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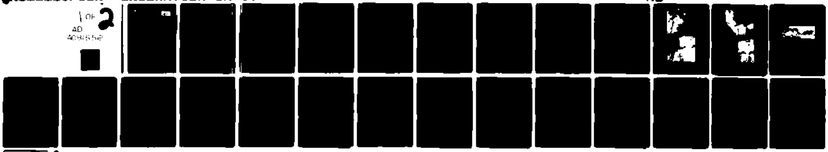

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SACLANT ASW RESEARCH CENTRE REPORT

THE ALBORAN SEA GYRE: SHIP, SATELLITE AND HISTORICAL DATA

by

BRIAN WANNAMAKER

15 JUNE 1979

NORTH
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THE ALBORAN SEA GYRE: SHIP, SATELLITE AND HISTORICAL DATA

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15 June 1979

This report has been prepared as part of Projects 01 and 04.

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B.W. LYTHALL
Director

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TABLE OF CONTENTS

List of Figures

THE ALBORAN SEA GYRE: SHIP, SATELLITE AND HISTORICAL DATA

by

Brian Wannamaker

ABSTRACT

The Alboran Sea is a strategically important but oceanographically complex region. Images from the NOAA 5 satellite and data from XBT sections, CTD stations and near surface temperature measurements are combined with historical data to describe the gyre existing between the Strait of Gibraltar and 3°W. The gyre is outlined by a thermal front between inflowing Atlantic and upwelled Mediterranean water. Although the gyre appears to be a permanent feature, the location and strength of the front will vary. The data imply that for environmental and acoustic prediction the Alboran Sea should be split into smaller regions with active boundaries updated from satellite data.

INTRODUCTION

One of the strategically important areas for NATO ASW efforts is the Strait of Gibraltar and the adjoining Alboran Sea. It represents the major entrance into the Mediterranean from the open ocean. Unfortunately the area is also oceanographically complex, with adverse effects upon sonar performance. The reason for the complexity is the presence of both Mediterranean and Atlantic water masses with their inherent differences.

The Mediterranean has an overall higher salinity than the Atlantic. The water flowing into the Atlantic has a salt content of 38.4‰, and is composed of about 95% Deep Mediterranean Water and 5% Mediterranean Intermediate Water *[1]*. The Atlantic surface water in the Gulf of Cadiz is close to 36‰. The corresponding density difference between the two water masses results in a two-layer flow in the Straits, the less dense Atlantic water flowing into the Mediterranean at the surface. This replaces the volume of water lost by the outward flow and by the excess of evaporation over precipitation in the Mediterranean Basin. The density-driven Mediterranean water flows outward between about 150 m and the top of the sill at 280 m and settles to about 1200 m in the ocean before reaching an equilibrium depth. The net inward flow of the surface layer averages about 1 knot (0.51 m/s). The tidal flow can be 4 to 5 kn. With an easterly wind, only the top 10 to 15 m of the surface layer is slowed *[2]*. The tidal components of the flow induce large scale internal waves which may greatly weaken the thermocline in the region *[3,4]*

This two-layer structure continues eastwards into the Alboran Sea. Atlantic water enters as a jet (≈90 cm/s) initially moving north-easterly along the line of the axis of the Strait. It then turns southwards between 3°30'W and 4°W and crosses the sea to the south shore, where it bifurcates. One stream flows westwards along the coast and circles into the incoming water forming a large anticyclonic eddy. The second stream, initially moving easterly along the Algerian coast turns northwards again east of Alboran Island and outlines a number of other gyres. This area has been the subject of a number of oceanographic and acoustic reports *[1,5-11]*.

The upsurge of interest in recent years is the result of the new possibilities of data coverage offered by satellite-based remote sensing. This report discusses satellite data in conjunction with oceanographic data collected from the SACLANTCEN research vessel MARIA PAOLINA G. in June 1977 and 1978 and with historical data contained in the SACLANTCEN oceanographic data base.

1 THE CRUISES

From 0800 GMT, 23 June to 1000 GMT, 24 June, 1977 the MARIA PAOLINA G. followed the track across the Alboran Sea shown in Fig. 1. Along this course, water temperature at a nominal depth of 4 m was measured continuously by a thermistor mounted on a rigid rod lowered through a well in the forward cargo hold. The thermistor was about 1 m below the hull. XBTs were launched every 15 min along the track while the ship maintained a speed of 10 kn (18.5 km/h). This resulted in a temperature profile roughly every 2.5 n.mi (4.6 km). BTs that malfunctioned were immediately repeated while the ship continued on course. Conductivity/temperature/depth (CTD) stations (1-4) were occupied at four positions along the ship's track. The ship was allowed to drift during the data acquisition. The Neil Brown CTD sampled every 1 to 2 cm at a lowering speed of 25 to 50 cm/s. During this cruise, the data from every second set of 40 depth values were recorded. Another station, number 8, was completed eight days later near the position of station 4. One year later a survey was made through the area with continuous near-surface temperature measurements (Fig. 1).*

**These cruises were part of more extensive studies of the Gulf of Cadiz on the Atlantic side of the Strait. This work will be reported upon later.*

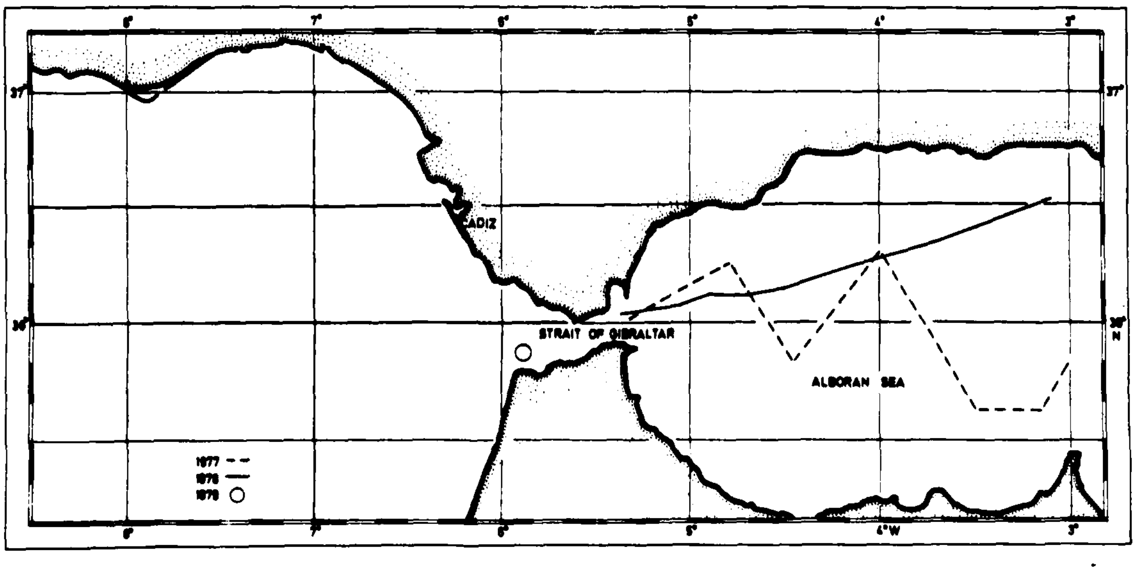


FIG. 1 TRACK OF THE MARIA PAOLINA G. IN THE ALBORAN SEA DURING 1977 (dashed line) AND 1978 (solid line)

2 DATA

Figures 2 and 3 are the NOAA 5 images of the Gibraltar area for 21 and 22 June 1977. The NOAA 5 satellite maintains a circular, near-polar, sun-synchronous orbit at a height of 1450 km. The Very High Resolution Radiometer (VHRR) scans the earth in the visible (0.6 to 0.7 microns) and thermal infrared (10.5 to 12.5 microns) portions of the electromagneti spectrum with a ground resolution of 1 km immediately below the space-craft. Data are transmitted continuously to all stations within its line of sight. The images shown in this report were received and enhanced at the University of Dundee, Scotland.

The visible image for 21 June (Fig. 2a), produced at about 1000 GMT, shows the effect of sun glint in the Alboran Sea. Along the south shore there is specular solar reflection, saturating the instrument. In a large zone around this the image has a light gray tone in the sea areas, from solar reflections filling only a portion of the instantaneous field of the instrument, i.e. reflections off the "random" sea surface. Further west, away from the specular reflection, the sea is black. Sun glint, except perhaps in the region of specular reflection, should have no effect on the infrared channel. Figure 3(a), the visible image of the next day, was taken about 50 min earlier in the day and shows no sign of sun glint. Both visible images show the Alboran Sea to be virtually cloud free.

In the infrared images (Figs. 2b and 3b) the emission temperature increases with the darkness of the grey shade and the image is enhanced for sea-surface features. Thus the cloud tops are over-saturated (white) and the warm land areas, unenhanced or black. On both days, the infrared images reveal a wide band of cooler water along the northern shore of the Alboran Sea. In the second image it can be seen that this extends southward to the south shore in a broad band. This is cold Mediterranean water that upwells and is entrained in and mixes with the jet of Atlantic surface water entering through the Strait.

Because of the high attenuation of infrared wavelengths in water the VHRR senses the temperature of only the top one or two millimetres of the surface layer. The long-wave radiation and evaporation from the surface may make this layer about 0.5°C cooler than water immediately below *[12]*. The temperature measured by bucket thermometer is representative of a value at 10 to 15 cm depth and thus may be higher than the radiation temperature at the surface. The correlation with deeper temperatures depends on local oceanographic conditions.

In July 1977 a Marisonde (a satellite tracked drifting spar-buoy) was released near Gibraltar by the Centre National pour l'Exploitation des Océans (CNEXO). This drifted eastward and made a loop in the western Alboran about 100 km in diameter at the expected location of the gyre. It then crossed the sea from north to south again further to the east than before and moved to the east near the Moroccan coast. It completed

FIG. 2 NOAA 5 IMAGES RECEIVED BY THE UNIVERSITY OF DUNDEE OF THE GIBRALTAR AREA 21 JUNE 1977
a) visible b) infrared

FIG. 3 NOAA 5 IMAGES RECEIVED BY THE UNIVERSITY OF DUNDEE OF THE GIBRALTAR AREA 22 JUNE 1977

a) visible b) infrared

the loop in 7.5 days at an average speed about 50 cm/s. At this velocity the centrifugal acceleration is an order of magnitude smaller than the Coriolis acceleration.

Figure 4 shows the NOAA 5 infrared image of the area for 25 June, 1978, one year later than the earlier images. Also shown are the ship track of the MPG and the temperature record at 4 m depth. The front between the warm and cold water of the gyre appears further south (about 10 n.mi or 19 km) than in 1977. The ship data illustrates that the difference between the grey shades at A and below B on the image was about 1°C at 4 m. The warm-cool-warm sequence from 1900 to 2100 GMT, with temperature changes of about 0.5°C, is evident on the image as a patch of lighter grey and a dark filament representing the warmer water extending across the ship track from the north.

FIG. 4a NOAA 5 INFRARED IMAGE OF 25 JUNE 1978

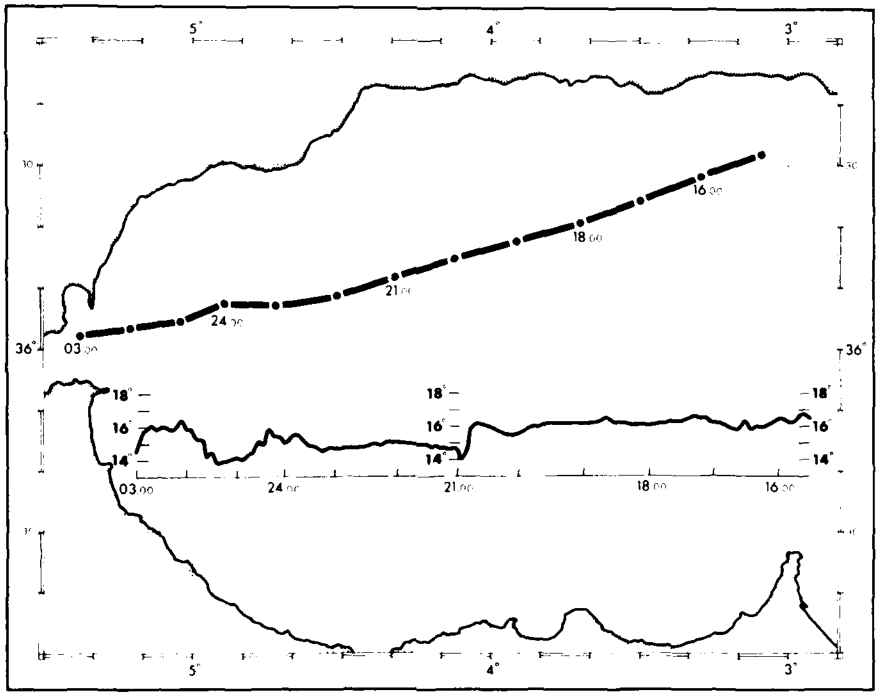


FIG. 4b TRACK OF THE MPG JUNE 1978 AND NEAR SURFACE (4m) TEMPERATURE MEASUREMENTS

3 SHIP DATA

3.1 XBT Sections and Near Surface Temperature (NST)

The XBT sections and NST plot from the 1977 data are shown in Fig. 5 a,b,c. Also shown is a schematic enlargement of a section of the infrared image for 21 June overlain by the ship's track. The track is not exactly mapped because of the distortion inherent in imaging the curved surface of the earth. A first-order linearization has been done to the image during the processing at the U. of Dundee. The BT sections were completed in 30 hours while the satellite image was completed in 10 min.

In the XBT section from A to B to C the detectable activity in the water column was confined to above the 14° isotherm at 100 m depth. The depth of the surface mixed layer varied from 15 to 40 m. The thermocline was convoluted, showing signs of the existence of subsurface fronts and lenses of different water types.

Over the 47 n.mi (87 km) from C to D the 14° isotherm rose slowly to a minimum of 44 m. The 16 to 17° isotherms rose much more quickly (0.1 to 0.2° slope with respect to the horizontal) and the surface mixed layer disappeared. Comparison with the infrared image implies that the rise and fall in the near-surface temperature and dipping of isotherms near D were related to the ingress of warmer water from the northeast.

As the ship moved southwesterly from D to E into the gyre, the surface temperature rose 3° in 13 n.mi (24 km) and then stabilized at about 17.5°C.

At 50 m the temperature decrease was 4.5°C. The encircling of warm water by the anticlockwise flow along the front, which is evident in the satellite image, is not evident in the profiles except as a curling of isotherms between 40 and 80 m. The lack of surface correlation can be related to the time delay of 36 h between the image and profiles. It was an active feature, only beginning to be in evidence in the image of 21 June (Fig. 2b). Unfortunately, scattered cloud after this date made it impossible to determine whether the surface effect of this had disappeared.

From E to F the isotherms rose on average along a slope of 0.2°. In the enlargement of the infrared (IR) image it is apparent that the front was encountered at a 45° angle along this track and the average slope may be estimated as 0.3°. Thus, if the front evident in the infrared images represents the intersection of the thermocline with the surface, then one could expect the thermocline to be at a depth of 100 m about 20 km south of the front. Gradients over short distances exceeded this value, the 15° isotherm rising over 30 m between the two BT casts 67 and 68 (0.5° slope).

On the last leg of the section the thermocline extended to the surface.

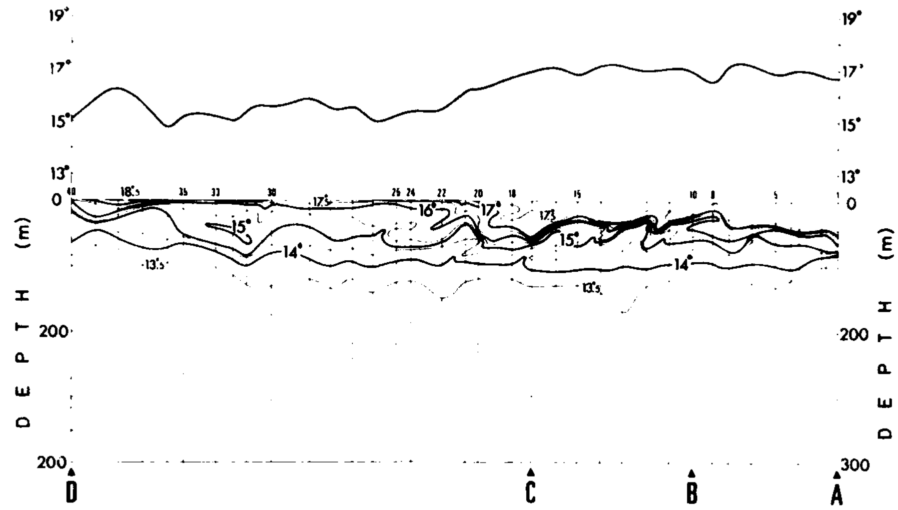


FIG. 5a XBT SECTIONS THROUGH THE ALBORAN SEA JUNE 1977

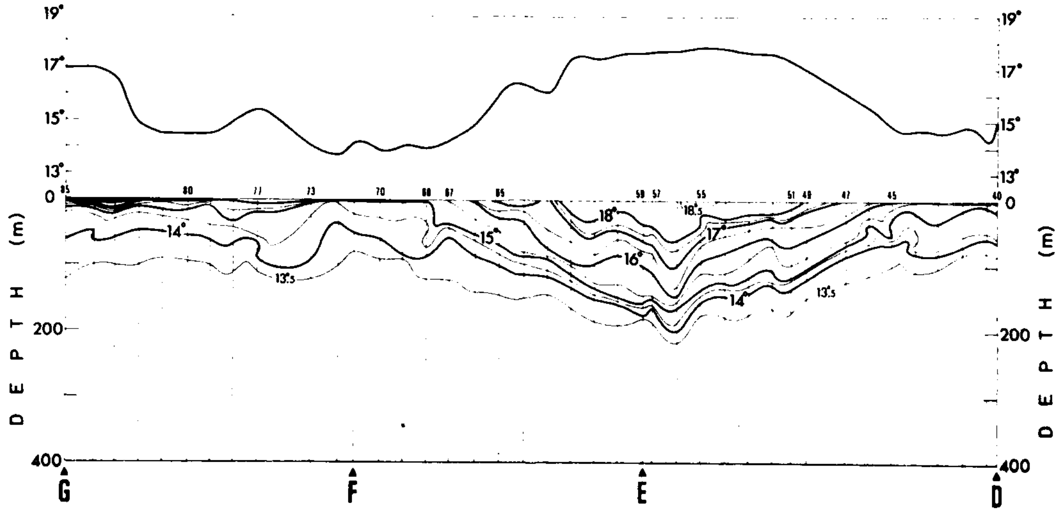


FIG. 5b XBT SECTIONS THROUGH THE ALBORAN SEA JUNE 1977

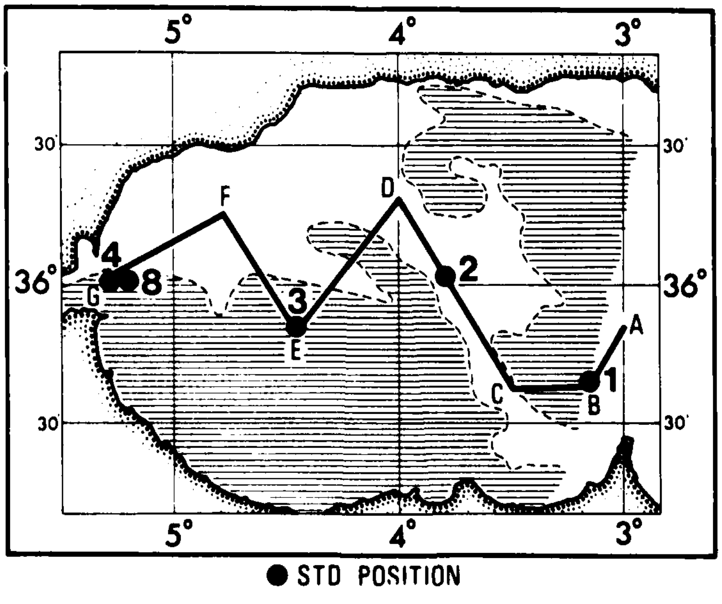


FIG. 5c LOCATIONS OF THE XBT SECTIONS AND CTD STATIONS (numbered)

The near-surface temperature in the upwelled Mediterranean water was about 14.5°C, rising quickly to 17°C as the Atlantic water was encountered near the eastern end of the Strait.

3.2 CTD Stations

Temperature, salinity and σ_θ determined at the CTD stations are shown in Figs. 6-8. Station 3, (Fig. 5c) in the gyre according to the historical data (Fig. 10) and satellite images, stands out quite clearly from the rest. Below 60 m depth the other stations are relatively similar, all showing a shallow (40 m) or non-existent mixed layer and a progression to a temperature of 13.2°, a salinity of 38.4‰ and a σ_θ of about 29. These are all in the region of mixing of the Atlantic and Mediterranean surface water. The Mediterranean surface water moves southward along the eastern Spanish coast. This water is characterized by a salinity of 37.6 ±0.34‰ in the top 75 m (from 25 historical casts in the Iberian Sea designated a domain in the SACLANTCEN data base).

Station 1 is the most easterly station and the upper layers of water have probably had the longest resident time near the surface in the area. The salinity profile was very similar to that at stations 2 or 8 but the heat content is much higher, the upper 50 m being 1-2°C warmer than at 2. The position of the station was east of the band of cooler water visible in the infrared image. The temperature inversion at 45 m was due to the intrusion of a lens of water immediately below this, about 10 m deep, 0.6° warmer and 0.2‰ saltier than a smoothed profile. This was a stable system however, the potential density increasing through this depth range at 1.9 x 10^{-2} σ_θ units/m. This illustrates a possible interpretation problem with only XBT data in the area. On the BT section, Fig. 5a, the 16° isotherm has been shown as a single folded surface through casts 8 and 10. The CTD station at the position of XBT cast 10 however indicated than the 16° water of the inversion at 45 m has a lower salinity than the 16° water at 60 m. Hence the inversion was due to a different water type and the 16° isotherm should be drawn as a closed loop indicating a lens of water of specific characteristics.

Station 2 appears from Fig. 5c to have been inside the cooler water. The water was cooler and denser than at station 1 above about 60 m. Around this depth there is a sudden transition (frontal region) to warmer, saltier water. As at station 1, the density increased monotonically downward and the water column was stable.

From the NOAA 5 image, station 3 was within the gyre. The temperature was 1 to 2°C warmer than at the other stations above 150 m and is 3°C warmer that at station 4 at 100 m. The salinity and density were lower at corresponding depths by up to 2.5‰ and 2.5 σ_θ units. The temperature profile showed a three layer structure with gradually decreasing temperatures separated by thermoclines (0.12 and 0.07°C/m). When the Mediterranean water proper was reached below 200 m the temperature become isothermal at 13.15°C within 0.025°. The modified Atlantic water of the upper two layers showed the effect of strong solar heating and evaporation;

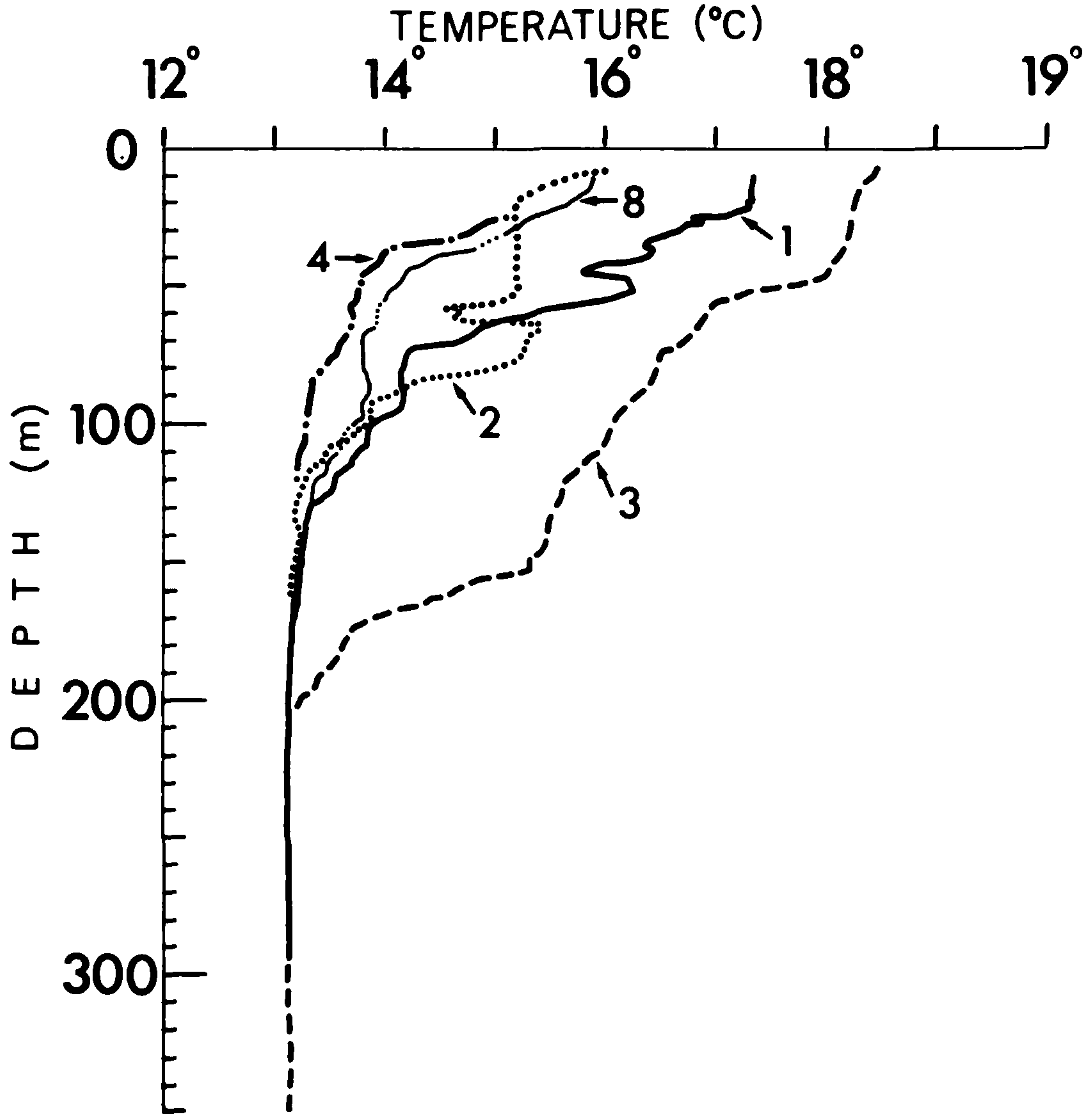


FIG. 6 TEMPERATURE PROFILES MEASURED AT THE CTD STATIONS OF FIG 5c

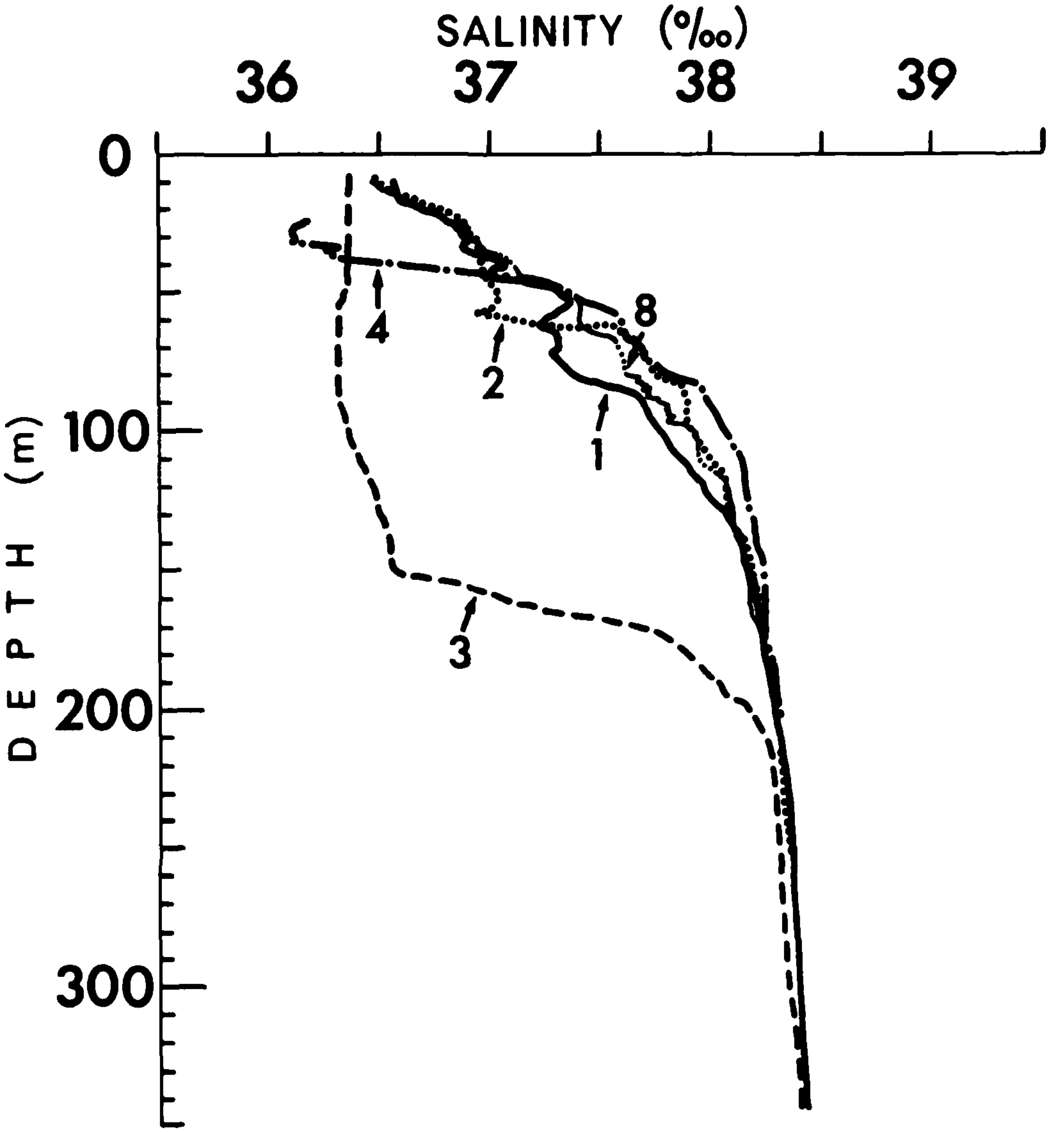


FIG. 7 SALINITY PROFILES MEASURED AT THE CTD STATIONS OF FIG. 5c

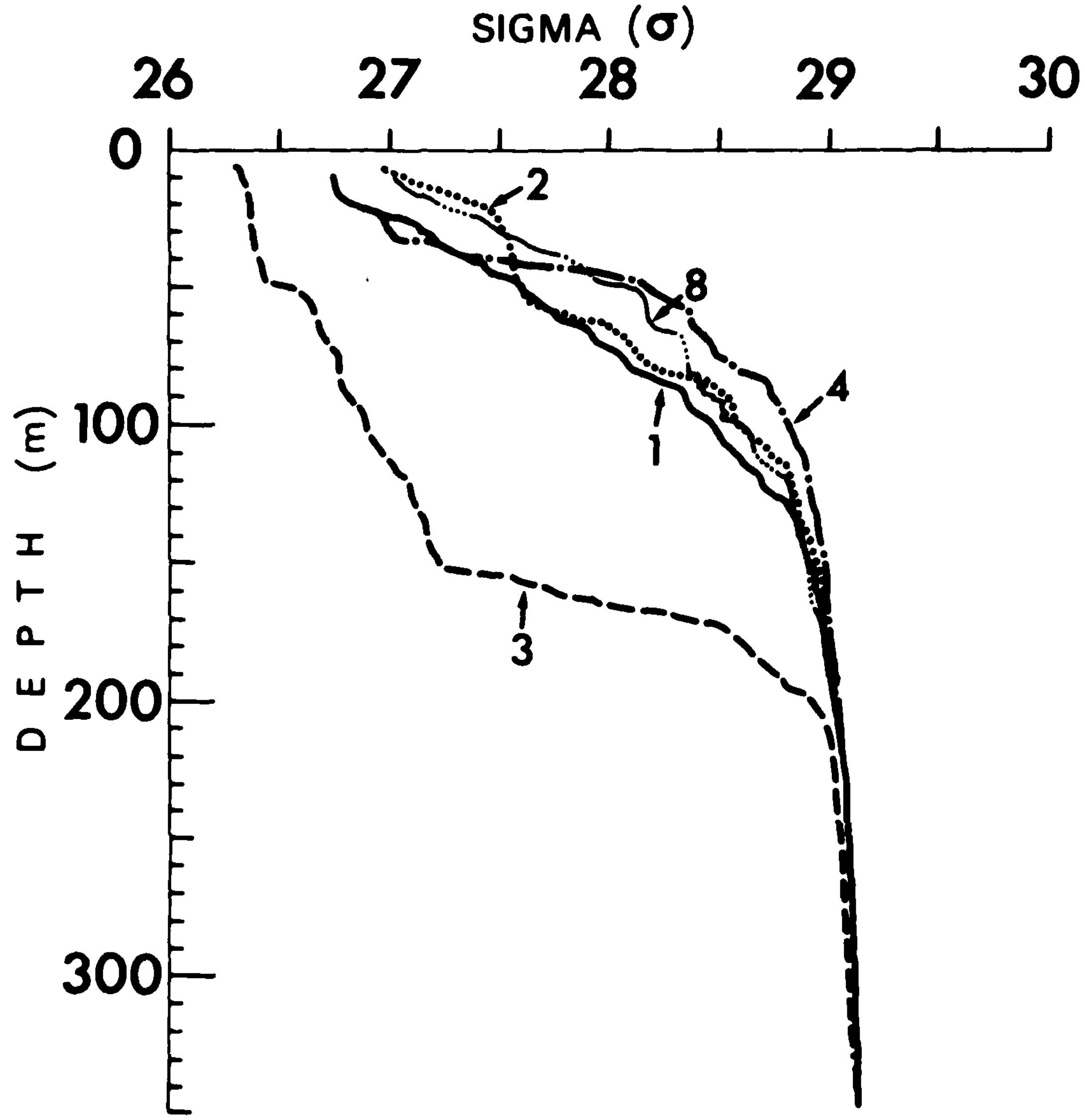


FIG. 8 SIGMA θ PROFILES MEASURED AT THE CTD STATIONS OF FIG. 5c

the upper, warmer layer was 0.05‰ more saline than the water below it. The density structure was temperature controlled here and showed an increase of 0.18 units in the 5 m thick thermocline below 48 m.

Station 4 at the east end of the Strait was occupied about five and a half hours before high water at Gibraltar. Thus the tidal flow would have been moving westward for only about a half hour. (Oceanographic Atlas of the North Atlantic Ocean.) The profiles showed the Atlantic water remaining in the near surface layers. The cast was not begun at the surface but at 25 m where the salinity was about 36.1‰. The temperature droped exponentially to the Mediterranean Intermediate value of 13.2°.

Station 8 was taken about 7 or 8 miles (13-15 km) east of the position of station 4 eight days later and about 2 h after high tide at Gibraltar. The surface tidal flow would then have been easterly for this two hour period. Neither stations 4 or 8 would have been affected by the internal waves which may move the isohalines or isotherms by 60 m vertically. These waves are to be expected around the time of low water at Gibraltar *[3,4]*.

Quite obvious in the salinity trace are a series of steps of increasing thickness from 8 m at 60 m to 24 m at around 150 m and decreasing salinity jumps from 0.15‰ to 0.5‰. These steps are also discernible but with difficulty on the temperature profile. The steps represent layers or lenses of different water types separated by transition regions *[13]*. The source of these cannot be stated definitely but two hypotheses are:

1. The mixing of surface waters in adjacent areas during the storm of a few days earlier and

2. The mixing induced in the thermocline via Kelvin-Helmotz instabilities on the large tidal-associated internal waves by the current shear.

In either case the resulting lenses had adjusted to the forces of gravity and buoyancy and the water column was stable. There were small scale density inversions between 80 and 100 m, perhaps representing the preliminary stages of the mixing involved in the formation of a new step.

The transition zones were very wide and smooth, about 4-5 m thick. This is probably caused by the current shear, due to the strong alternating tidal flows and the two layer structure of the net flow *[4,5]* inducing high eddy diffusion rates across the boundaries.

3.3 Sound Speed Profiles

The sound speed profiles calculated from the CTD data for each station are shown in Fig. 9.

The first result from the data analysis was that the Alboran Sea does not become homogeneous for acoustic propagation until a depth of more than 200 m. The difference in sound speed in the deep water between

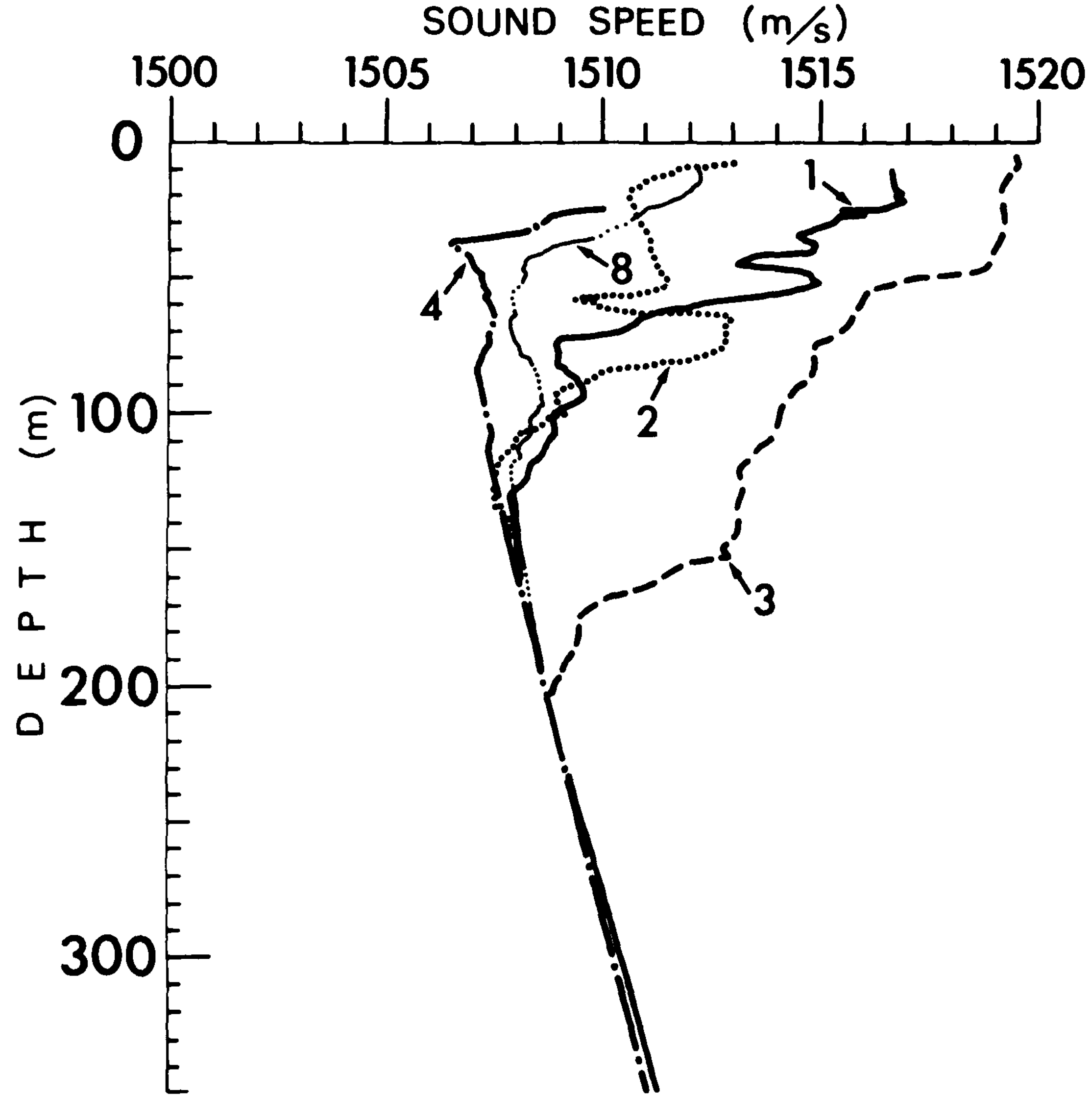


FIG. 9 SOUND-SPEED PROFILES MEASURED AT THE CTD STATIONS OF FIG. 5c

stations 1 and 4 was a result of temperature and salinity differences too small to be seen in Figs. 6 and 7. At 315 m depth, the difference in sound speed of 20 cm/s corresponded to a 0.06°C lower temperature and a 0.003% lower salinity than at station 4. The greatest difference measured was about 12 m/s at a depth of 40 m between stations 3 and 4. These stations were 78 km apart but it can be expected that much of the sound speed change occurred below the front in evidence in the satellite image near station 4.

From these profiles and the BT's it is clear that under the cooler water in the satellite image there was virtually no surface mixed layer. At station 1 it was 15 m deep and at station 3 the first layer was 48 m deep. Each station had a sound channel at the depth where the pressure effect on sound speed just becomes significant in the virtually isothermal, iso-salinity Mediterranean water. This varied from 80 m at station 4 to 200 m at 3 and back up to 120 m at station 2. Except for station 3, each station also exhibited a shallower sound channel due to lenses or fronts although the density was stable. The stability in density is important because the XBT's showed temperature inversions so strong that they might have been considered BT noise or transient overturnings and thus ignored by operators unfamiliar with the area. In fact, there were three sound channels at station 2, although the strong one at 60 m depth had a horizontal extent of only about 5 n.mi (9-10 km) along the ship track.

The major acoustic feature in the region is the frontal boundary between the Atlantic and Mediterranean water encircling the gyre and moving on to the eastward *[1,8,9,11]*. Within the limits of the data coverage the most complex region, with distortion of the thermocline on kilometre scales horizontally, was between 3° and 4°W, i.e. under and to the east of the cooler band of water marking the easterly boundary of the gyre.

4 HISTORICAL DATA

SACLANTCEN maintains a data base of 21,000 Nansen Casts and about 70,000 XBT records. The data has been supplied from the U.S. Naval Oceanographic Office and the United Kingdom Hydrographic Office. The data base can be accessed, analyzed and presented in various formats [14]. The analysis uses a contouring system based on that developed in the Canada Department of Energy Mines and Resources [15].

This historical data set was used to check the stability of the gyre during the year. In the winter the feature is difficult, or impossible, to observe from satellite infrared images because of the similar temperatures of Atlantic and Mediterranean surface water. The 37.5‰ isohaline was taken as a boundary surface between the two water masses and the depth of this surface was contoured (Fig. 10). Sufficient historical data exists for monthly analysis in January, February, June, July and August.

The June analysis (Fig. 10c) agrees well with the ship and satellite survey. It is consistent with the interpretation that the Atlantic water enters and circles cyclonically back along the south shore spiraling downward into the middle of the gyre at about 35°50'N and 4°30'W. The 37.5‰ isohaline at this position is at a depth of more than 200 m; and below this the water becomes spatially homogeneous as shown in the CTD and XBT stations. Along the northern shore there is an upwelling of water which can be seen in the historical data as a rising boundary surface. This is the region where the strongest horizontal gradients (and acoustic effects) will occur. The absolute value of the gradient may be lessened by the averaging and smoothing inherent in automatic contouring. The June data give in fact a 0.3° slope.

Other features notable in the June data are: the abrupt deepening of the boundary outside the Straits and the deeping about 2°W, indicating the presence of the second gyre. This gyre is also detectable in infrared images [8,10].

The data for the other four months all confirm the presence of the gyre. Thus the gyre does exist during winter months as well. The boundary between Atlantic and Mediterranean water lies below 200 m in the centre of the gyre and rises to above 40 m along the N.W. coast where the Mediterranean water upwells.

The January historical data can be compared to measured data in the region by the U.S.S. KANE in January 1977 (Fig. 11) [9]. The latter data extend further to the east, concentrated in the region of the southward flow of surface water. Along 4°W the two 100 m contour lines are within 10 n.mi. The "historical" gyre is longer in the east west direction however, the 100 m contour line turning southward 30 n.mi further east in the contoured data derived from the historical data set. The KANE data also depict an enclosed region less than 20 m deep in the centre of the cyclonic motion of the flow. The older data do not include stations far enough to the east to indicate any northward curvature of the contours.

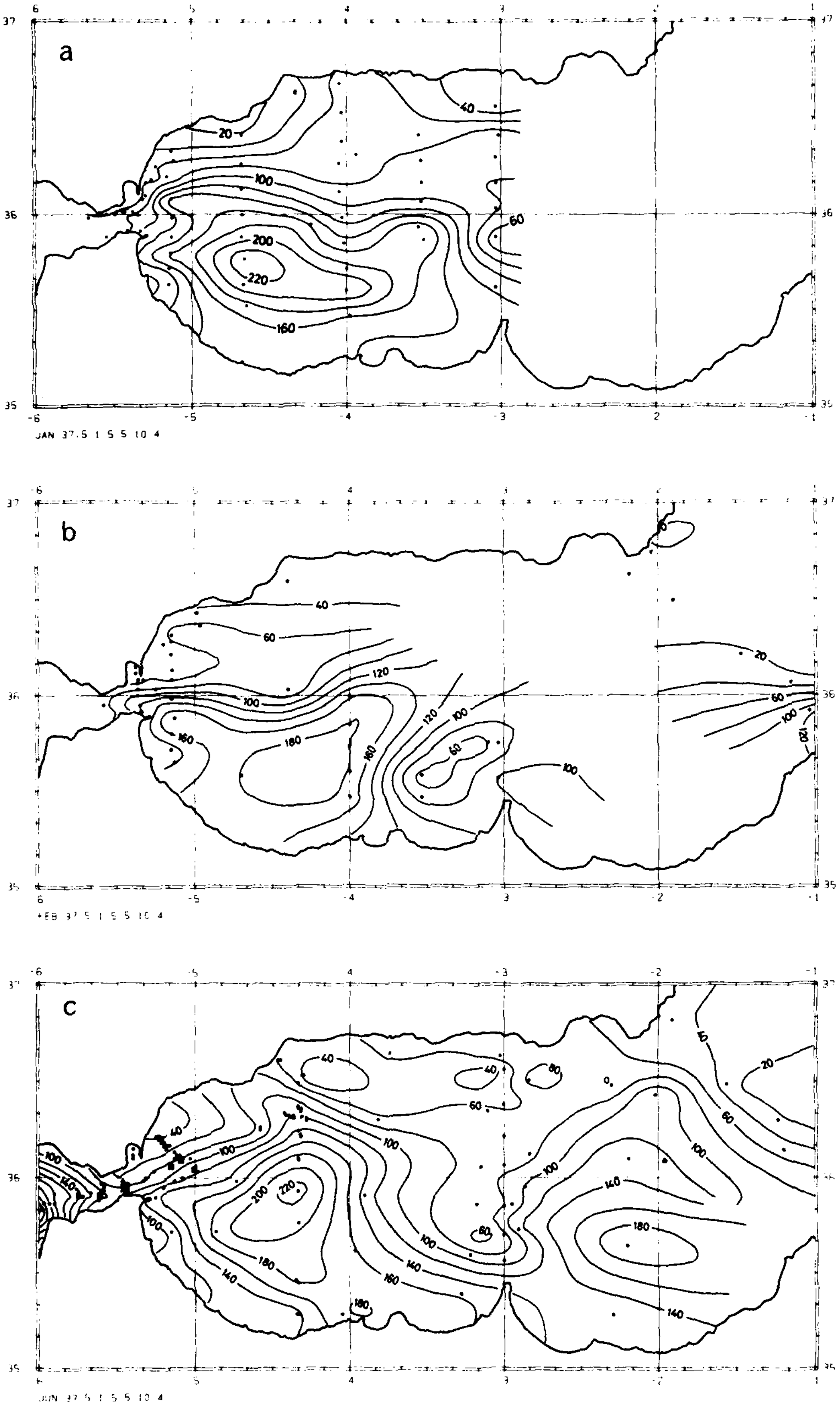
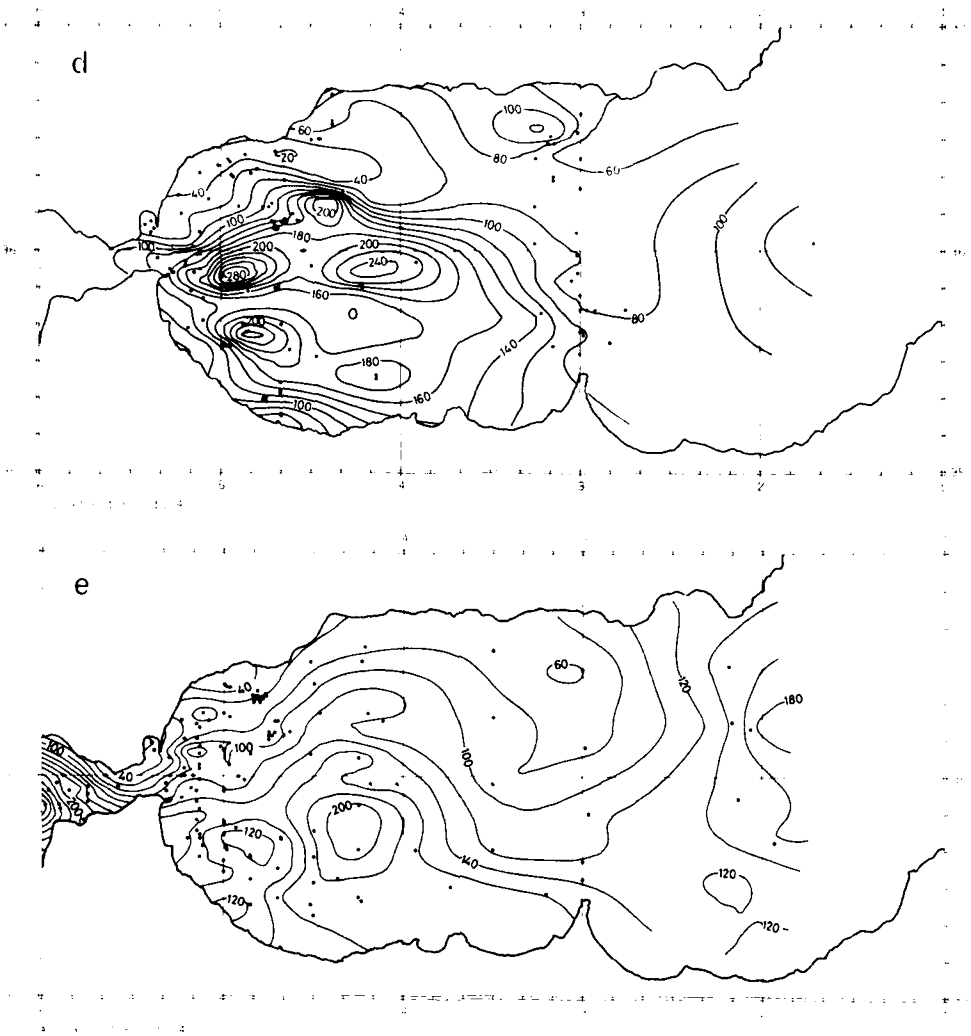


FIG. 10 COMPUTER CONTOURED HISTORICAL DATA OF THE DEPTH OF THE BOUNDARY BETWEEN ATLANTIC AND MEDITERRANEAN WATER REPRESENTED BY THE 37.5‰ ISOHALINE FOR JANUARY, FEBRUARY, JUNE, JULY, AUGUST



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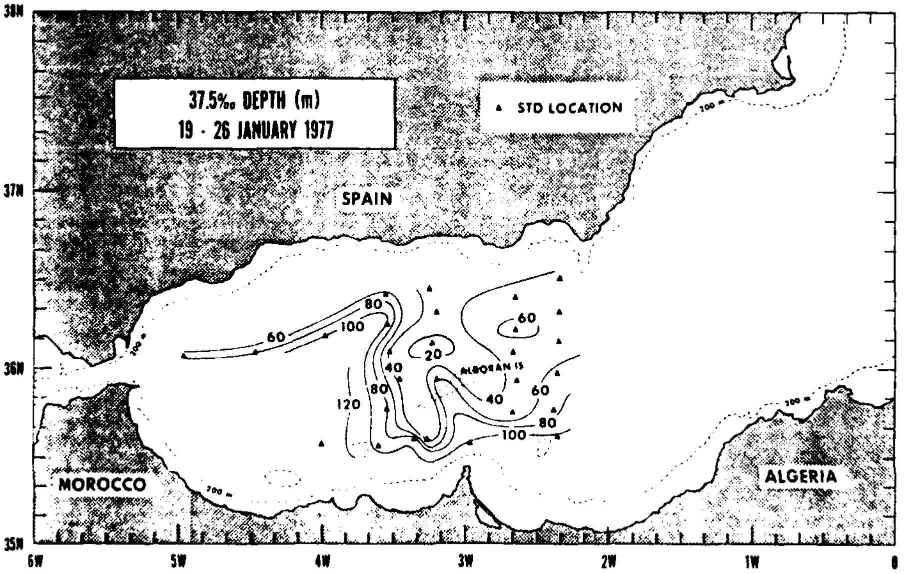

FIG. 11 DEPTH OF THE 37.5‰ ISOHALINE IN JANUARY 1977 (U.S. NAVAL OCEANOGRAPHIC OFFICE)

SUMMARY AND CONCLUSIONS

A series of gyres and current meanders exist in the Alboran Sea where the inflowing Atlantic water through the Strait of Gibraltar encounters Mediterranean surface and upwelled water. In summer these gyres are visible in satellite infrared images because of the temperature differences between the water masses. The most prominent gyre lies between 3°W and the Strait. The Atlantic water flows east-north-easterly into the Mediterranean, at a speed of about 50-90 cm/s. Mediterranean water upwells to the north of this jet. A combined flow turns southeasterly between 3° and 4°W and splits into an easterly and returning westerly flow along the south shore.

In June 1977 the research vessel MARIA PAOLINA G. made an XBT section through the area including five CTD stations. Water temperature measured continously at 4 m depth correlated well with NOAA 5 satellite infrared images. Analysis of historical data indicated that the gyre is present in the winter as well as the summer months, suggesting that the feature is permanent.

The surface of the Mediterranean water, taken as the 37.5‰ isohaline, slopes down into the centre of the gyre to a depth of about 200 m. Below this, the water is nearly isothermal (13.2°C) and iso-salinity (38.4‰) down to the depth surveyed (300-400 m). The slope of the front in a north-easterly direction was estimated as 0.3° to the horizontal from both historical data and cruise data. The interior of the gyre is marked by warmer temperatures (3°C) lower salinities (2.5‰) and higher sound speeds (12 m/s). The front or fronts, between water masses may be distorted by waves, and the encirclement or ingress of water across the boundary. Lenses of water of various types were detected which would have adverse effects on high frequency sound propagation. Strong temperature inversions were salinity compensated, resulting in a stable density structure.

Sound speed in one statically stable lens was more than 2 m/s lower than immediately above or below the lens. Acoustic propagation would be further complicated by tidal associated internal waves spreading from the Strait where they have an amplitude of 60 m.

The area is complex oceanographically and environmental prediction cannot be made for the entire Alboran Sea by considering it to be one horizontally homogeneous domain. It may be possible however to use active domains delineated by satellite infrared images of the area, combined with historical data and an understanding of the local dynamic processes.

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ERRATUM

WANNAMAKER, B. The Alboran Sea gyre: ship, satellite, and historical data, SACLANTCEN SR-30, 1979.

SACLANTCEN has been informed that the statement in the last paragraph of p.7 of the reference report, in which the launching of a Marisonde buoy was attributed to the French Centre National pour l'Exploitation des Océans, is incorrect.

Marisonde buoys were designed by the French Establissement d'Etudes et de Recherches Météorologiques and the buoy referred to (buoy B 03) was launched by them near Gibraltar (36°15'N, 5°01'W) on 15 July 1977.

The following references are relevant:

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