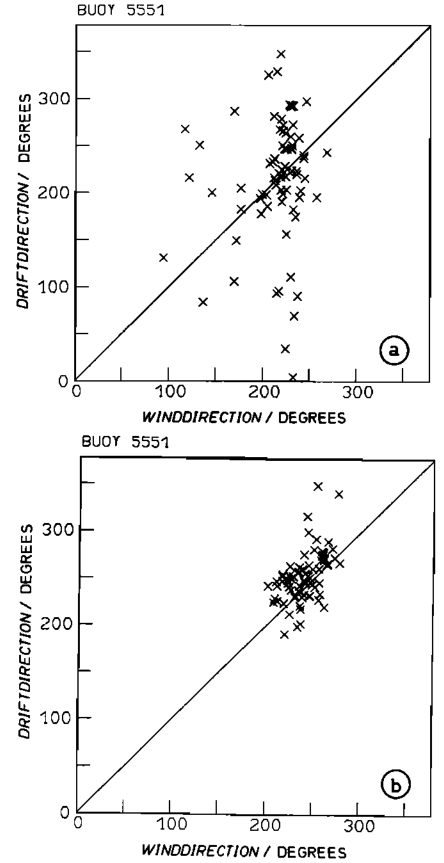

Fig. 8. Comparison of drift and wind direction for drifter 5551: (*a*) January–April (before drogue loss) and (*b*) June–October 1986 (after drogue loss).

where the buoys were situated in the high-speed core of the Stream for some time, we find that both drogued and undrogued drifters move with maximum speeds of more than 150 cm/s. The undrogued buoy 6946 seems to have slightly larger variances, but if we did not have the drogued one for comparison, this would probably go unnoticed.

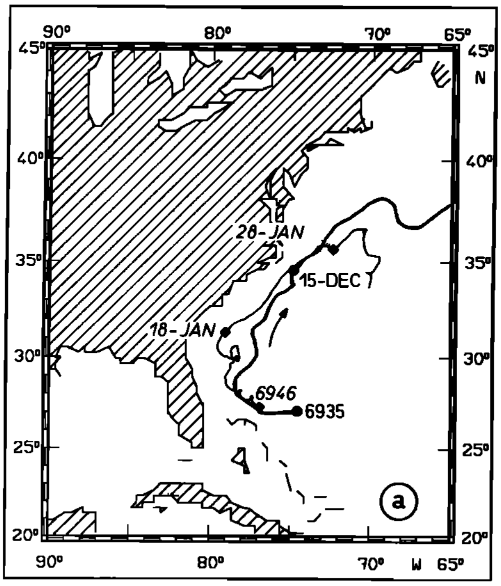

Fig. 9*a*. Trajectories of buoy 6935 (drogued) and 6946 (undrogued) west of it in the Gulf Stream.

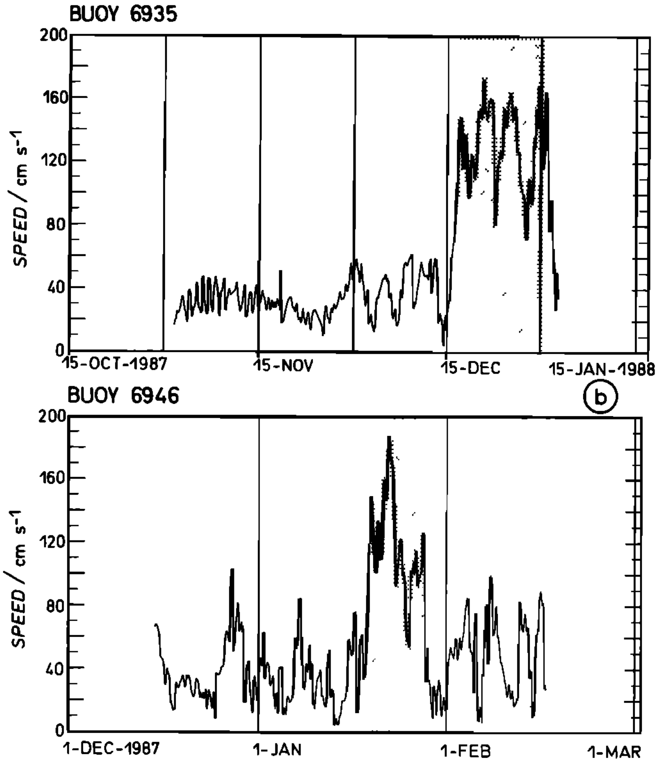

Fig. 9*b*. Time series of drift speed for (top) drifter 6935 and (bottom) drifter 6946 during their course in the Gulf Stream. Shaded period indicates drift in the region off Cape Hatteras.

The monthly plots of drift and wind direction for the relevant period (Figure 10*a*) clearly show a steady movement toward the north in November and toward the northeast in December, independent of the wind for the drogued buoy (Figure 10*a*, top). In the undrogued case (Figure 10*a*, bottom) this signal obscures the correlation between wind and drift directions that we get from our buoys without drogues. The same is true for the correlation between speeds of drift and wind (Figure 10*b*). In both cases, drift speeds are high and no significant correlation is visible because there are only short periods of winds that are strong enough to dominate the drift. If the buoy had been in the Gulf Stream at a season different than midwinter, there may not have been any strong wind events, and we would not have found any correlation at all. The differences in mean drift speed are so small because the Gulf Stream exhibits little current shear in the top 100 m [cf. *Pierce and Joyce*, 1988].

The same problem arises when the drogue comes off at a time or in an area of light winds. We often had difficulties with buoys in the region between the Azores and Capverde Islands, where due to the Azores high-pressure cell, light winds prevail for a large part of the year. In cases like this we can detect the drogue loss only after winds have become stronger or after the drifter has moved to a region with more intensive wind systems.

Drifter 7835 (Figure 11) in the east Atlantic is an example. There is no detectable signal in the time series, but the wind correlation (Figure 12) shows that the buoy moved with the wind from February 1988 onward. The problem is that these correlations are not statistically reliable because the number

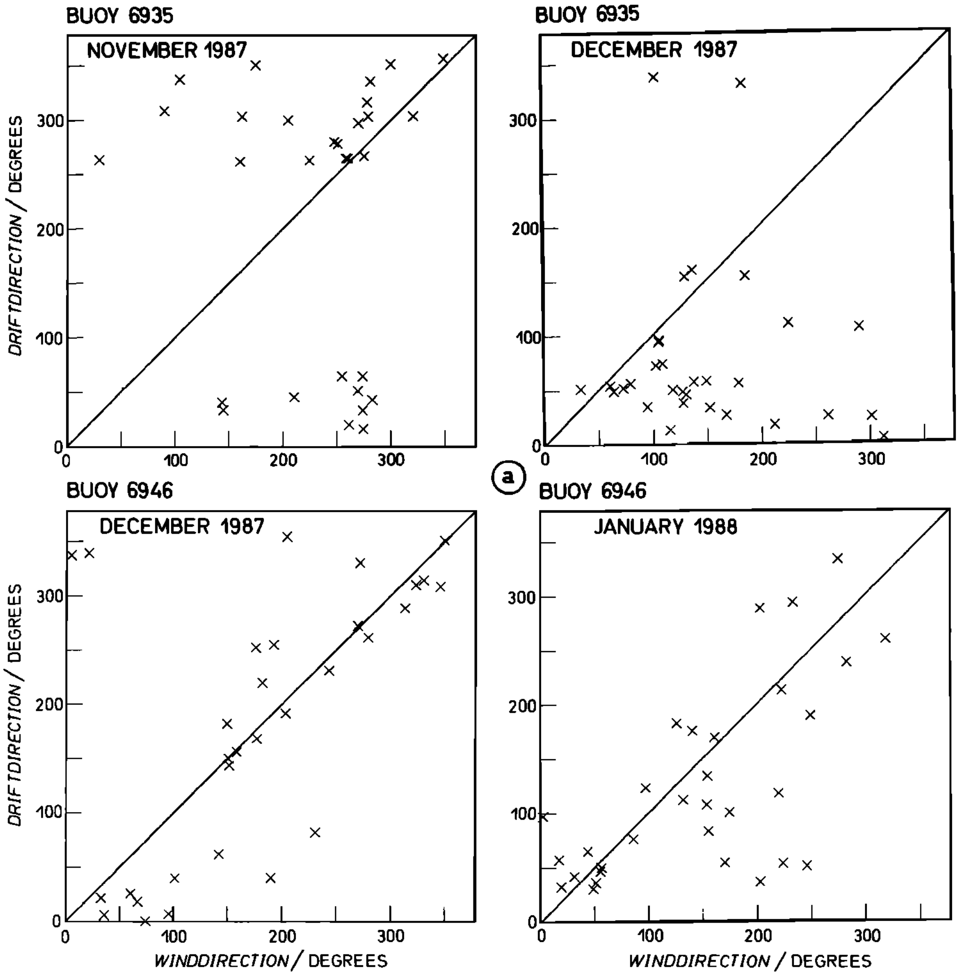

Fig. 10. Comparison of drift and wind for (top) drifters 6935 and (bottom) 6946. (*a*) Directions: November and December for buoy 6935 and December and January for 6946. (*b*) Speeds from December 1 to 31 (6935) and January 15 to February 15 (6946).

of data at high wind speeds is too small, and for low wind speeds the errors of our method are too large.

In 1980 and 1981 we had a small number of buoys with drogues in 10 m and 30 m which posed serious problems when we tried to determine their drogue loss with our method. This could be due to a number of reasons, the most likely being, as mentioned above, that for this particular construction the drogues did not detach completely from the buoy but were torn apart in the middle. The buoys were still ballasted, but the effective cross section of the drogue was reduced. In addition, most of these drifters were deployed in the North Atlantic Current, where the surface current is still strong enough to obscure the signal of drogue loss. Another reason is that movement in the surface Ekman layer is related to the wind, and so one should expect to get different results for the directional correlations than in the case of the loss of drogues that were originally in 100 m.

So, although in the Baltic we found systematic differences between the behavior of a drogued surface drifter, an undrogued buoy with ballast and a buoy with neither drogue nor ballast, in the case of our Atlantic data it is extremely difficult to distinguish between drifters with a drogue near the surface and undrogued buoys.

5. Drifter Statistics: Comparison of Drogued and Undrogued Buoys

The question now arises to what extent the differences in drift performance of drogued and undrogued buoys can influence conclusions drawn from a large data set. In order to investigate this, an area in the North Atlantic was chosen where our separation method worked very well and where enough data from both kinds of buoys were available to perform a statistical analysis. Here we will calculate only basic statistical parameters such as mean drift and eddy kinetic energy because we feel that this will suffice to prove our point. A more detailed analysis of the complete data set will follow at a later time.

Figure 13 depicts the area under consideration. It extends from 41° to 53°N and from 20° to 40°W and is subdivided into eight 3° × 10° boxes. The box size is a compromise between geographical resolution and the need for enough data in each box to calculate statistically significant results. The rectangular shape with the smaller meridional extension takes into account that in this region the meridional velocity gradient of the current is larger than the zonal one. The meridional boundary between the boxes at 30°W coincides approxi-

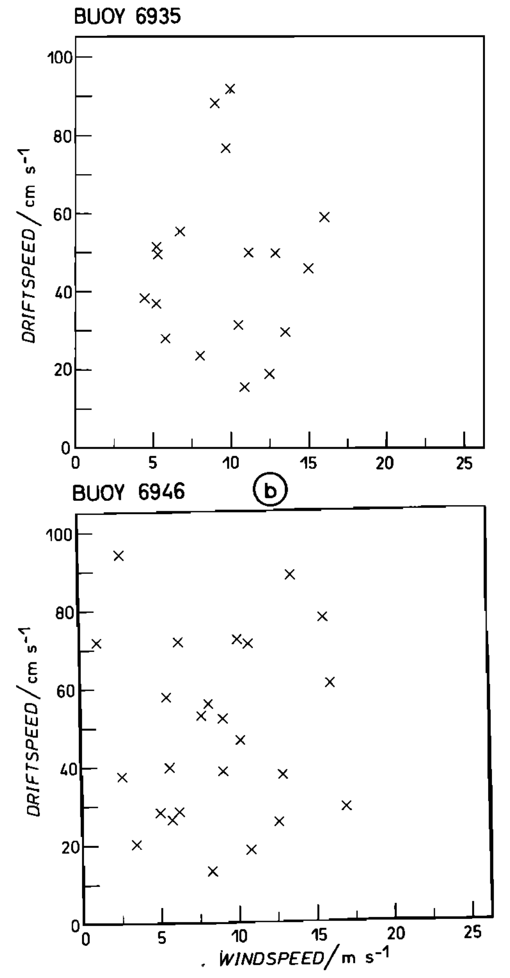

Fig. 10. (continued)

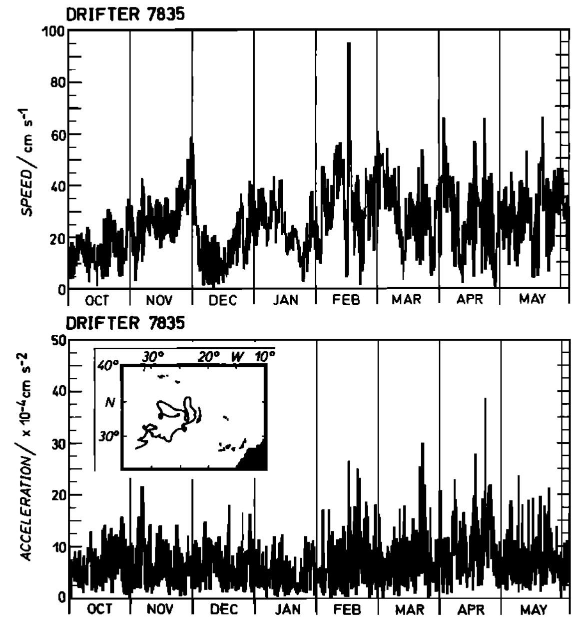

Fig. 11. Time series of speed in cm/s and acceleration in 10^{-4} cm/s^2 for buoy 7835. Trajectory is shown in the small box.

mately with the position of the Mid-Atlantic Ridge (MAR, dashed line) so that boxes 1–4 represent the situation east of the MAR and boxes 5–8 lie to the west of it. Boxes 4, 7, and 8 include the Subarctic Front (dotted line); the other five boxes are located further south.

The 164 trajectories from drogued buoys and 116 trajectories from undrogued buoys form the data base for the comparison. Only those trajectories were used for which the time of drogue loss was clear.

Time and ensemble averages [cf. *Krauss and Böning*, 1987] of all data in each box gave the mean drift velocity and the rms velocities. Data will be presented as

$$|\bar{u}| \pm \left|\frac{2(\overline{u'^2})^{1/2}}{(N_m)^{1/2}}\right| \qquad (1)$$

where $|\bar{u}|$ is the absolute of the mean velocity, the corresponding standard deviation and N_m is the number of statistically independent data in the box, i.e., the total number of observations per box divided by the Lagrangian integral time scale. The latter was assumed to be 2.5 days, a mean value taken from *Krauss and Böning* [1987] for their boxes in the same area. (Due to their precautions, the number of data from undrogued buoys was small, so that this time scale seems reliable.) The second term in (1) represents the error of the mean value given by the 95% confidence interval. The rms velocities are given as

$$(\overline{u'^2})^{1/2}[1 \pm 1.96/(2N_m)^{1/2}] \qquad (2)$$

where the second term is the error of the standard deviation within the 95% confidence interval.

It has to be pointed out that although the standard deviations due to the eddy velocities are large, the mean can be statistically stable. This is shown in Figure 14, which depicts the mean speeds in box 3 as a function of the number of data used to calculate them. The computed rms error bars are much larger than the fluctuations of the means once they reach an approximately stable level. This is in agreement with investigations of cumulative means by *Colin de Verdiere* [1983], who came to the conclusion that "the convergence of the mean values looks more encouraging than indicated by statistical principles."

The statistical results are listed in Table 1, and Figure 15 displays the mean drift velocities and the corresponding ellipses of rms velocity in the 8 boxes for both drogued and undrogued data. As expected, the undrogued buoys move with higher mean drift speeds than the drogued ones. In most boxes their speeds exceed 10 cm/s, whereas this value is reached by the drogued drifters only in boxes 7 and 8, where the core of the North Atlantic Current (NAC) is situated. Almost everywhere the differences in speed are considerable, and even with the relatively high errors, they are statistically significant in boxes 1, 2 and 4–6.

In boxes 7 and 8 the number of observations from undrogued buoys is too scarce to get stable means so that the calculated values are not very reliable. The same holds for the rms velocities. There does seem to be a tendency to higher values for undrogued buoys, however. The only box that shows no statistically significant difference, although there are enough data, is box 3. The cumulative mean speeds in Figure 14 are stable and do not overlap in spite of the large standard deviations we get from the statistics. Therefore we

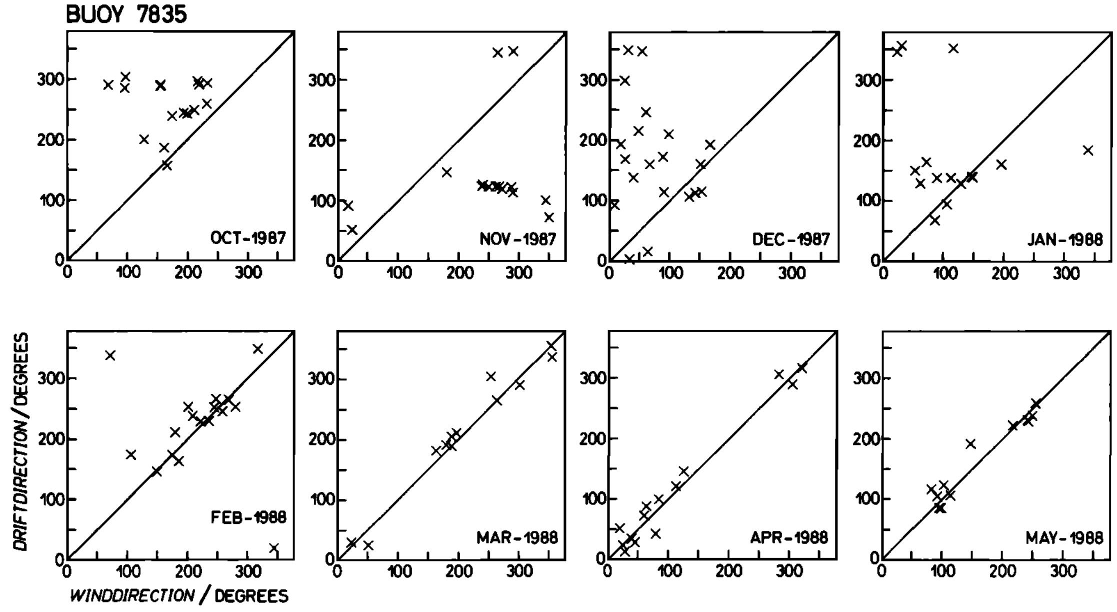

Fig. 12. Monthly plots of correlation between wind and drift direction for buoy 7835 from October 1987 to May 1988.

would tend to conclude that the difference in box 3, although small, is nevertheless real.

The biggest differences occur in box 6, which represents an area where the eddy field associated with the NAC dominates the dynamics of the upper ocean. This results in a weak mean drift speed of about 4 cm/s and large rms velocities for the drogued case. On the other hand, the undrogued data suggest a strong easterly mean flow of about 20 cm/s not present in reality. This striking difference is caused by the enhanced influence of the strong westerly winds on the undrogued buoys.

Large deviations can also be observed in box 4, which includes a part of the NAC eddy field north of the Subarctic Front and in boxes 1, 2, and 5, representing areas of the North Atlantic with weak currents and low kinetic energy. In regions with relatively strong and steady currents, the differences between drogued and undrogued buoys seem to be smaller (boxes 7 and 8). This confirms the point made in the previous chapter, i.e., that in regions where the surface current dominates over the wind influence on a buoy, it is harder to distinguish between drogued and undrogued drifters.

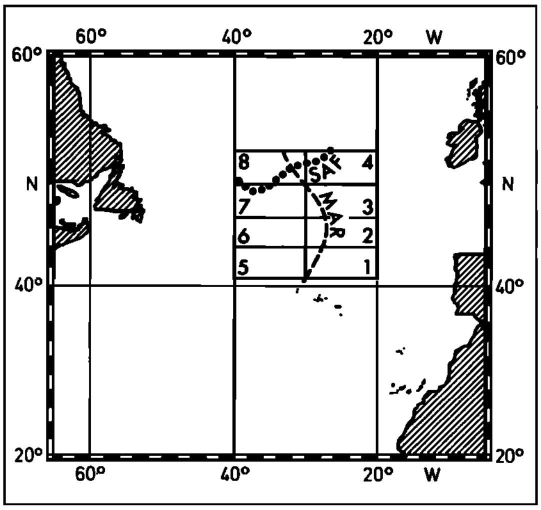

Fig. 13. Geographical location of the study area in the North Atlantic. Dashed line indicates the Mid-Atlantic Ridge (MAR) and dotted line the Subarctic Front (SAF).

Another feature of Figure 15 is that the mean drift of drogued buoys east of the Mid-Atlantic Ridge (MAR) and south of 50°N (boxes 1–3) has a southward component. This is an indication that the separation zone between the northeastward NAC regime and the subtropical gyre is situated at a latitude of about 50°N and that the Subarctic Front forms the boundary between these regimes. Undrogued buoys have a strong northward component in boxes 3 and 4, so that these data would lead to the conclusion that the separation occurs further to the south between 40° and 45°N.

Like the means, the rms velocities calculated from the undrogued buoys are generally larger than those from drogued data. The differences in the rms velocities are statistically significant at the 95% confidence level in boxes 1–5, and the plot of the cumulative rms velocities depicted in Figure 16 indicate that this holds also for box 6. Again, in

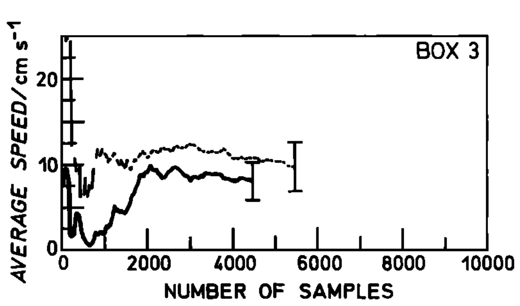

Fig. 14. Cumulative mean speeds in box 3 for drogued (solid line) and undrogued buoys (dashed line) as a function of the number of data used to calculate them. Error bars indicate rms error given in Table 1.

TABLE 1. Statistical Results of Drift for Drogued and Undrogued Buoys

	Data, buoy days		Mean Speed, cm/s		rms Velocity, cm/s	
Box	Drogued	Undrogued	Drogued	Undrogued	*u* Drogued *v* Drogued	*u* Undrogued *v* Undrogued
1	934	1009	2.6 ± 1.2	6.5 ± 2.1	11.6 ± 0.8	20.1 ± 1.4
					12.4 ± 0.9	21.7 ± 1.5
2	794	1108	5.9 ± 1.5	12.6 ± 2.2	13.2 ± 1.0	22.4 ± 1.5
					14.4 ± 1.1	24.3 ± 1.6
3	558	683	8.0 ± 2.3	9.9 ± 2.9	18.0 ± 1.6	23.7 ± 1.9
					17.0 ± 1.5	25.0 ± 2.0
4	582	469	6.5 ± 2.7	14.5 ± 4.1	21.0 ± 1.9	29.1 ± 2.8
					21.3 ± 1.9	29.6 ± 2.9
5	1230	385	4.0 ± 1.4	14.3 ± 3.9	16.5 ± 1.0	22.9 ± 2.5
					16.1 ± 1.0	27.0 ± 2.9
6	1099	391	3.9 ± 2.4	20.0 ± 4.6	24.6 ± 1.6	28.8 ± 3.1
					26.3 ± 1.7	30.6 ± 3.3
7	983	146	10.0 ± 2.6	15.4 ± 7.1	25.3 ± 1.7	28.4 ± 4.8
					28.3 ± 1.9	29.1 ± 5.0
8	819	184	10.0 ± 2.6	10.5 ± 6.3	22.9 ± 1.7	28.9 ± 4.5
					24.8 ± 1.9	27.7 ± 4.3

areas with low kinetic energy (box 5 and, especially, boxes 1 and 2) the differences are highest, whereas the smallest deviations can be observed in areas with high kinetic energy (boxes 6 and 7). For both types of drifter, the rms velocities are isotropic, which can be seen from the almost circular ellipses in Figure 15 and from the *u* and *v* components in Table 1, whose ratio is close to 1 in each case (within the limits of confidence). This agrees with the results of *Colin de Verdiere* [1983] and *Krauss and Böning* [1987]. The rms speeds are 2–6 times larger than the mean speeds for drogued drifters and 1.5–3 times for undrogued buoys.

The drogued buoys show that east of the MAR (boxes 4–1) there is a clear decrease of the rms velocities from north to south, whereas west of the MAR they have a maximum between 45° and 50°N. In addition there is an obvious decrease across the ridge from west to east. In contrast, the rms ellipses of undrogued buoys yield a fairly uniform picture. From these data one would derive higher, more uniform kinetic energy levels. Real oceanic structures are obscured.

In order to investigate the distribution and the composition of kinetic energy the total kinetic energy computed for each box is split up into the kinetic energy of the mean flow, the eddy kinetic energy, and a high-frequency portion. Eddy kinetic energy here is defined as the contribution of fluctuations with periods of more than 24 hours; fluctuations with shorter periods (including the influence of variable winds, tidal and inertial currents) form the high-frequency part. The result is presented in Figure 17.

In each category the energy of undrogued buoys exceeds that of drogued drifters. The range of eddy kinetic energy of drogued buoys extends from values of ≤ 100 cm^2/s^2 in low-energy areas east of the MAR (box 1) to 620 cm^2/s^2 in regions directly influenced by the core of the NAC (box 7). For undrogued buoys the minimum value is 330 cm^2/s^2, and the maximum 680 cm^2/s^2.

The latter is also found when comparing the energy of the mean flow. Drogued buoys have values of ≤ 100 cm^2/s^2, whereas the mean energy of undrogued drifters reaches values of up to 400 cm^2/s^2. South of the Subarctic Front, only the values from undrogued buoys decrease from west to east.

The high-frequency part of the kinetic energy is generally ≤ 100 cm^2/s^2 for drogued drifters and lies between 100 and 200 cm^2/s^2 in the undrogued case. East of the MAR the drogued values remain approximately constant (around 50

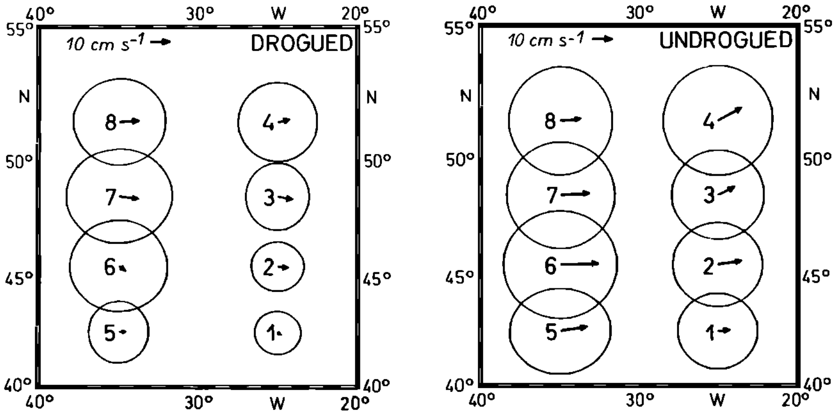

Fig. 15. Vectors of mean drift velocity and corresponding ellipses of rms velocities for the eight boxes in Figure 12. (Left) Drogued buoys and (right) undrogued buoys.

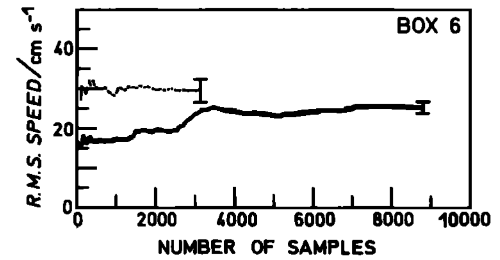

Fig. 16. As in Figure 14, for cumulative rms speeds in box 6.

cm^2/s^2), while the energy of undrogued buoys increases from 110 cm^2/s^2 in the south to 200 cm^2/s^2 in the north. This increase could be due to the influence of the wind field, which is more intensive in the north.

It is important to note that the composition of the total kinetic energy changes in the undrogued state. If the average of all eight boxes is considered, eddy kinetic energy makes up 74% of the total in the drogued case, but only 62% in the undrogued one (Figure 18). The contribution of the mean kinetic energy increases from 10% to 19% for undrogued buoys. In some regions these differences are even more pronounced (cf. Figure 17). This means that although both mean and rms speeds increase, the mean part gains in relative importance. A reason for this could be the larger spatial scales of the wind field.

Here we have compared the two extreme cases of purely drogued and undrogued data in order to get a feeling for the best and worst results possible. For mixed data the answers lie somewhere in between, depending on the proportion of undrogued data that contaminate the set. As we have seen, in areas with strong and steady currents the error is not very large, but in other regions a small percentage of undrogued data can seriously alter the results. For example, only 20% of undrogued buoys in box 6 would give an error in mean speed of 83%.

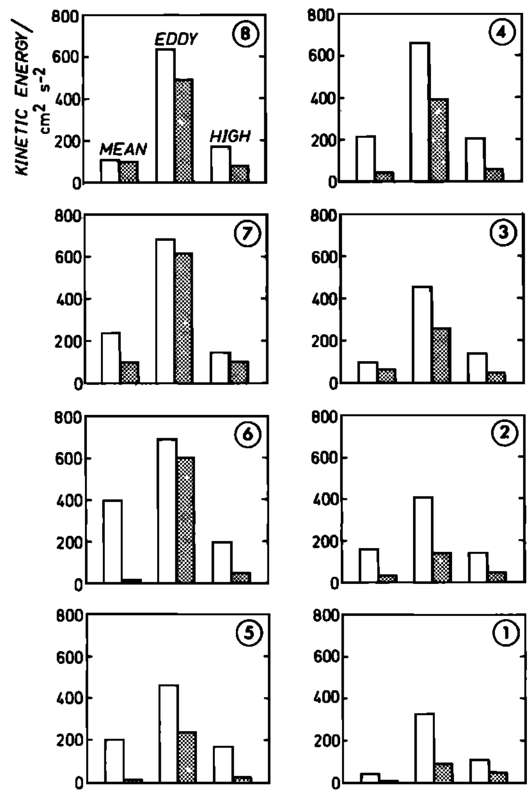

Fig. 17. Distribution of kinetic energy in the eight boxes. Shaded blocks represent drogued data. Shown are the kinetic energy of the mean flow, the eddy, and the high-frequency contribution as defined in the text. Units are cm^2/s^2.

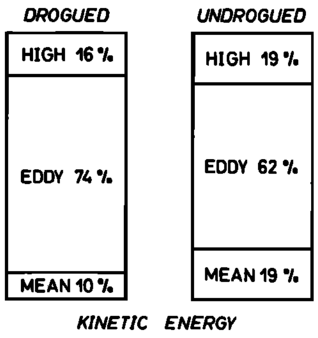

Fig. 18. Percentage distribution of the different contributions to total kinetic energy (average over all eight boxes). (Left) Drogued buoys and (right) undrogued buoys.

6. COMPARISON WITH OTHER RESULTS

There have been a number of papers that argued that drifters with and without drogues can be used equally well to study ocean circulation. We will take a look at some of the evidence presented to support this view in order to find out why we arrived at different conclusions.

Colin de Verdiere [1983] is quoted as evidence that data from surface drifters are "not severely contaminated by windage" [*Large and van Loon*, 1989]. However, Colin de Verdiere's paper dealt with drogued buoys only (drogue depth 100 m), and as we have shown, these are not necessarily representative for the movement of undrogued buoys.

In order to justify the indiscriminate use of drogued and undrogued FGGE drifters, *Garrett* [1980] is frequently given as a reference. He compared the mean speed of buoys that were equipped with drogues when deployed and others that were not and found that there is no difference. From this it is usually deduced that undrogued FGGE drifters followed the surface current well and were not influenced by wind. This is quite possible if the ensemble of undrogued drifters consisted mainly of buoys that offered little resistance to the wind. It is also possible if these buoys stayed in strong and energetic currents where differences tend to be small. However, a more elaborate test than the one performed by Garrett is necessary to prove this beyond doubt. If we used his method on our data, we would not find a difference either, although we know it exists, for the following reason: Even though the buoys had drogues at deployment, they lost them at some later stage. If the average of these time series is calculated, it looks very much like the average of an ensemble of undrogued buoys, if the part of the trajectories after drogue loss is larger than the one before.

Daniault and Ménard [1985] argue that trajectories of undrogued buoys exhibit inertial oscillations, and from this they conclude that "drifting buoys do follow oceanic surface currents rather than winds in the atmospheric boundary layer." Although this is true for the type of drifter used for their studies [*Daniault et al.*, 1985], other drifter types are more exposed to the influence of the wind after drogue loss and, nevertheless, perform inertial oscillations. In fact, for our undrogued drifters the energy at the inertial frequency is much higher than for buoys with a drogue in 100-m depth. (This is not surprising because inertial energy increases in the mixed layer, as shown by *McNally and White* [1985].) For some time we have been using this increase in inertial energy as a criterion for drogue loss, but later we found that correlations with the wind are easier to interpret.

7. SUMMARY AND CONCLUSIONS

The aim of our work was to find characteristic differences in the drift behavior of drogued and undrogued buoys and to obtain some information on the degree to which mixed or purely undrogued data sets can modify the quality of the results.

In order to determine the state of the buoy's drogue, we adopted the method described in section 4. It is fairly reliable and at the same time economical in terms of effort and computer time. However, it does not work in every case, and so each drifter time series still has to be examined individually and cross checked with a number of different criteria, because any single one may fail in some case. (As additional information, we use other methods like spectral analysis, but they are not as straightforward and more difficult to interpret in routine analysis.)

It has to be stressed once again that our conclusions are based on drifting buoys with a window-shade drogue in 100-m depth and undrogued Hermes-type buoys with specific drift characteristics after drogue loss. Therefore our results apply mainly to drifter types that are greatly influenced by the wind in their undrogued state.

We were able to determine a number of characteristics which we think are typical for this kind of buoy. In the undrogued state these drifters move with larger velocities and accelerations as well as larger variances of these parameters. They tend to align closely with the wind, and their speed as well as their direction is strongly correlated with wind data. Furthermore it was shown that our undrogued buoys do not contain the same information as surface drifters with better water-following qualities.

There are regions like the Gulf Stream or other strong currents where we had difficulty finding any difference between drogued and undrogued drifters. This might lead to the conclusion that in these areas it does not matter if undrogued data are used. Nevertheless, especially at large wind speeds the effect of the wind is there and will tend to shift mean drift speeds to larger values. In addition, drifters will leave these concentrated currents at some stage, and with undrogued buoys, one may not be able to tell if this was caused by the wind. In some cases one may not even be able to recognize that the buoy has left the current.

For an area in the central North Atlantic (41°–53°N, 20°–40°W), we demonstrated that undrogued buoys can lead to severe errors when data are analyzed. Mean and rms speeds are higher than in reality, and the distribution of kinetic energy is more uniform. Greatest differences were found in areas with low kinetic energy. The contribution of the mean to the total kinetic energy is larger for buoys without drogues. This means that current speed and kinetic energy levels can be overestimated, and even the direction of the mean current can be misjudged in some regions. The geographical distribution of rms velocities and kinetic energy is blurred; existing gradients of these parameters can be wiped out completely in some areas due to the effect of the wind. In this way, data sets with undrogued buoys can obscure real structures in the ocean, thus distorting not only the quantitative results but also our qualitative picture of the circulation.

For this reason we think that it is strongly advisable to be apprehensive of data that contain undrogued drifters. Unless acceptable water-following properties of the buoy type used have been demonstrated, for most purposes undrogued buoys should be avoided.

Acknowledgments. We would like to thank W. Krauss and C. Böning for many helpful discussions. We are also very grateful to Annegret Schurbohm, Hella Bonnes, and Sabine Trier for assistance in preparing the figures and the manuscript. This study was supported by the Deutsche Forschungsgemeinschaft, Sonderforschungsbereich 133.

REFERENCES

Colin de Verdiere, A., Lagrangian eddy statistics from surface drifters in the eastern North Atlantic, *J. Mar. Res.*, *41*, 375–398, 1983.

Daniault, N., and Y. Ménard, Eddy kinetic energy distribution in the Southern Ocean from altimetry and FGGE drifting buoys, *J. Geophys. Res.*, *90*, 11,877–11,889, 1985.

Daniault, N., P. Blouch, and F. -X. Fusey, The use of free-drifting meteorological buoys to study winds and surface currents, *Deep Sea Res.*, *32*, 107–113, 1985.

Garrett, J. F., Availability of the FGGE drifting buoy system data set, *Deep Sea Res.*, *27*, 1083–1086, 1980.

Garrett, J., FGGE Buoys: 5 years later, *Eos Trans. AGU*, *64*(49), 962, 1983.

Kirwan, A. D., Jr., G. McNally, and J. Coehlo, Gulf Stream kinematics inferred from a satellite-tracked drifter, *J. Phys. Oceanogr.*, *6*, 750–755, 1976.

Krauss, W., The North Atlantic current, *J. Geophys. Res.*, *91*, 5061–5074, 1986.

Krauss, W., and C. W. Böning, Lagrangian properties of eddy fields in the northern North Atlantic as deduced from satellite-tracked buoys, *J. Mar. Res.*, *45*, 259–291, 1987.

Krauss, W., and R. H. Käse, Mean circulation and eddy kinetic energy in the eastern North Atlantic, *J. Geophys. Res.*, *89*, 3407–3415, 1984.

Krauss, W., J. Dengg, and H.-H. Hinrichsen, The response of drifting buoys to currents and wind, *J. Geophys. Res.*, *94*, 3201–3210, 1989.

Krauss, W., J. Dengg, and H.-H. Hinrichsen, Reply, *J. Geophys. Res.*, 95, 801–803, 1990*a*.

Krauss, W., R. Döscher, A. Lehmann and Th. Viehoff, On eddy scales in the eastern and northern north Atlantic ocean as a function of latitude, *J. Geophys. Res.*, *95*, 18,049–18,056, 1990*b*.

Large, W. G., and H. van Loon, Large scale, low frequency variability of the 1979 FGGE surface buoy drifts and winds over the southern hemisphere, *J. Phys. Oceanogr.*, *19*, 216–232, 1989.

Madelain, F., and E. G. Kerut, Evidence of mesoscale eddies in the northeast Atlantic from a drifting buoy experiment, *Oceanol. Acta*, *1*, 159–168, 1978.

Maillard, C., and R. Käse, The near-surface flow in the subtropical gyre south of the Azores, *J. Geophys. Res.*, *94*, 16,133–16,140, 1989.

McNally, G. J., and W. B. White, Wind driven flow in the mixed layer observed by drifting buoys during autumn–winter in the mid-latitude North Pacific, *J. Phys. Oceanogr.*, *15*, 684–694, 1985.

McNally, G. J., W. C. Patzert, A. D. Kirwan, and A. C. Vastano, The near-surface circulation of the North Pacific using satellite-tracked drifting buoys, *J. Geophys. Res.*, *88*, 7507–7518, 1983.

Meincke, J., Note on trajectories of satellite-tracked buoys in the Southern Ocean, *Meeresforschung*, *28*, 85–89, 1980.

Niiler, P. P., R. E. Davis, and H. J. White, Water-following characteristics of a mixed layer drifter, *Deep Sea Res.*, *34*, 1867–1881, 1987.

Peterson, R. G., Drifter trajectories through a current meter array at Drake Passage, *J. Geophys. Res.*, *90*, 4883–4893, 1985.

Pierce, S. D., and T. M. Joyce, Gulf Stream velocity structure through inversion of hydrographic and acoustic Doppler data, *J. Geophys. Res.*, *93*, 2227–2236, 1988.

Poulain, P.-M., and P. P. Niiler, Statistical analysis of the surface circulation in the California Current System using satellite-tracked drifters, *J. Phys. Oceanogr.*, *19*, 1588–1603, 1989.

Richardson, P. L., Gulf Stream trajectories measured with free-drifting buoys, *J. Phys. Oceanogr.*, *11*, 999–1010, 1981.

Richardson, P. L., Eddy kinetic energy in the North Atlantic from surface drifters, *J. Geophys. Res.*, *88*, 4355–4367, 1983.

Robinson, M. K., R. A. Bauer, and E. H. Schroeder, Atlas of North Atlantic–Indian Ocean monthly mean temperature and mean salinities of the surface layer, *Ref. Publ. 18*, U.S. Nav. Oceanogr. Office, Washington, D. C., 1979.

B. Brügge and J. Dengg, Institut für Meereskunde an der Universität Kiel, Düsternbrooker Weg 20, D-2300 Kiel 1, Germany.

(Received August 7, 1990;
revised December 10, 1990;
accepted December 10, 1990.)