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by
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DEEP-SEA CIRCULATION IN THE ALBORAN SEA

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Abstract. Alboran Sea circulation between 220 and 1100 m depth is studied. Interaction between three types of water masses in this area causes a complicated flow pattern. Atlantic water flowing as a jet through the Strait of Gibraltar into the Mediterranean often forms an anticyclonic gyre to the depth of 200 m, and its features are now well documented. A few works based on geostrophic calculations and Bernoulli's equation treat the deep flow. Nine free floats were released at different depths and locations from January to May 1982 and acoustically tracked every 2 hours for 40 to 90 days. Acoustical tracking was done from three listening stations moored in the area. The tracks of the floats at all depths from 220 to 1100 m revealed broad and slow (approximately 2.5 cm/s) cyclonic circulation located under the surface anticyclonic gyre. Part of the flow, following the bottom topography, turned near the Moroccan Continental slope as a jet (approximately 5 cm/s) to Gibraltar and part turned to the east following the southern boundary of the deep channel to the Isle of Alboran.

Introduction

The Alboran Sea is the area to the east of the Strait of Gibraltar. As it is part of the Mediterranean Sea, the main source of dynamical forcing is the gradient of gravity geopotential due to the excessive evaporation in the Mediterranean. As a result, relatively fresh Atlantic water flows through the Strait of Gibraltar as a jet into the Alboran Sea, and deeper, more saline and warmer water of Mediterranean origin flows out through the strait into the Atlantic. The Coriolis force, atmospheric disturbances, and mainly semidiurnal tides modify the circulation. The interaction between the different water types in the Alboran in this highly energetic environment causes a large variation of oceanographic features. Three types of water are distinguished: Atlantic, Levantine, and Deep Western Mediterranean [Bryden and Stommel, 1982].

Atlantic water in a top layer about 150 m thick flows into the Alboran Sea as a 20 km wide jet at a speed of several kilometers per hour; it has a characteristic average salinity of 36.5 and a temperature that depends on the season. This energetic layer creates anticyclonic circulation in the southern part of the Alboran Sea. Its extension and depth are quite variable. It is documented by Lacombe [1971], Lanoix [1974], Cheney and Doblar [1978], Gallagher et al. [1981], Bucca and Kinder [1984], and by participants of the "DONDE VA" experiment [Parrilla, 1984]. Laboratory and numerical modeling has been reported by Whitehead and Miller [1979] and Preller and Hurlburt [1982], respectively. This anticyclonic circulation is clearly visible on the satellite infrared images of the sea-surface temperature, as shown by Wannamaker [1979], Philippe and Harang [1982], and La Violette [1983].

Under the surface layer is water of Mediterranean origin, first the intermediate Levantine water with a characteristic maximum potential temperature of 13.13°C and a salinity of 38.466 to 38.485, and deeper, the Deep Western Mediterranean water originating in the western Mediterranean, which is less saline but colder.

Stommel et al. [1973], Bryden and Stommel [1982], Pistek [1984], and Kinder [1984] have addressed the deep flow. Bryden and Stommel [1982] found the enhanced flow near the southern boundary from geostrophic calculations; their current meter data from one mooring showed a current directed along the Moroccan continental slope toward Gibraltar, with small annual variability. Kinder's [1984] current meter data taken in the northern Alboran showed slow (~1 cm/s) southwesterly flow at 500 m and very sluggish easterly flow at greater depth. Current meter and free-floating vertical current meter data obtained in 1980 [Pistek, 1984] also indicated the slow flow in the center of the Alboran Sea with a westerly direction for the intermediate water and a changeable direction for the deep water, and an enhanced and accelerated flow along the Moroccan continental slope toward Gibraltar. Relative contributions of Levantine and Deep Western Mediterranean waters to the outflow of Mediterranean water through the Strait of Gibraltar are important parameters for Mediterranean circulation.

In the Alboran Sea the proportions of the different water masses in this outflow are established. Hence the knowledge of the deep flow pattern, its time variability, and eventual coupling with the upper layer is important for understanding the mixing and its dynamics. The purpose of the present work was to investigate the general pattern of deep circulation by tracking the swallow-type floats and simultaneously observing the upper-layer variability.

Experimental Procedure

Acoustically tracked free floats (swallow type) were used to determine the circulation pattern [Pistek et al., 1984]. Six current meter moorings were also deployed (with two current meters per mooring), and conductivity, temperature, and depth (CTD) data were collected. Acoustic tracking was done from three moored listening stations; their design is described by Bradly and Tillier [1980]. This work considers only the Lagrangian measurements.

The floats' electronics were housed in glass spheres with cylindrical transducers hanging beneath. They were furnished with pressure transducers and some of them with an electro-

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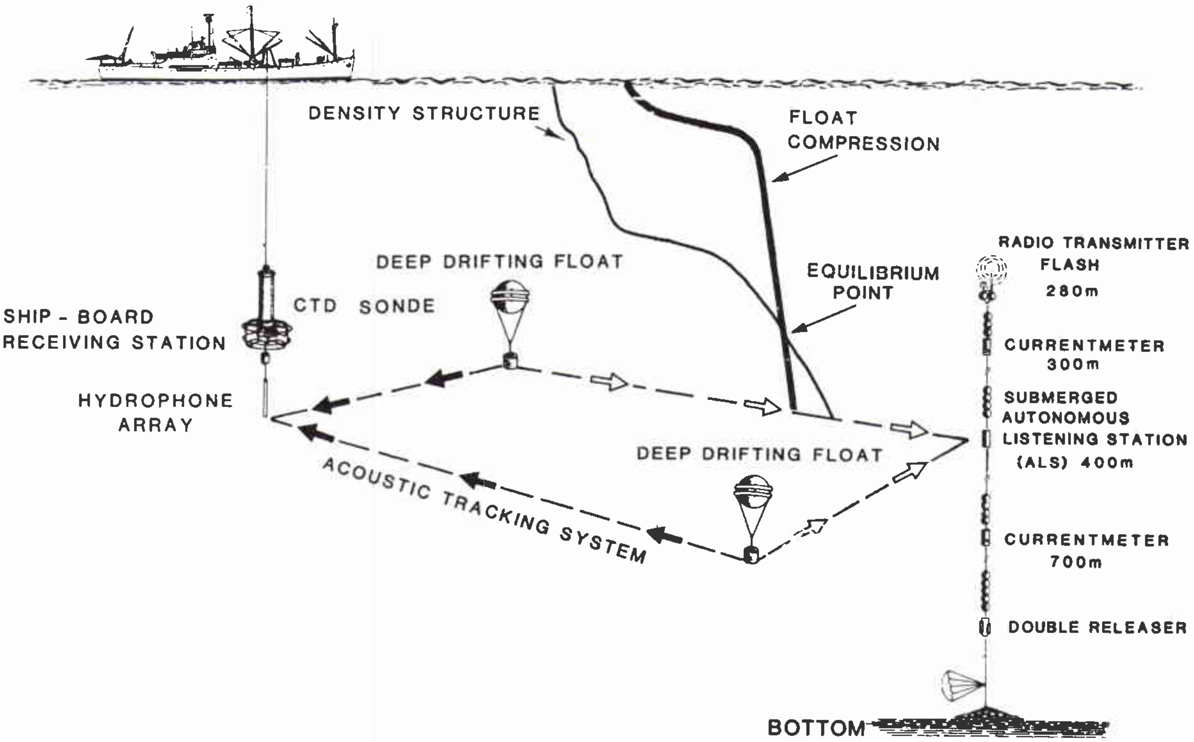

Fig. 1. Schematic diagram of the deployment of equipment and the tracking of floats from listening stations. Density structure and compression of floats establish the deployment depth.

magnetic releaser that could be acoustically activated from the ship by a 10-kHz signal. Each float transmitted at 2-hour intervals, the signal lasting 20 s in a frequency sweep from 1562.5 to 1572.07 Hz. During the first four successive transmissions (8 hours), information about depth was transmitted as a repetitive signal, with the delay of the second signal being proportional to the depth. Tracking was done automatically from three moored acoustic listening stations positioned at 400-m depth. Each station was composed of a vertical array of four hydrophones, together with an amplifier, microprocessor, and recorder. The station sampled the acoustic environment every 25 ms and cross correlated the received signal with the standard signal stored in the memory of its microprocessor. The four highest cross correlations in each 4-min interval were stored, together with corresponding times, on magnetic tape.

All floats and listening stations were synchronized. Transmissions from different floats were separated by 10-min intervals. As the delay in arrival time was proportional to the distance of the float from the station, triangulation from three stations established the position of the float every 2 hours.

One additional listening station was located on the ship. An acoustic array and amplifier were mounted on a Grundy temperature, depth, salinity, and sound velocity (TDSsV) system whose sound velocity channel was used to transmit acoustic measurements. Both TDS measurements and acoustic listening were performed with this arrangement. In the later measurements the TDS system was replaced by a Neil Brown CTD Mk III system. The station was equipped with a printer instead of a magnetic-tape recorder, and every 4 min it printed and plotted the four highest correlations and time. After the measurements were finished, the floats were located from the ship with the help of this shipborne receiver and were acoustically released to the surface; a radio transmitter and a flash mounted on each float helped to locate them on the sea surface. The tracking procedure is shown in Figure 1.

Measurements and Data Treatment

Nine floats were released in two periods from the end of January to the beginning of May 1982 (3 months). The positions and periods of deployment of the floats are given in Figure 2. Deployment positions for the first set of floats (1, 2, 4, 5, 9) were selected on the basis of 1980 measurements [Pistek, 1984]. Current speed, assumption of westward drift, and the deployment period of the floats established the spatial scale. Positions for deploying the second set of floats (3, 6, 7, 8) 1½ months later were selected after the rather unexpected motion of the first set, to check the steadiness of flow and to see more details in the central Alboran and along the Moroccan continental slope. The positions of listening stations A, B, C were based on acoustic considerations. There were three periods of CTD measurements, as indicated in the same figure.

Every 2 hours the floats transmitted and their positions were identified. Precision of float positioning depends on the precise localization

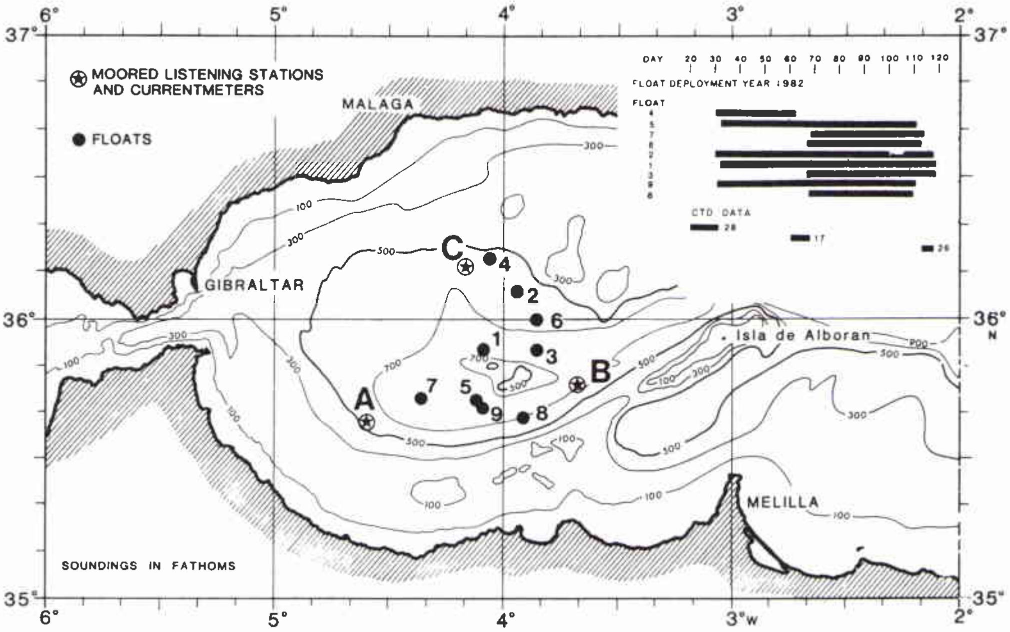

Fig. 2. Deployment positions and time schedule for floats and CTD data. Days are the Julian days. Deployment position for the subsurface moored listening stations A, B, C with hydrophone array at 400 m.

of the three listening stations, the precision of synchronization, the drift of the clocks in the floats and stations, multipath propagation of the sound (possibly reflections), and the sharpness of cross correlation. The positions of the listening stations were established by radar and satellite navigation within an error of less than 1 km, which establishes the error in absolute positioning of the float tracks. Before deployment, each instrument was synchronized aboard ship in the Alboran Sea to within 1 ms by 5-MHz radio signals from the Istituto Elettrotecnico Nazionale Galileo Ferraris in Torino, Italy. The drift of the oscillators (except one in the listening station) was much smaller than specified by the company ($<5 \times 10^{-7}$Hz/Hz/yr) and was taken into account in the computation of distance. The random variation of the oscillator was less than 2 ms/h. The frequency bandwidth allowed the arrival time to be established to an accuracy of 0.1 s.

Influences of multipath propagation and reflection were sometimes visible as a broadening of the cross correlation. They are hard to evaluate because the bottom topography in the Alboran Basin is very variable. The average

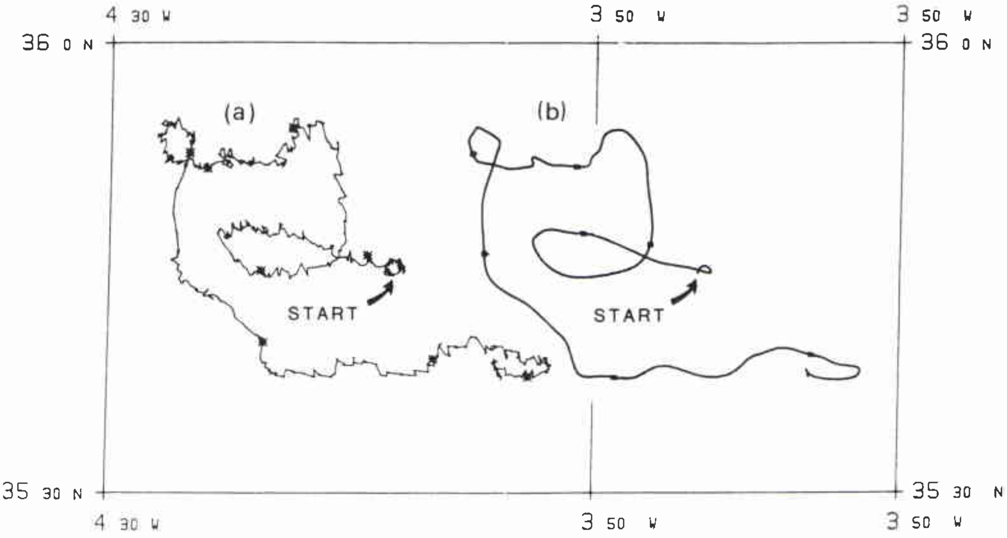

Fig. 3. Example of float track (float 5). (a) From raw 2-hourly data. Tides and inertial oscillations are visible but not well resolved. (b) After filtration.

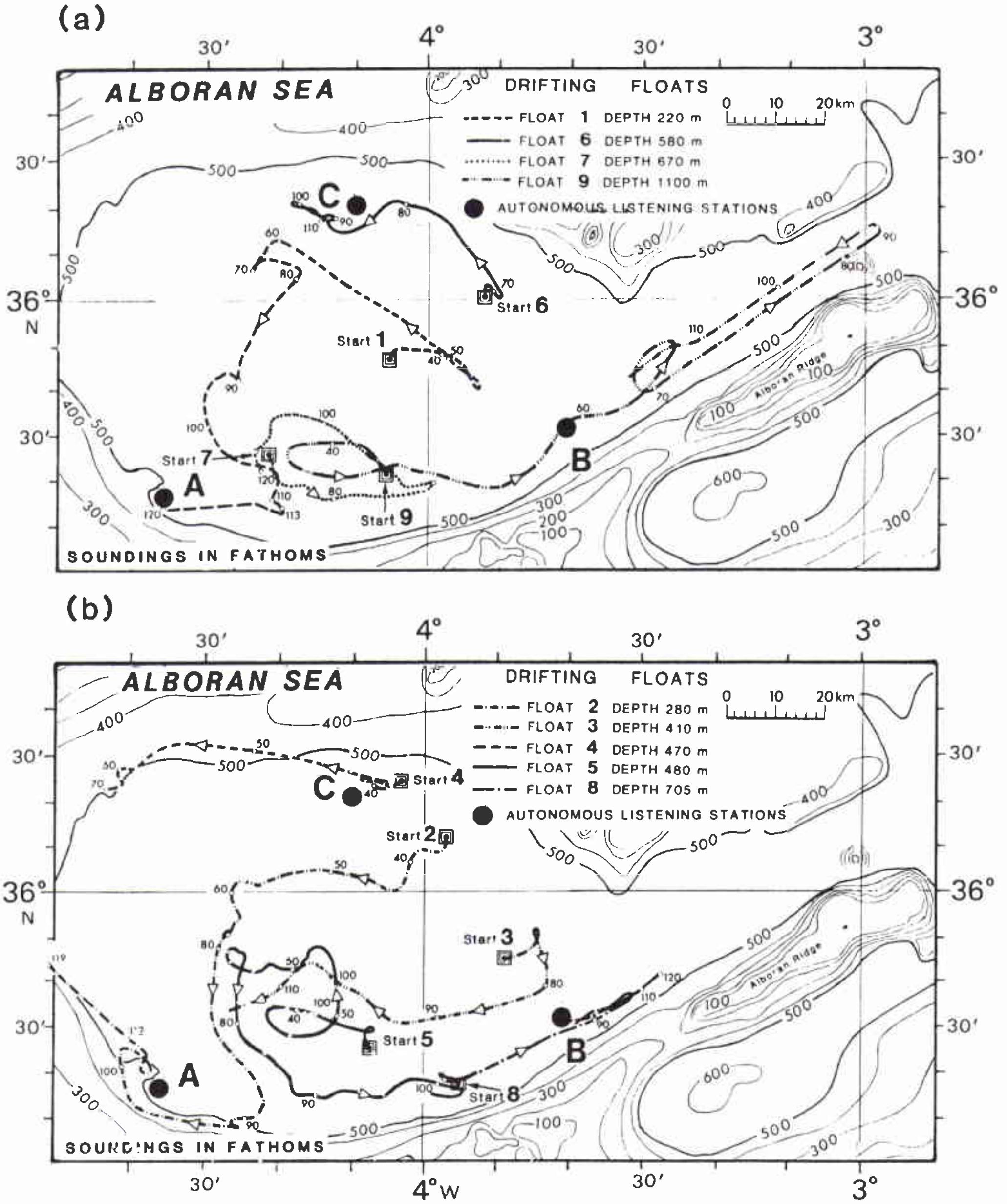

Fig. 4. Tracks of floats deployed in three months. (a) Floats 1, 6, 7, and 9 and (b) floats 2, 3, 4, 5, 8. "Start" indicates the starting point, and numbers near the tracks are Julian days. When float 9 moved east of B (days 75 to 109) it was shadowed from A and C and was tracked only by B. Float 6 at day 92 had a power loss in transmitted signal, later was retrieved from near bottom after water had penetrated into the releaser. Positions at day 119 for float 2 and at day 120 for floats 1 and 8 were established from shipboard receiver, because autonomous listening stations at A, B, and C were already retrieved.

propagation path was about 60 km long, and the triangulation was mostly good, with a final precision of about 250 m.

The float-position data (one point every 2 hours) were recomputed into average 2-hourly velocities. Groves's [1955] filter was used to remove tidal effects selectively and as a low-pass filter; only the variations of periodicity greater than 1½ days were preserved after filtration. Examples of a float's path plotted from raw data and from the data after filtration are given in Figure 3. Tides and inertial oscillations are visible, but positioning is not good enough to resolve them well.

CTD data were ordered progressively with depth (no return loop permitted) and averaged to 1-m values.

Results

Figure 4 presents the tracks of the floats. Between 220 and 1100-m depth, all floats show the broad cyclonic circulation during the whole

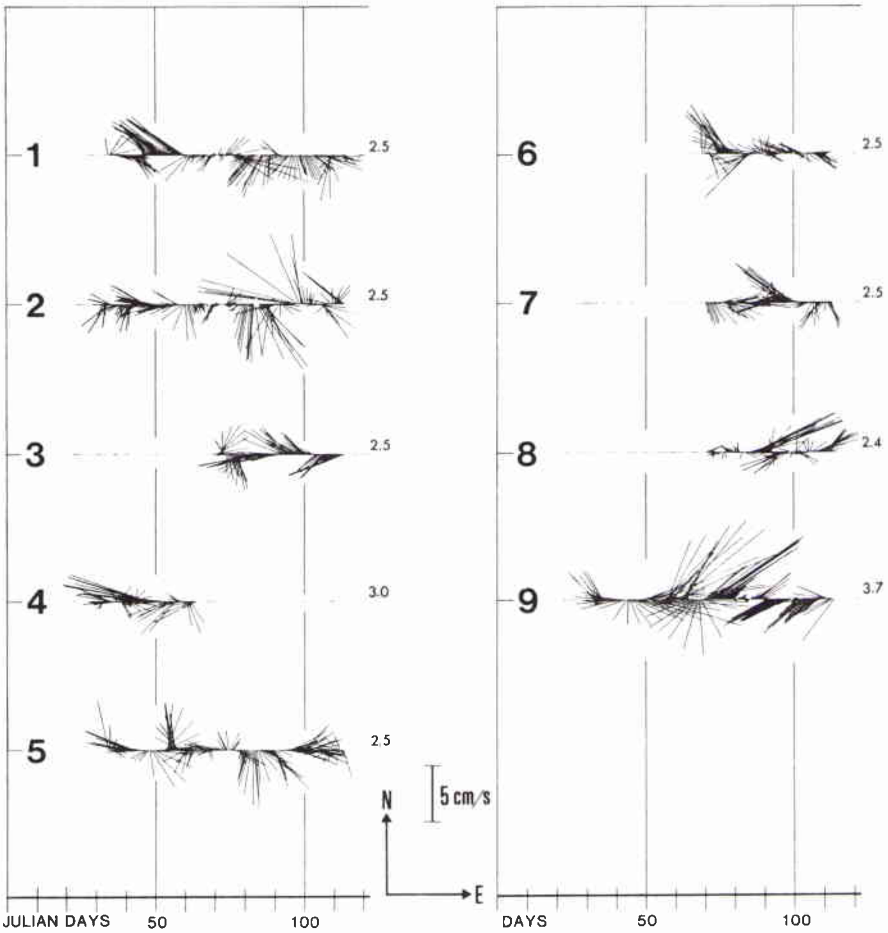

Fig. 5. Time series of velocity vectors for all floats. Number signifies the float number, days are Julian days, number on the right signifies the average velocity amplitude in centimeters per second.

period of their deployment. The motion is slow, with an average speed of approximately 2.5 cm/s. There is an interesting situation along the southern boundary. Floats 1 and 2 after reaching the sloping topography in the south started to move west along the Moroccan continental slope toward Gibraltar. Between days 112 and 119, float 2 moved with an average speed of about 5 cm/s (positions of floats after day 114 were established by the shipborne station). When floats 5 and 8 reached the boundary near 35.6 N 4.0 W, they stagnated for many days, and float 9, and finally also float 8, moved along the southern sloping bottom in the opposite direction, toward Alboran Island. Float 9 was in an acoustic shadow from day 75 to 110 and was audible only from mooring B. Being deep (1100 m), it moved in the channel, passed the Alboran Island, and returned back along the northern slope of the channel. Float 4, moving in the northern part, was retrieved, and it is not clear if it would have moved to Gibraltar or turned south. Figure 5 shows the time series of velocity vectors for the floats. These are the synchronized, decimated versions of filtered velocity data sampled every 12 hours. Variability in amplitude and phase is large, with an average velocity amplitude of from 2.4 to 3.7 cm/s.

Satellite data show considerable variation in the structure of the sea-surface temperature during the period of the experiment, but they indicate the presence of an anticyclonic gyre in the south. Figure 6 shows a few examples from that period. The darker shades in the images represent warmer water; however, the temperature variation for this period was only about 1°C (12.8° to 13.7°C). The images indicate considerable variations in the extension of the gyre, it being larger in January and smaller and fragmented in February and March.

CTD measurements were performed in three periods. Data sets are small, but contours of dynamic height anomaly for January and April (Figure 7) show an anticyclonic circulation in the surface layer. The geostrophic current computed from the CTD cross section on March 8 (Figure 8) also shows anticyclonic circulation. The January and March CTD measurements reveal the well-developed gyre shown by the sea-surface temperature data of Figure 6; however the March data indicate a stronger anticyclonic circulation of smaller extent.

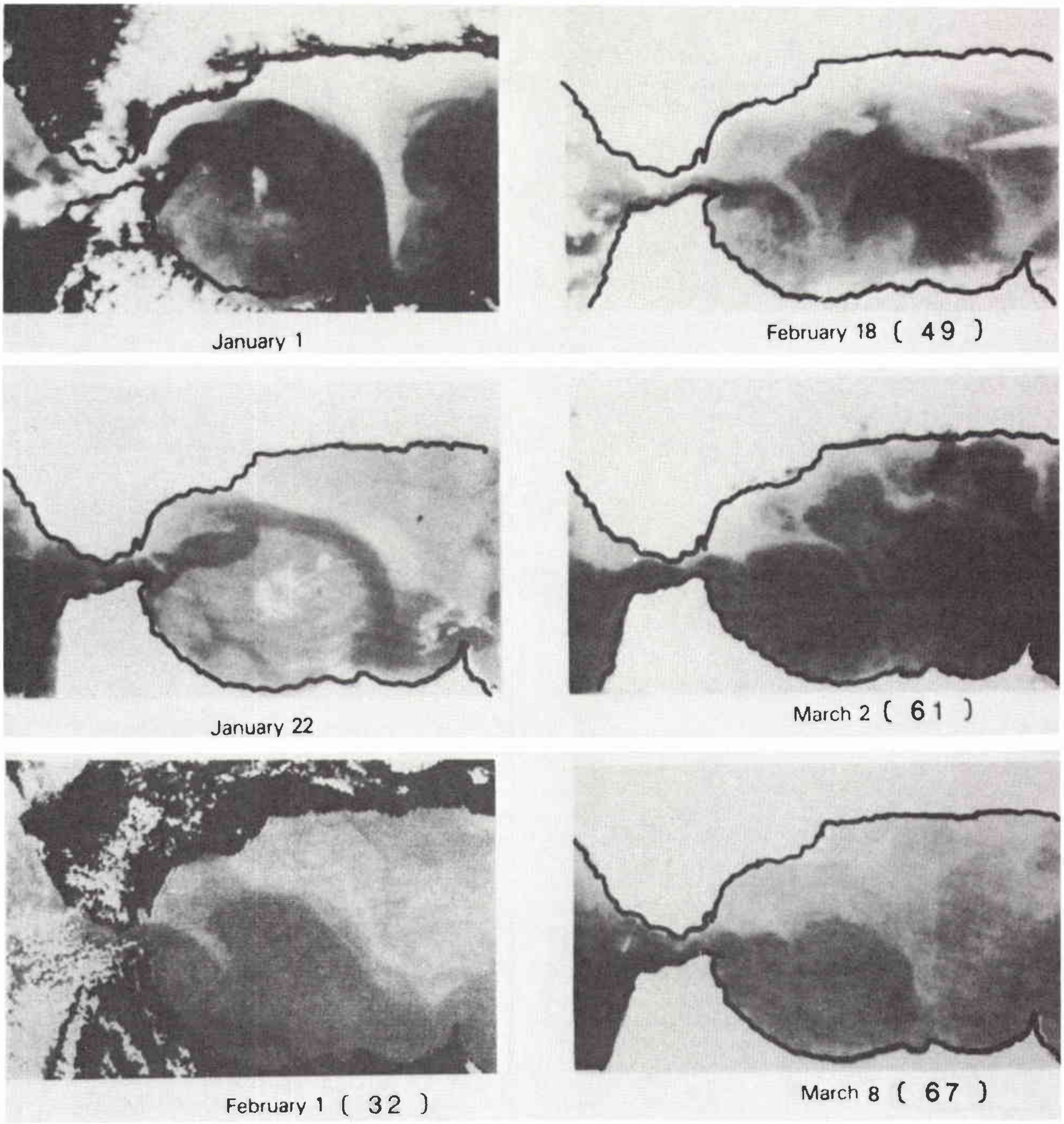

Fig. 6. Satellite-measured data of sea surface temperature, NOAA 7. Considerable variability is visible but agreement with CTD is good (from La Violette, NORDA).

Conclusions

Between depths of 220 and 1100 m, weak coherent cyclonic motion with the center of the vortex at about 35.75°N, 4.25°W persisted in the Alboran Sea during the period of measurements (3 months). Circulation was not steady, periods of stagnation being followed by faster motion averaging between 2.4 and 3.7 cm/s. The sloping bottom topography of the southern Alboran Basin marked the southern boundary of the floats' motion, even though the topography was much deeper than the depth of some of the floats. When the floats reached this boundary west of 4.0°W, floats 1 and 2 moved toward Gibraltar, with an average speed, for float 2 between Julian days 112 and 119, of about 5 cm/s. This is in agreement with previous data of Bryden and Stommel [1982] and Pistek [1984].

Floats reaching the boundary east of 4.0°W moved in the direction toward Alboran Island, but not persistently. In agreement with Pistek [1984], flow in the central Alboran was slow. Floats deployed in the middle section of the Alboran moved cyclonically and did not cross into the area west of 4.5°W, indicating the main path of Levantine and Deep Western Mediterranean waters. Float 9, deployed at a depth of 1100 m, indicates that the flow of the Deep Western Mediterranean water into the Alboran is along the northern slope of the deep Alboran channel. Kinder's [1984] data from current meters positioned in the western Alboran north of 36°W

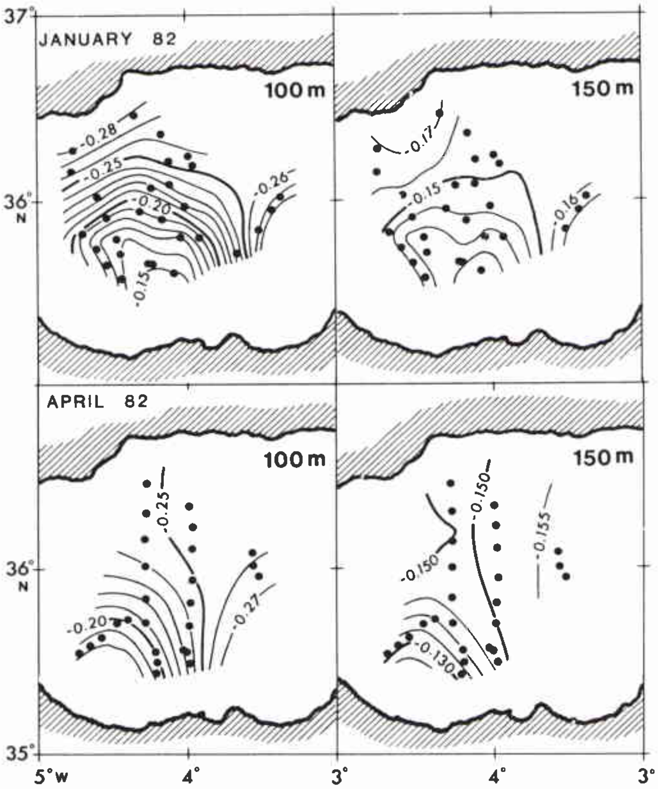

Fig. 7. Contours of dynamic height anomaly in dynamic meters for the depths of 100 and 150 m (relative to 200 m) from January and April 1982. They show broad anticyclonic circulation. Dots signify the positions of CTD casts.

latitude show the flow at 500 m to the west. Floats 4 and 6 deployed near the Spanish continental slope show that there is a partial flow of Levantine and Deep Western Mediterranean waters along the Spanish continental slope toward Gibraltar, but there was no indication in the northwestern Alboran, either in CTD's or float motions, of the steady flow displayed along the western Moroccan continental slope. Float 4, for instance, deployed for 32 days at a depth of 470 m, stagnated in the northwestern Alboran for more than 10 days.

The deep potential temperature and salinity structures in the Alboran Sea exhibit very sharp slopes in the isotherms colder than 12.9°C and in the isohalines below the salinity maximum against the Moroccan continental slope. This feature was first observed by Bryden and Stommel [1982] and later found by many investigators. This upwelling is important for the mixing of Levantine and Deep Western Mediterranean waters and, in connection with the enhanced flow along the slope toward Gibraltar, as described above, would indicate the path of unmixed flow of Deep Western Mediterranean water out of the Mediterranean to the Atlantic. Deep extension of surface circulation was assumed to be a source of forcing for the described features. Some satellite and CTD observations were made during the experiment to indicate the upper-layer structure.

Satellite infrared images taken during the experiment show the existence of the upper-layer anticyclonic gyre in the south. January images and CTD data show the large and well-developed gyre, but February and March images and March CTD data show the smaller gyre with the eastern boundary around 4.5°W. Likewise April CTD data show the smaller extent of anticyclonic circulation.

Whitehead and Miller's [1979] laboratory simulation of the Alboran circulation shows a large

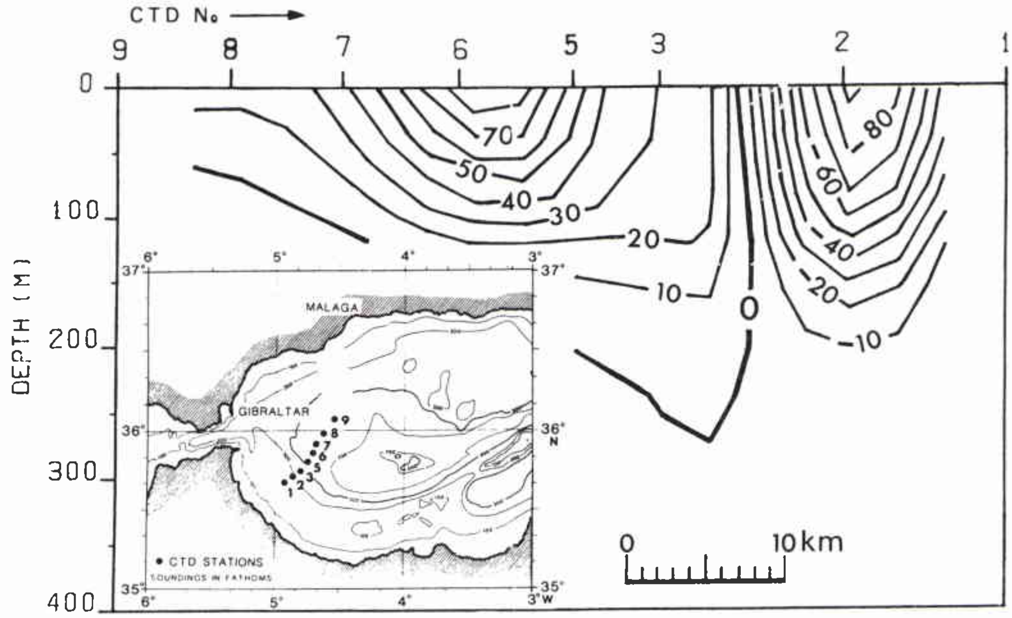

Fig. 8. Cross section of computed geostrophic current in cm/s from March 8, 1982. CTD stations are indicated in the map. Level of no motion at 200 m.

anticyclonic gyre with its stagnation point north of Cape Tres Forcas (~3°W). Also Bryden and Stommel [1982] assumed the existence of the deep and extended anticyclonic gyre in the explanation of westward flow along the western Moroccan continental slope and upwelling of Deep Western Mediterranean water across it.

Our measurements do not show the existence of deep and extended anticyclonic circulation. They indicate the rather shallow (200 m) depth of the large anticyclonic gyre. Nevertheless the existence of a deep-reaching, transient and energetic anticyclonic vortex of smaller extent (west of 4.5°W), as indicated for example by satellite image and corresponding cross section of geostrophic current from March 8, 1982, is not excluded.

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