Mesoscale Current Fields Observed with a Shipboard Profiling Acoustic Current Meter

LLOYD REGIER

University of California, San Diego, La Jolla 92093

(Manuscript received 25 February 1982, in final form 13 April 1982)

ABSTRACT

Measurements of the near-surface currents obtained with a shipboard profiling acoustic current meter during the POLYMODE Local Dynamics Experiment are discussed. The large-scale spatial structure of the directly measured currents is very similar to that obtained from simultaneous hydrographic observations assuming geostrophic dynamics. The vertical shear of geostrophic currents is half that observed directly, and the two are poorly correlated. Vertical shear is dominated by currents having spatial scales shorter than about 180 km and having no geostrophic signature. Although the shear of the ageostrophic component is clearly evident, estimation of the ageostrophic current is hampered by large experimental uncertainties.

1. Introduction

In May–July of 1978 an intensive hydrographic survey was conducted in the Sargasso Sea near 31.5°N, 69.5°W as part of the joint US-USSR POLYMODE experiment. Two research vessels surveyed a region 200 km in diameter centered on the current-meter moorings of the Local Dynamics Experiment (LDE). Six surveys of the region, each requiring 6–9 days, were taken with stations spaced at intervals from 13 to 25 km. During the first five surveys an acoustic current meter onboard the R.V. *Gyre* measured the horizontal and vertical structure of near-surface currents in the northern half of the area. This experiment marked the first use of a shipboard acoustic profiling current meter in conjunction with an extensive hydrographic survey. The purpose of the experiment was to measure the horizontal structure of near-surface currents with a resolution commensurate with that of the hydrographic observations and to compare the structures sensed by the two methods.

For centuries mariners have estimated surface currents from the discrepancy between the trajectory made good by a ship and the trajectory computed by dead-reckoning. The actual ship track over the earth is determined from navigational fixes of the ship's position and the dead-reckoned course is computed from knowledge of the ship's heading and speed through the water. Typically the ship's forward speed is estimated from the propeller revolution rate and may be in error if the hull is badly fouled. The athwartships component of ship velocity is generally ignored or is estimated from the wind speed by an empirical windage factor. In our implementation, the vector of relative velocity between the ship and the water is directly measured with an acoustic instrument. This instrument, in addition to reducing the errors normally associated with the method, also allows the relative velocity to be determined simultaneously at several different depths. This permits measurement of currents as a function of depth. As in the classical method, the velocity of the ship over the earth is determined from fixes of the ship's position, obtained in the present experiment with LORAN-C.

2. The instrument

The acoustic instrument is a modification of a standard ship log manufactured by AMETEK/Straza Division. The instrument transmits a 20 ms burst of 300 kHz sound along four narrow acoustic beams. Two of the beams lie in the fore–aft plane of the ship and the other two are in the port–starboard plane. All beams are transmitted downward 60° from horizontal from a transducer mounted flush with the bottom of the ship's hull. By measuring the Doppler shift between the transmitted signal and the energy reflected by the scatterers, the relative velocity between the transducer and the scatterers may be determined. Plankton, which are assumed to drift freely in the water, are the dominant scatterers of acoustic energy at the frequency transmitted by the instrument. The difference of the Doppler shift of the aft beam and that of the fore beam is proportional to the horizontal component of relative velocity, the Doppler shift due to vertical motion of the ship being the same for both beams. Similarly, the athwartships component of horizontal velocity is computed from the difference of the port and starboard pointing beams. The frequency of the echo is determined at seven time intervals following transmission by counting the number of zero crossings of the echo in 20

0022-3670/82/080880-07$05.75

ms intervals. In each depth bin the velocity thus obtained is the vertical average over about 25 m with the center of the depth bins falling at 23, 36, 49, 62, 75, 88 and 101 m. The rapid attenuation of high-frequency sound precludes profiling to greater depths. A determination of the profile of relative velocity is made each 0.6 s.

One serious deficiency in the instrument is the lack of any means to ascertain whether the electronics are in fact accurately tracking the frequency of the acoustic return. The received echo is highly modulated in amplitude and contains frequent dropouts. During these periods of low signal level, the electronics are not able to track accurately and the instrument gives spurious readings of the relative velocity. Signal dropouts are more pronounced when the ship is steaming at high speed, on account of increased flow noise, and in the deeper bins where the absorption of sound by the water greatly reduces the signal levels. Lacking any clear indication from the electronics of a low signal-to-noise ratio, it is difficult to judge objectively the reliability of the data. Inspection of the data reveals that the deepest two depth bins have a far greater degree of variability than do the shallower ones. We thus regard the data deeper than 75 m as being suspect. The shallowest depth bin is also discarded since the relative velocity estimates there are biased towards zero on account of an echo from some portion of the ship's hull and an inability of the electronics to respond to the large transients at the beginning of the data-gathering cycle. As a result this discussion is limited to currents at depths between 36 and 75 m. Throughout the experiment the surface-mixed-layer depth was less than 20 m. Thus the observations pertain to the near-surface, but not surface, currents. Joyce *et al.* (1982) describe a more recently developed instrument which corrects some of these deficiencies and which allows profiling to depths exceeding 120 m.

The scope of the present discussion does not include a complete examination of the factors limiting the accuracy to which the relative velocity between the ship and the water is determined by the acoustic system. Such an exposition is in preparation and will be presented elsewhere. Joyce *et al.* discuss some of the relevant concerns. In general, the expected errors decrease as the time interval over which data are averaged is increased. Averaging is required to reduce the variability of velocity estimates due to noise in the acoustic processing system and to reduce the contamination due to wave-induced motions of the ship. These two error sources limit the accuracy to which the vertical shear of currents may be determined. When acoustic observations are averaged over a 2 h period, the length of a typical hydrographic station, the velocity difference between two depths has an expected error less than 1 cm s^{-1}. Thus the shear averaged from 36 to 75 m has an expected error of 3×10^{-4} s^{-1}. The error is proportional to the reciprocal of the vertical averaging interval.

The absolute current velocity relative to the earth is computed from the vector sum of the acoustically measured velocity of the water relative to the ship and the velocity of the ship over the earth. As the latter vector is determined from the distance traveled between sequential LORAN fixes, errors in the fixes cause errors in the absolute currents. When the ship is on station, the dominant error in absolute currents is due to inaccuracy in the computation of the fix. The fixes were computed manually using graphical methods and it is estimated that this results in a 200 m uncertainty in the distance traveled between fixes. For fixes taken at the beginning and end of a 2 h station, the velocity error is 4 cm s^{-1}; the expected error is proportional to the reciprocal of the time interval between fixes. When the ship is steaming, other error sources become important and the expected error increases to at least 10 cm s^{-1}. The large ratio of ship speed to current speed makes the absolute current estimates sensitive to errors in the installation of the acoustic transducer relative to the ship's gyrocompass and to errors in the synchronism between the LORAN fixes and the acoustic observations. Because of the large expected errors in absolute currents obtained while steaming, we consider only observations made while on station. The errors due to asynchronous LORAN and Doppler observations as well as those due to installation errors and the velocity contamination caused by wave-induced motions of the ship are reduced to substantially less than 1 cm s^{-1} by averaging all profiles taken during a 2 h station. The 4 cm s^{-1} error due to inaccurate fix computation is random in nature, and there is no correlation of errors between data obtained at different stations.

3. Discussion of results

The vertical shear of currents may be obtained directly from the acoustic observations by taking differences between the observations at each depth cell. However, since the instrument functioned reliably at only four depths and since these observations are themselves averaged over a vertical extent of 25 m, the instrument in its present configuration does not allow examination of the structure of vertical shear. The average vertical shear obtained from the difference between currents at 36 and 75 m is a smoothed representation of the actual vertical shear. The vertical shear estimated in this fashion is significantly above the expected error level of 3×10^{-4} s^{-1} and is typically around 1.3×10^{-3} s^{-1}, occasionally getting as large as 4×10^{-3} s^{-1}. Because of the vertical smoothing the actual shear is probably larger than these estimates. The largest shears were distributed chaotically throughout the horizontal sur-

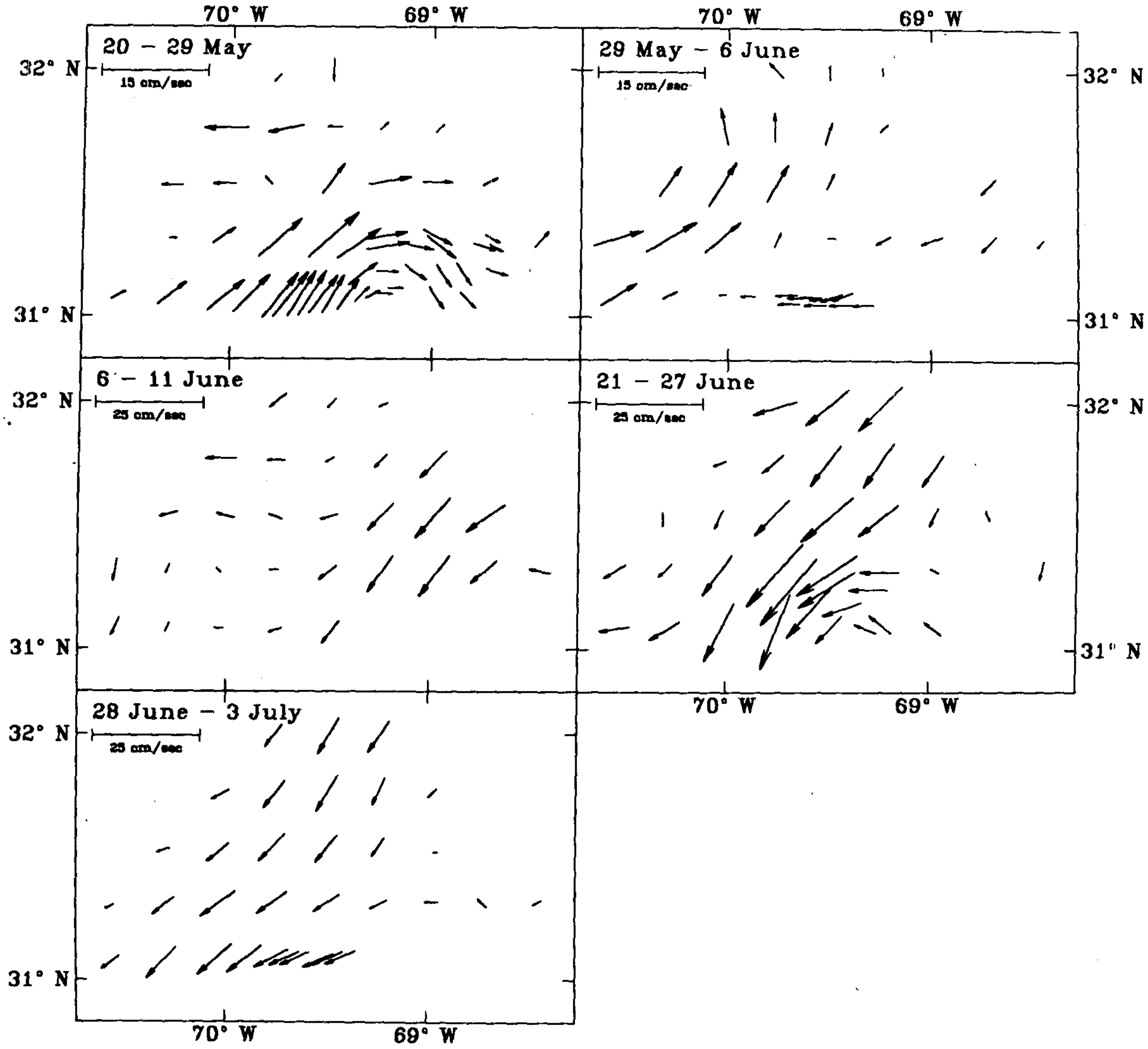

FIG. 1. Vectors of geostrophic currents at 50 db relative to 600 db. The scaling of vector magnitude changes between frames. The midpoint of each vector is at the position of the hydrographic station.

veys, and maps of vertical-shear magnitude had no discernible relation to the circulation patterns presented below. The average geostrophic shear observed over the same depth interval is generally half as large, typically $6.6 \times 10^{-4}\ s^{-1}$. Based on data from all five surveys, the correlation between the total and geostrophic shear is less than 0.2, indicating that the bulk of the shear is due to currents not having a geostrophic signature. Currents due to internal waves, inertial oscillations, and to direct wind forcing are obvious candidates. To distribute the shear properly among these or other sources, repeated profiles are required during an inertial cycle as well as knowledge of the wind field and the intra-station temporal variability of density; this information is not available.

As the candidate sources of non-geostrophic shear have relatively short spatial scales, the magnitude of vertical shear should decrease as the observations are smoothed horizontally. Indeed, the shear magnitude does decrease by one-half when scales < 180 km are removed. The shear averaged over all surveys is about $5 \times 10^{-4}\ s^{-1}$ in the longer scales. The geostrophic shear is also reduced by the same factor when similarly smoothed, amounting to $3 \times 10^{-4}\ s^{-1}$ for scales > 180 km. Smoothing to remove even larger scales causes no further decrease in the shear since the maximum extent of the surveys is 200 km.

Although at scales exceeding 180 km the spatially smoothed total shear agrees with the geostrophic shear to within the uncertainties in the estimates, the total observed shear is consistently larger than the geostrophic shear. That the total shear should be twice the geostrophic shear even at scales exceeding 180 km is rather surprising. The shear due to internal waves is most certainly negligible at these scales. The contribution of inertial currents to the shear should be greatly diminished at scales exceeding 180 km since Webster (1968) and Sanford (1975) report

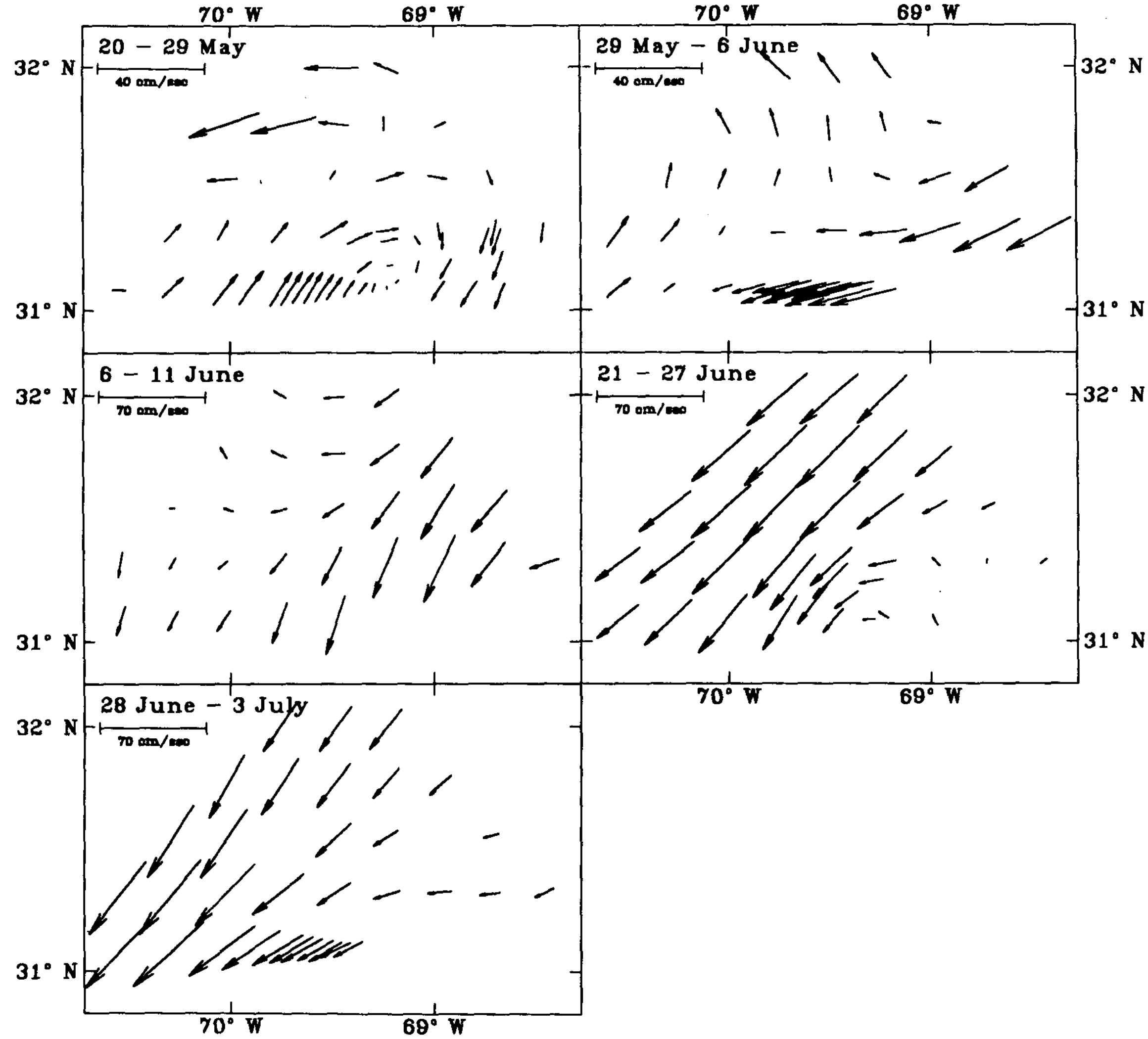

FIG. 2. Vectors of total current observed acoustically. Note that the scaling of vector magnitude changes between frames and is different from that of Fig. 1. The velocity has been averaged from 36 to 75 m and only data taken while on station have been used. The same spatial structure is evident at each depth level of the acoustic instrument.

their correlation scales to be less than 30–50 km. Thus the shear in the longer scales is thought to be due to direct forcing from large-scale wind events having time scales too short to allow geostrophic adjustment.

Fig. 1 shows the geostrophic current at 50 db relative to 600 db computed from each of the five hydrographic surveys completed by the *Gyre*. These maps were produced using the objective analysis technique described by Bretherton *et al.* (1976). The maps have been smoothed by a spatial Gaussian filter with its half-amplitude point at a 25 km radius to reduce features having wavelengths < 100 km to less than half their original amplitude. The currents in the first two surveys are lower in amplitude than in later surveys. During the third survey an energetic jet-like feature enters the southeast corner of the area. Following a 10-day gap between the third and fourth surveys this feature dominates the entire region, and it is still present in the fifth map. From surveys of only the northern half of the LDE region it is difficult to determine the propagation direction of this feature, but combining the surveys of both vessels reveals propagation toward the northwest. Because of low confidence in the estimated propagation speed and direction, no attempt has been made to remove a mean advection of the field from the objective maps. The propagation of the density field during the survey distorts the maps and introduces an error in the geostrophic currents computed from the horizontal gradients of the dynamic topography. As the survey was conducted more slowly in the north–south direction than in the east–west direction (the ship track scanned along a series of east–west lines from the northern to the southern extreme), the error is more pronounced in the east–west component

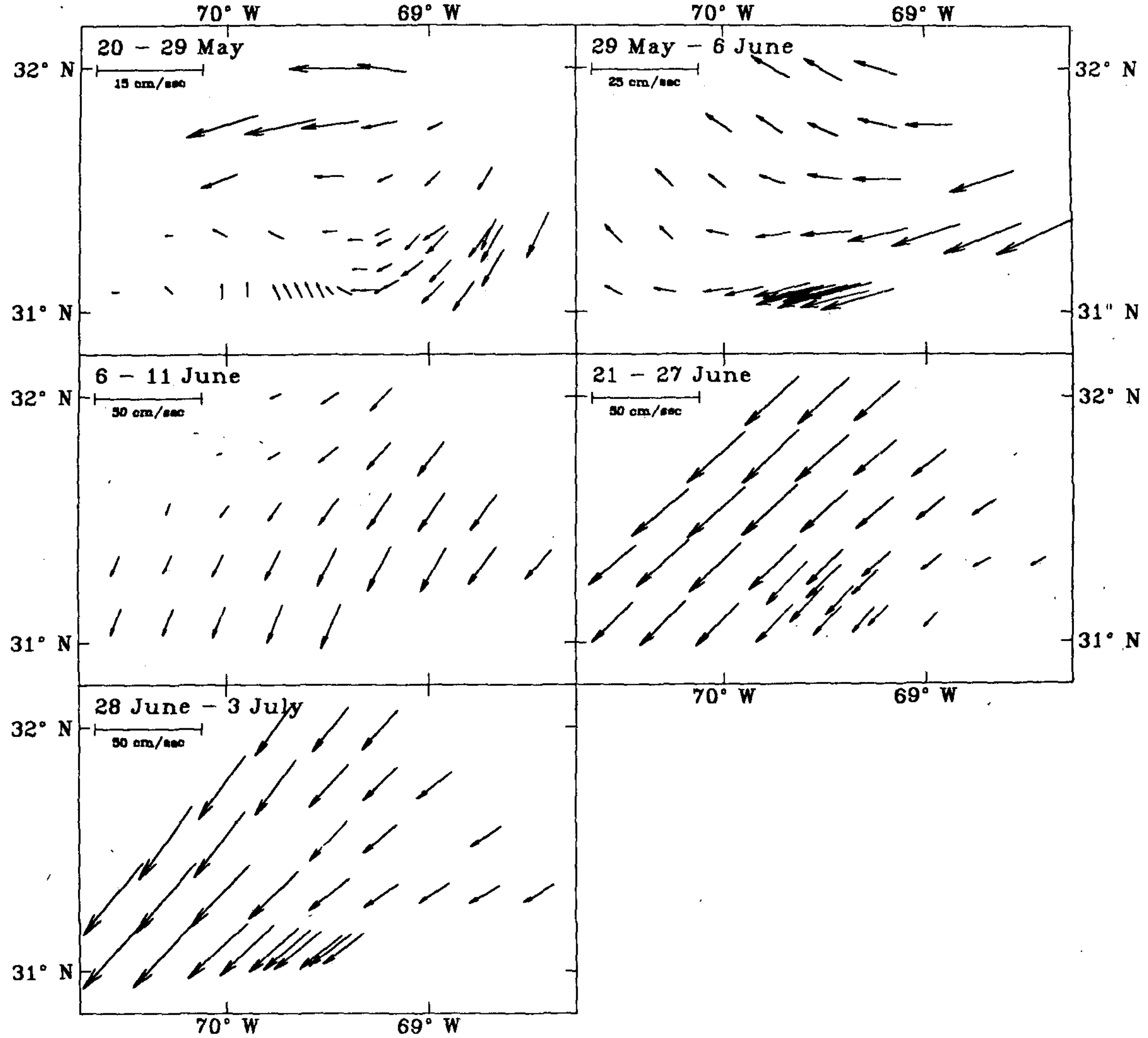

FIG. 3. Vector fields of the difference between total observed current and geostrophic current relative to 600 db. Note the change in scaling of vector magnitude between frames. The fields have been spatially smoothed over a 50 km radius to remove scales < 180 km.

of geostrophic velocity. From the observed rate of change of dynamic topography at fixed locations, we estimate that the error in the geostrophic velocity can be as large as 10 cm s^{-1} in the third through the fifth surveys where the gradients of dynamic topography are large. In the earlier surveys the expected error is less than 5 cm s^{-1}.

Fig. 2 contains objective maps of the total velocity field measured with the acoustic instrument. The same spatial smoothing used in Fig. 1 has been applied to this figure to reduce the effects of currents due to internal waves, inertial oscillations, and other processes having scales < 100 km. At these long scales the horizontal structure of currents was found to be the same at all depths observable with the acoustic instrument. However, as discussed earlier, there is appreciable vertical shear. In Fig. 2 the velocity field has been averaged between depths of 36 and 75 m.

In all surveys there is good agreement between the structures of the total observed currents and the geostrophically computed currents. The correlation coefficient between the two fields is 0.8, 0.7, 0.7, 0.6 and 0.4, respectively, in the five surveys. The magnitude of the total observed currents is substantially larger than that of the geostrophic currents relative to 600 db. However, when geostrophic currents are computed relative to 3000 db, the spatial structure remains essentially unchanged and there is better agreement in the magnitudes of total and geostrophic currents. With this deeper reference surface, the correlation between the total and geostrophic fields is 0.8, 0.7, 0.8, 0.7 and 0.8 in the five time periods. During the fifth survey there must have been substantial horizontal variation in the density field between 600 and 3000 db to increase the correlation from 0.4 to 0.8 when the deeper reference surface is employed. That the total observed currents agree

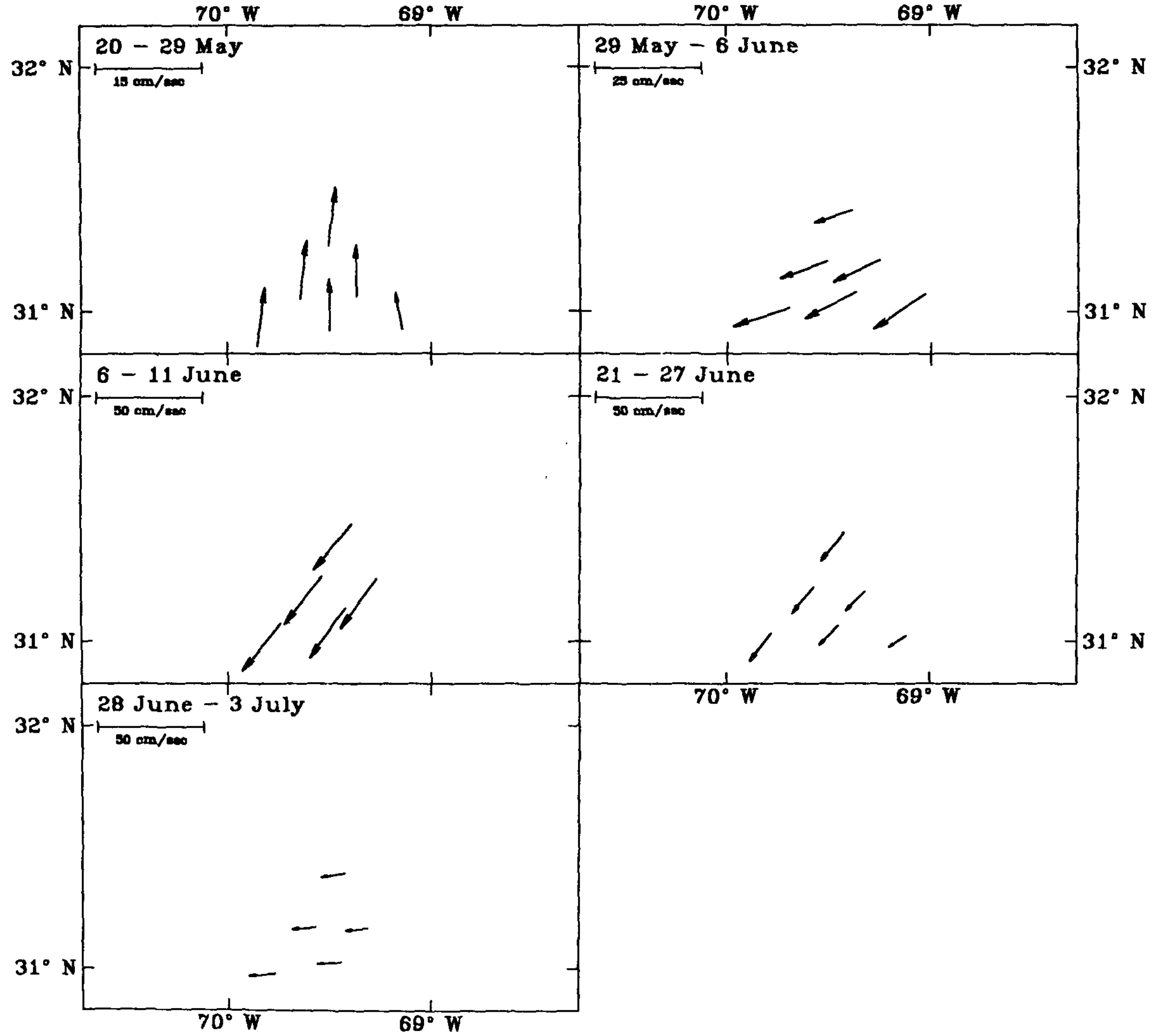

Fig. 4. Currents measured at 600 m by the LDE current-meter array. For ease of comparison the scaling of vector magnitude and the degree of spatial smoothing are the same as those of Fig. 3.

best with the geostrophic currents referenced to 3000 db indicates that 3000 db is a better reference level than 600 db, at least for the estimation of near-surface flows. This is to be expected since the permanent thermocline in the LDE is near 600 db and its depth is greatly perturbed by mesoscale activity. We have chosen the 600 db reference level since the LDE current meter array had six instruments at this depth and only one at 3000 db. The current-meter data are used below to estimate the current at the geostrophic reference level.

If the only currents present were governed by geostrophic dynamics, then the current at the reference pressure surface for the geostrophic computation could be obtained by subtracting the geostrophic current from the total observed current. However, the earlier discussion of shear shows that there is also present a significant ageostrophic component. In addition both the total and geostrophic current estimates are contaminated by errors. Thus the difference between the total observed current and the geostrophic current computed relative to 600 db has four components: errors in the total current, errors in the geostrophically computed current, the actual current at 600 db, and the ageostrophic current generated between 600 db and the depths of the acoustic observations. The ageostrophic component may be extracted if independent observations of the current at 600 db are available. However, since the error of the total currents is expected to be 4 cm s^{-1} and the error of the geostrophic currents is estimated to be as large as 10 cm s^{-1}, estimation of the ageostrophic current is subject to large errors.

Maps of the field obtained by subtracting the geostrophic currents (relative to 600 db) from the total observed currents are presented in Fig. 3, in which the maps have been smoothed to remove scales < 180 km. These maps represent our estimate of the sum of the actual current at 600 db and the ageostrophic component generated between 600 db and the depth of the acoustic observations. It should be noted that since the total velocity has been averaged from 36 to 75 m, the ageostrophic component referred to is the average over the same vertical interval. The LDE current-meter array contained six current meters at a nominal depth of 600 m in the south-central area of our surveys. The average current for each meter is computed for each survey from the data of Mills *et al.* (1981), smoothed spatially to the same degree as Fig. 3, and the resulting maps are presented in Fig. 4. During the second through fourth surveys, the vectors in the respective frames of Figs. 3 and 4 are nearly identical. Thus we conclude that the ageostrophic component is very small in these three surveys and that the geostrophic reference velocity could be estimated quite well from the difference between total observed and the geostrophically computed currents. The ageostrophic component has a magnitude of 10 cm s^{-1} in the first survey with an expected error of ~9 cm s^{-1}. Although the estimated ageostrophic current is larger, about 15 cm s^{-1}, in the fifth survey, the expected error is also larger, ~14 cm s^{-1}, because of the large gradients in the dynamic topography. Thus, although the ageostrophic component is large in the first and fifth surveys, its magnitude is marginally above the expected error level. In these two surveys it would be unwise to estimate the geostrophic reference level from the difference between the total and geostrophic currents because of the large size of the ageostrophic component. We have not yet devised a diagnostic to indicate when a large ageostrophic component might be present. There is no apparent difference between the first and second surveys, during the first of which there was an appreciable ageostrophic current that was not present in the second survey several days later. Nor can we distinguish a difference between conditions in the fourth and fifth surveys.

4. Conclusions

The general structure of near-surface currents is predicted rather well from the density field assuming geostrophic dynamics. The current magnitudes are better estimated using a reference level at 3000 db than at 600 db, the level of the main thermocline. Notwithstanding this apparent agreement, an ageostrophic current component is present in all the surveys as the vertical shear of the total current between 36 and 75 m is twice that of the geostrophic component over the same interval. The ageostrophic shear is most pronounced at scales < 180 km but remains twice the geostrophic shear even at longer scales. Estimates of the ageostrophic current component vertically averaged from 36 to 75 m, obtained by combining the acoustic, hydrographic, and current-meter-array data, are above a noise level of 9 to 14 cm s^{-1} in only two of the surveys. In the other three surveys the vertically averaged ageostrophic component is undetectable although its shear is clearly evident. This suggests that the ageostrophic component is highly sheared and has a near-zero vertical average over our observable depth range.

Because of limitations in the instrument, currents could not be observed reliably at depths less than 36 m or deeper than 75 m. These limitations have been corrected in contemporary versions of the instrument and should lead to much more interesting experiments in the future. The experience gained in this experiment has increased our understanding of the method and of the considerations necessary for the design of future experiments. Identification and examination of ageostrophic currents is crucially dependent upon the density surveys being more nearly synoptic than in the present experiment. To study the physical source of the ageostrophic motions, the structure of atmospheric forcing is required, both locally and to scales exceeding 180 km.

It should be noted that estimation of the ageostrophic component is limited by errors not in the acoustic system but in the determination of currents using the classical geostrophic method. The ability of the geostrophic method to determine currents whose local rate of change is large is critically dependent upon the rapidity with which a density survey is completed. Clearly new techniques of determining the density field are required to make reliable computations of geostrophic currents in a rapidly evolving environment.

Acknowledgments. This research was funded by the Office of Naval Research, Code 481, which purchased the instrument. Data analysis was performed with funding from the National Aeronautics and Space Administration, Oceanic Processes Branch. The author is deeply indebted to R. Boehme of AMETEK/Straza who installed the instrument, and to the crew and officers of the R.V. *Gyre.* Curt Ebbesmeyer and Bruce Taft graciously supplied the density data used in creating Fig. 1. Special thanks to Henry Stommel, Russ Davis, and R. Pinkel for many stimulating questions.

REFERENCES

Bretherton, F. P., R. E. Davis and C. B. Fandry, 1976: A technique for objective analysis and design of oceanographic experiments. *Deep-Sea Res.*, **23**, 559–582.

Joyce, T. M., D. S. Bitterman and K. E. Prada, 1982: Shipboard acoustic profiling of upper ocean currents. *Deep-Sea Res.* (in press).

Mills, C. A., S. A. Tarbell and R. E. Payne, 1981: A compilation of moored instrument data and associated hydrographic observations, POLYMODE Local Dynamics Experiment, 1978–1979, No. 28. WHOI Tech. Rep. WHOI-81-73.

Sanford, T. B., 1975: Observations of the vertical structure of internal waves. *J. Geophys. Res.*, **80**, 3861–3871.

Webster, F., 1968: Observations of inertial period motions in the deep sea. *Rev. Geophys.*, **6**, 473–490.