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The *Aries* current measurements in the western North Atlantic

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A series of current measurements was made using neutrally buoyant floats, mainly from the research vessel *Aries*, in the western North Atlantic Ocean in 1959–60, revealing unexpectedly strong variable currents in the deep water. Their main features are briefly recapitulated, and it is shown that, so far as can be ascertained, they appear to be geostrophic. More evidence is presented indicating that, in the area studied, speeds tend to increase with depth below the main thermocline. Some observations at shallower depth in a rotating lens of 18 °C water are described, and the effectiveness of conventional water sampling as a means of delineating relative currents is briefly discussed.

INTRODUCTION

The *Aries* current measurements consist of 80 trajectories of neutrally buoyant floats, most of them at nominal depths of 2 km or 4 km, in water 5 km deep to the west of Bermuda. They were observed during a 14-month period in 1959–60, in a project sponsored jointly by the Woods Hole Oceanographic Institution and the National Institute of Oceanography. These trajectories, which were typically 4 to 10 days long, revealed relatively high speeds in the deep water, of the order of 5 to 10 cm/s averaged over several days. The observations were summarized by Crease (1962), and have been interpreted by Longuet-Higgins (1965) as possibly examples of wind-generated planetary waves, and by Phillips (1966) and Hansen (1970) as being in some way related to the meandering of the Gulf Stream. Despite the irregular distribution and sparseness of the observations in space and time, it was clear that much of the energy in these deep currents was in transient motions with periods of several weeks. Such motions must be nearly geostrophic, but it is of some interest to see whether indeed they are, and to see how well the baroclinic part of the vertical profile of current can be estimated from the very limited amount of water sampling data obtained at the same time. Only a few cases exist in the *Aries* observations which permit the vertical distribution of the baroclinic component of current to be estimated simultaneously from direct measurements and from the density distribution, but such evidence as there is, presented below, suggests that the two methods agree within the expected accuracy (about ± 1 cm/s). This gives one some confidence in the reality of vertical profiles of deep currents inferred by combining a single direct measurement with the relative currents computed from suitably placed hydrographic stations. In most cases these profiles confirm the tendency, seen in the vertically spaced pairs or groups of direct observations, for the currents at 4 km depth to run faster than those at 2 km, and in nearly the same direction.

Above the main thermocline, the *Aries* data are less satisfactory as a means of assessing the reality of computed profiles of geostrophic current. Only a few direct observations of shallow currents were made. Some of these, within a rotating lens of 18 °C water, are described below. The rotation was evidently for the most part geostrophic, and it seems likely that the discrepancies encountered were due to inadequate sampling of the density distribution.

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Description of the current measurements

These measurements were made in the areas marked in figure 1. Choice of area was limited by Loran coverage, on which the navigation depended. It would have been an advantage to be able to work at a greater distance from the Gulf Stream, but the quality of Loran fixes deteriorated towards the southeast of Bermuda to an unacceptable extent. Most of the observations were made on the western side of the Bermuda rise, in water approximately 5100 m deep, with a bottom slope of about 10^{-3}, downwards to the west. The Bermuda rise is not as smooth as the contours of figure 1 suggest; there were undulations of the order of 100 m peak to trough with wavelengths of several tens of kilometres.

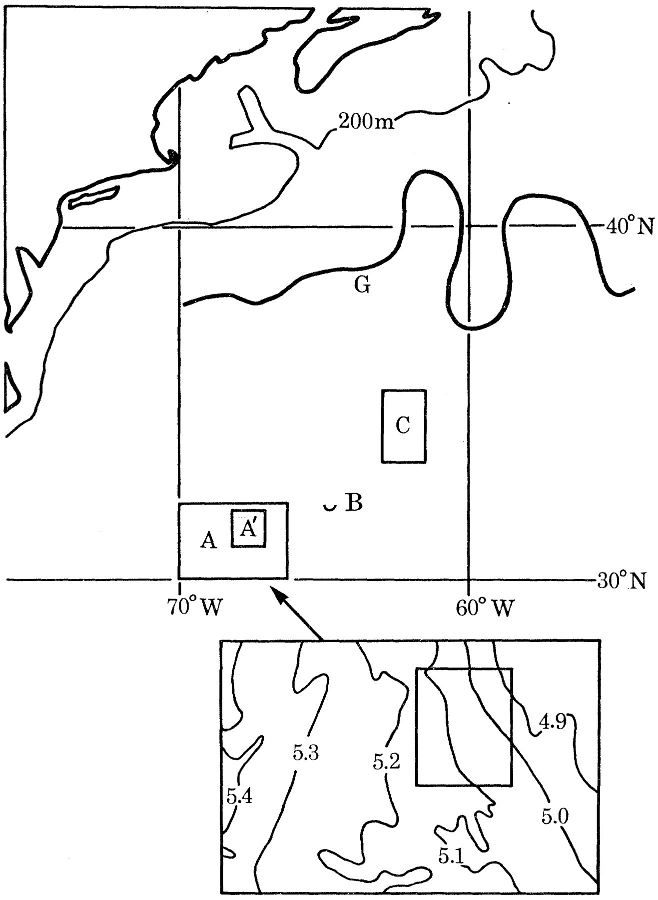

Figure 1. Location of the *Aries* measurements. Most of the observations were in area A and more than half of those were in the subarea A′. Bathymetry for area A is shown inset, adapted from Pratt (1968). Contours are in kilometres. The dot marked B is Bermuda. Area C was visited twice; on one of those visits the highest speeds were observed (see table 1). G indicates the position of the Gulf Stream in April to June 1960 (Fuglister 1963).

The floats and the method of tracking were similar to those used by Swallow & Worthington (1961). At first, it was assumed that the deep currents would be quite slow, with mean speeds of 1 cm/s or less averaged over a few days, and floats had been made that would transmit acoustic signals for a few hours every 2 days for 6 months. It soon became clear that the currents were about ten times faster than had been expected, and it proved impracticable to track the floats from one cruise to the next with the limited acoustic range obtainable (about 6 km). The long-

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term floats were therefore subdivided into units that could be used for periods of about 2 weeks, and a new group of floats was started for each cruise, with fixes being usually obtained once per day on each float.

Repeated observations on anchored buoys indicated that the relative accuracy of fixes based on Loran-A was about ± 1 km, and this was considerably improved when a Loran-C receiver became available, from September 1959 onwards (Walden 1961). Current velocities are deduced from the trajectories by dividing the observed displacement by the time interval, and of course only an average value over the time interval can be obtained. For a current averaged over a period of 2 days, the error due to inaccuracies of position fixing will in most cases be appreciably less than 0.8 cm/s.

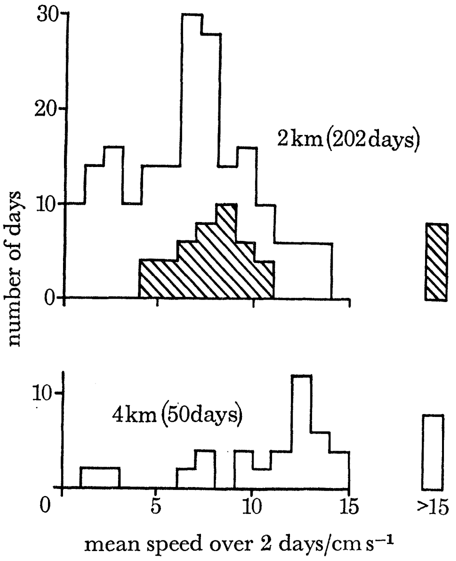

FIGURE 2. Distribution of speeds averaged over 2-day intervals at nominal depths of 2 and 4 km. The shaded area indicates the distribution of those observations at 2 km that were closest in time and position to those at 4 km.

For the purpose of comparing directly measured and geostrophic currents, the effects of inertial, tidal and higher frequency oscillations are to be regarded as noise and ideally should be filtered out first. The fixes on floats were too infrequent and irregularly spaced for that to be done. However, in cases when more frequent fixes were made and the components of displacement were plotted as a function of time, the departures from a linear relationship over a period of a few days rarely exceeded ± 1 km. It seems unlikely therefore that inertial and higher frequency oscillations would add significantly to the upper limit of the error in mean current already expected from uncertainties in navigation.

The distribution of speeds, averaged between fixes approximately 2 days apart, is shown in figure 2. The choice of a 2-day averaging time is to some extent arbitrary, it was intended to be long enough to give a result that should be comparable to geostrophic currents and yet short enough to allow a number of samples to be taken from the longer trajectories.

Many more observations were made at 2 km nominal depth than at 4 km. To allow a fair comparison to be made between the two distributions, those at 2 km depth that were nearest in time and place to those at 4 km are shaded in figure 2.

Speeds at 4 km depth can be seen to be generally higher than those at 2 km. Mean and extreme values are given in table 1. 'Nominal depth' is the depth for which the float was loaded; actual

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depths often differ from the nominal by a few hundred metres. Table 1 includes observations at all depths within ± 0.5 km of the nominal values.

Since these observations were made at irregular intervals during a period of 14 months, they may represent the speed distribution better than a single record of 202 days or 50 days would. However, the float trajectories cannot all be regarded as independent samples since they were

TABLE 1

nominal depth ...	2 km	4 km
duration of observations	202 days	50 days
mean speed (2-day average)	7.0 cm/s	13.7 cm/s
mean for those nearest to 4 km obs.	9.5 cm/s	
highest speed (2-day average)	21.2 cm/s	41.0 cm/s

TABLE 2. MEAN VELOCITIES FOR PAIRS OF SIMULTANEOUS NEIGHBOURING TRAJECTORIES

2 km		4 km	
cm/s	°T	cm/s	°T
5.2	231	7.0	167
8.6	193	12.2	187
4.9	320	3.8	350
20.6	343	41.0	346
8.8	215	10.5	204
7.8	305	11.5	340

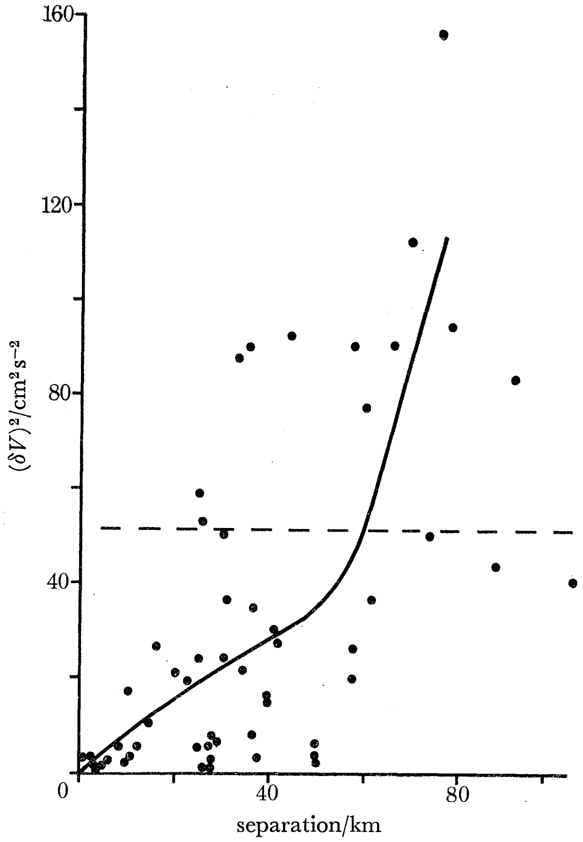

FIGURE 3. The square of the difference of velocity ($\mathrm{cm^2\,s^{-2}}$) as a function of separation (km) for simultaneous pairs of 2-day samples of current at 2 km nominal depth. The solid curve is drawn through the mean of points in each 20 km separation interval, to 80 km. The dashed line represents the mean square speed (omitting fastest moving float).

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arranged in more or less closely spaced pairs or groups. Of the possible pairs of nearly simultaneous and closely spaced trajectories at 2 and 4 km, only six cases can be considered independent. In five of these, the speed at 4 km exceeded that at 2 km, and in all six cases the direction of the current at 4 km was within 60° of that at 2 km and was more nearly meridional. They are listed in table 2.

Floats spaced a few kilometres apart horizontally, and only a few hundred metres vertically, usually had nearly identical 2-day average velocities, but differences increased with increasing horizontal separation. This is illustrated in figure 3.

The mean curve is very similar to that given by Crease (1962) based on mean values over complete trajectories. The direction of separation was not entirely random in relation to the mean current direction; at the smaller spacings less than about 40 km, attempts were made in some cases to spread the floats out deliberately across the current, but at larger separations the direction was generally not well defined. The data seem too sparse to warrant further division into cross-stream and downstream groups. The fastest moving floats were omitted in compiling figure 3, they would have been well off scale, and the dashed line drawn across it represents the mean square speed of the remainder. The mean square velocity difference becomes equal to the mean square speed at a separation of approximately 60 km. This has been interpreted by Phillips (1966) and by Hansen (1970) as indicating that the variable currents have a wavelength of the order 300 to 400 km.

The time scale of these variable currents can be estimated from the five series of float trajectories shown by Crease (1962). They were observed during April to August 1960 in the 1° quadrangle 31° to 32° N, 67° to 68° W, the area A′ of figure 1. Large changes of current direction were revealed, with an apparent period of 50 to 100 days. The accelerations observed along the trajectories, up to 10 days in length, were generally consistent with such a long period.

COMPARISON WITH GEOSTROPHIC CURRENT PROFILE

Hydrographic stations were occupied during the current measurements, usually in pairs spaced about 30 km apart across the general direction of the float trajectories. The spacing was a compromise, intended to be wide enough to give significant estimates of the horizontal gradient of dynamic height anomaly but small enough for the currents to be assumed fairly uniform within the spacing. Before making any comparisons, let us consider what accuracy may be expected in estimates of the difference of geostrophic current between 2 and 4 km from such a pair of stations. The dynamic height anomaly is obtained by intergrating the specific volume anomaly with respect to pressure. Below the main thermocline (i.e. below 1.5 km approximately) the specific volume anomaly decreases slowly with increasing depth, and the main contributions to dynamic height error come from uncertainties of temperature and salinity and not from depth errors. In these stations, water samples were taken at 200 m intervals. The salinities were determined ashore on a thermostat salinometer (Cox 1958). Their standard deviation from the mean potential temperature–salinity curve is no more than ± 0.002 ‰ in the deep water. Temperatures have a standard deviation of ± 0.01 °C. With ten samples in the depth range 2 to 4 km, the standard deviation in dynamic height difference over the pressure range 2000 to 4000 dbar (2 to $4\times10^7\,\mathrm{N\,m^{-2}}$) will be ± 1.4 dyn. mm† due to temperature and salinity errors alone, assuming that they are all independent. For two stations 30 km apart, this corresponds to a standard deviation

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† 1 dyn. mm $\approx 10^{-2}\,\mathrm{m^2\,s^{-2}}$.

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of ± 0.9 cm/s for the estimate of the difference of geostrophic current over the same pressure interval. This is the minimum error that can be expected; possible contributions due to inadequate sampling in the vertical and in time have been ignored.

For comparison with the geostrophic profile, simultaneous direct current measurements spread across the 30 km space between the stations, at each of two widely separated depths, are needed.

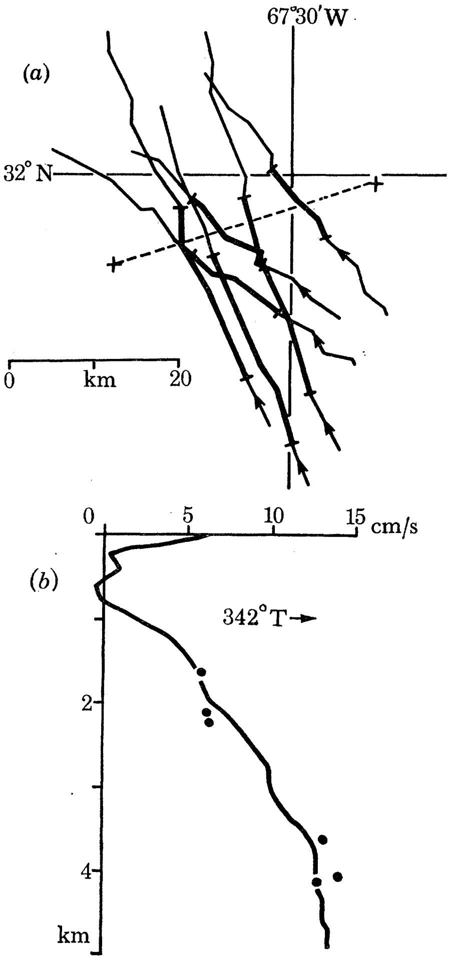

FIGURE 4. (*a*) Two groups of three trajectories passing between a pair of hydrographic stations (marked +). The group starting in the south was at 4 km nominal depth. The trajectories are drawn with a heavy line between fixes approximately 2 days apart for the period most nearly coinciding with the time of occupation of the hydrographic stations. (*b*) Geostrophic current profile and components of current from the float trajectories (marked ●).

With most of the pairs of observations listed in table 2, at least one of the depths had only a single trajectory. It seems likely from figure 3 that the mean current at some depth through a section 30 km wide could easily differ from a single sample at that depth by a few centimetres per second. The only set of trajectories that is suitable for comparison with a geostrophic current profile is illustrated in figure 4*a*. Six floats were tracked simultaneously, and two hydrographic stations were occupied on successive days at the positions shown.

Figure 4*b* shows the components of current derived from the float trajectories for the appropriate 2-day period, and the computed vertical distribution of relative geostrophic current with its zero adjusted for best fit to the direct observations. The mean components of current and mean

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depths for the two groups of three trajectories are 6.0 cm/s at 1980 m and 13.3 cm/s at 3940 m. The directly observed difference in current through the section between these depths is therefore 7.3 cm/s. The computed difference of geostrophic current between the same two depths is 6.4 cm/s. The discrepancy of 0.9 cm/s between these two estimates is no more than the minimum estimate of the standard deviation of the geostrophic current difference alone.

This good agreement may of course be partly fortuitous. In other cases, with only one trajectory at each depth, the discrepancies between observed and computed differences of current are 2 to 5 cm/s, as is to be expected in view of the horizontal variability indicated in figure 3. There is no disagreement between directly observed and computed geostrophic currents that cannot be accounted for by the estimated errors of observation and the expected variability.

This satisfactory result, although it would have been better if it could have been based on a few more detailed observations, does give some confidence in the interpretation of geostrophic current profiles derived from other pairs of hydrographic stations. It seems unlikely that any serious errors need be feared because of the point-like nature of the hydrographic stations in time and in the horizontal plane, or because of the sparse sampling in the vertical. This similarity of relative currents derived from two discrete sets of water samples, each collected more or less instantaneously at times about a day apart, with directly measured currents averaged over 2 days, bears some analogy with the correlation shown by Schroeder & Stommel (1969) between the mean sea level from the Bermuda tide gauge and dynamic height of the sea surface relative to 10 MPa (100 bar) for the *Panulirus* stations. Both of these depend on there being relatively little high-frequency noise in the low-order vertical modes in the distribution of density.

Of the single float trajectories, or groups of trajectories at nearly the same depth, passing between a pair of hydrographic stations, there are four examples which can be regarded as independent of those listed in table 2 and in which the component of velocity of the float, through the section defined by the stations, exceeded 5 cm/s. That speed seems large enough to ensure that the mean component of current through the section, at the depth of the float, would be in the same direction. In three of these four cases the component of geostrophic current increases in the same direction downwards from 2 to 4 km depth, and in the remaining case (the most nearly zonal) it remains constant.

Observations in a rotating lens of 18 °C water

Very few current measurements were made by the *Aries* above the main thermocline, and it is difficult to assess the reality of those parts of the geostrophic profiles shallower than about 1 km. The important sources of instrumental error, and probably of natural noise as well, are not the same as for profiles of relative current in the deep water. The specific volume anomaly changes rapidly with pressure in going through the main thermocline, and a systematic error in pressure can have a serious effect on the dynamic height anomaly. Pressures were determined from paired protected and unprotected reversing thermometers on alternate water bottles, i.e. 400 m apart. The depth of the whole of the main thermocline usually depended therefore on a single pressure measurement, with a standard deviation of about ± 5 dbar ($\pm 5 \times 10^4\,\mathrm{N\,m^{-2}}$). This alone would contribute ± 6 dyn. mm to the dynamic height difference between two pressures, one above and one below the main thermocline, or ± 4 cm/s to the calculated difference of current for a pair of stations 30 km apart.

The only shallow current measurements made by the *Aries* that are suitable for comparison

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with geostrophic currents were made in a rotating patch of abnormally thick 18 °C water. This feature was noticed first on bathythermograph sections, made by the R.V. *Crawford*, as an elevation of the isotherms with roughly the same horizontal scale as had already been noticed in the deep currents. For that reason it was kept under observation, and current measurements were made in and below it. During 50 days in October and November 1959 it moved 216 km towards 252° T, at a fairly uniform speed of 5 cm/s (Swallow 1961).

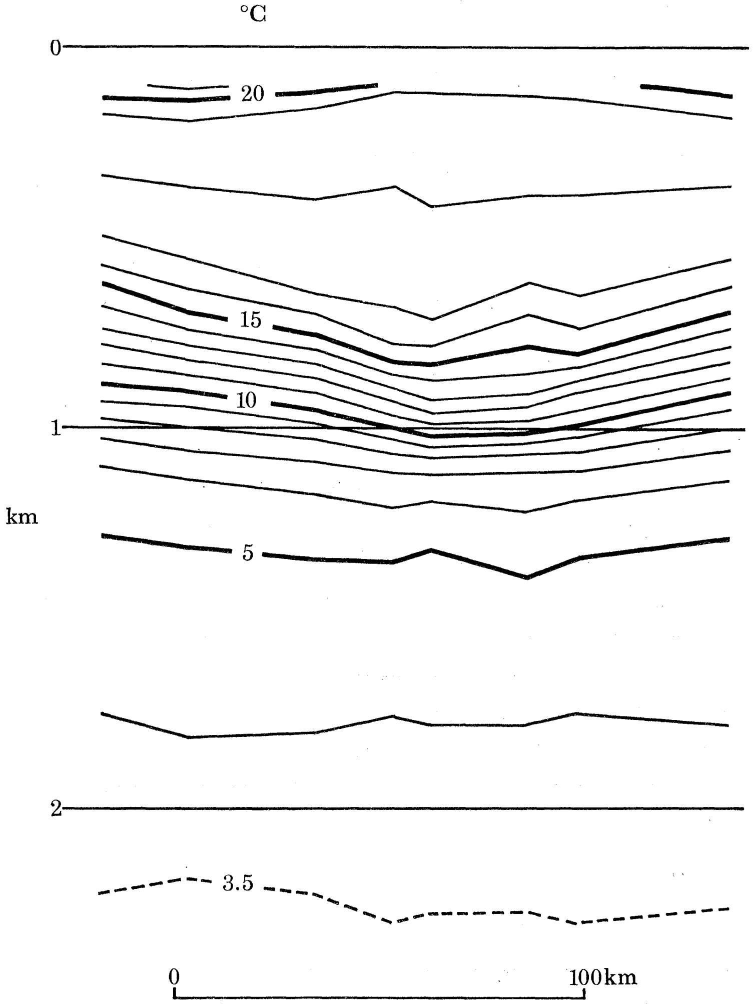

FIGURE 5. Temperature section showing thickening of 18 °C water.

Hydrographic stations occupied in the neighbourhood were adjusted in position to give a series of nearly synoptic surveys of the patch. A temperature section is shown in figure 5. The extreme depression of the main thermocline in the centre implies clockwise rotation of the thickened layer between 17 °C and 19 °C relative to, say, 2 km depth.

The floats illustrated in figure 6 moved with uniform speeds along arcs of circles and suggest radial symmetry more clearly than the thickness values do. For comparison between directly measured and geostrophic currents it seems more appropriate to use the mean radial distribution of dynamic height anomaly, shown in figure 7, in preference to working from individual pairs of hydrographic stations. The upper part of figure 7 shows clearly the horizontal scale and the extreme nature of this particular feature; at the centre of the patch the dynamic height anomaly

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differs from the mean outside it by four times the standard deviation for all the stations outside the patch. In figure 7, a pair of straight lines has been fitted to the dynamic height values, which are sufficiently scattered to make more elaborate curve fitting seem unjustified. They imply a fairly uniform speed of rotation at 400 dbar ($4 \times 10^6\,\mathrm{N\,m^{-2}}$) (relative to 2000 dbar ($2 \times 10^7\,\mathrm{N\,m^{-2}}$)) of the order of 50 cm/s, in the range 20 to 80 km radius. These values of speed calculated from the two straight lines, with curvature taken into account, are shown in the lower part of figure 7.

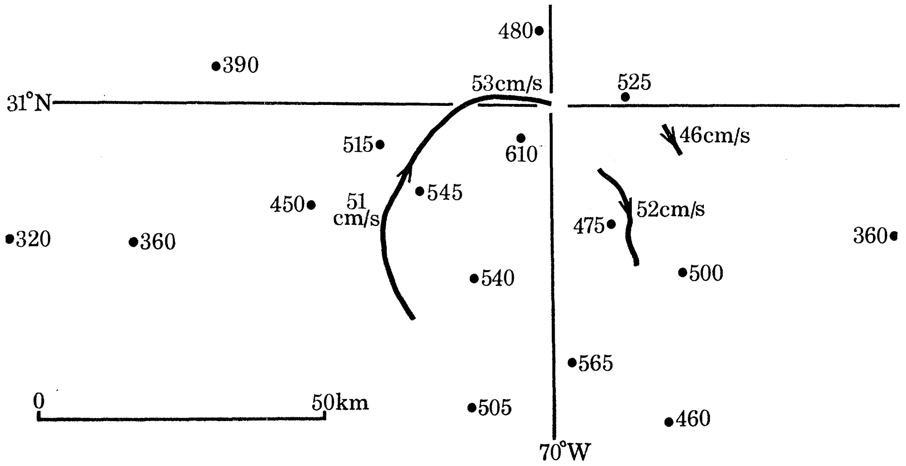

FIGURE 6. Float trajectories at 400 m nominal depth, and thickness of 18 °C water. The dots represent positions of hydrographic stations, adjusted to the mean time at which the trajectories were observed. The number near each dot is the thickness in metres, between the 17 and 19 °C isotherms, at that station.

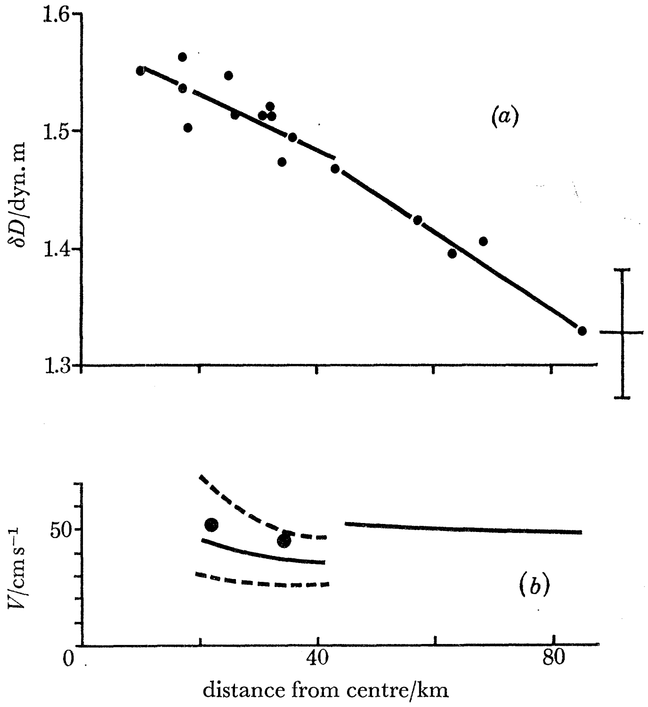

FIGURE 7. (*a*) Dynamic height anomaly at 400 dbar ($4 \times 10^6\,\mathrm{N\,m^{-2}}$) relative to 2000 dbar ($2 \times 10^7\,\mathrm{N\,m^{-2}}$) as a function of distance from the centre of rotation indicated by the float trajectories. On the right, the mean value and standard deviation for all *Aries* stations outside the patch is shown. (*b*) The solid curves indicate velocities deduced from fitted straight lines in (*a*), standard deviation of velocity estimates from inner line are shown dotted. Observed values from float trajectories are marked ●.

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They are consistent with the directly observed values. Float trajectories at 2 km showed no significant rotation at that depth under the patch.

The standard deviation of the dynamic height anomalies from the fitted straight lines was quite large, ± 2 dyn. cm for the line nearer the centre, and the corresponding standard deviation of the estimate of geostrophic speed was at least ± 12 cm/s. It was pointed out above that the expected uncertainty in estimating the depth of the main thermocline would contribute an error one third that size. Other sources of error are the coarse sampling interval in the vertical (usually 200 m) and the adjustment of station positions, occupied several days apart, assuming a mean velocity for the whole patch. The assumption of radial symmetry may be a source of error, but since the patch seems certainly not to have been in solid rotation but had a higher angular velocity towards the centre, it might be expected that any asymmetry would tend to be removed.

Conclusions and comments

The *Aries* observations show that, on the western edge of the Bermuda rise, deep currents averaged over periods of 2 days appear to be geostrophic and tend to increase downwards, from values of about 5 cm/s below the main thermocline to about 10 cm/s at 4 km. Current directions tend to be more meridional with increasing depth. The downward increase of speed is often spread uniformly through the deep water column; if it is an effect of the bottom topography it is certainly not confined to a thin layer near the bottom. Hydrographic stations 30 km apart appear to be adequate for describing the relative currents in the deep water within the limits imposed by the temperature and salinity measurements themselves. Above the main thermocline, greater instrumental uncertainties are inevitable but would be reduced considerably by supplementing the hydrographic stations with continuous profiling (s.t.d.) observations. The mean velocity and rapid rotation of an exceptionally thick lens of 18 °C water were observed by means of repeated bathythermograph and hydrographic surveys and a few brief trajectories of neutrally buoyant floats. It would have been much more difficult to detect these motions with an array of anchored current meters. There may sometimes be advantages in combining Lagrangian measurements with those from fixed arrays, as a means of resolving some kinds of ambiguity in interpretation.

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