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A search for meddies in historical data

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ABSTRACT

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A search was made using historical hydrographic data from the eastern North Atlantic to find measurements of very salty layers between 700–1300 m that could be observations of the warm, salty lenses known as meddies (Mediterranean water eddies). Twenty-five stations were found out of a total of 13 551 with positive salinity anomalies of at least 0.4 psu, about half that of a strong meddy in the Canary Basin. These possible meddy observations were combined with additional reported observations to show that meddies generally lie in an oval whose long axis extends 3000 km southwestward from the coast of Portugal. Five possible meddy observations were found north of this region, near 44° N, where they have previously never been reported.

1. INTRODUCTION

One of the most prominent features of the North Atlantic is the Mediterranean salt tongue that extends at mid-depths from Gibraltar westward across the Atlantic. This salinity originates from the excess evaporation over the Mediterranean Sea and is carried by an overflow of dense waters through the Strait of Gibraltar and into the main thermocline. High salinity from this layer is traceable southward from the main tongue through the South Atlantic and into the Pacific and Indian Oceans. Most depictions of the salt tongue show its broad scale with contours outlining the gradual decrease in salinity with distance along the tongue (Reid, 1978). Recent studies, however, have revealed that the salt tongue, at least in the Canary Basin, is populated by very salty lenses of Mediterranean water called meddies. Meddies are typically 100 km in diameter, 800 m thick, centred near a depth of 1000 m, and have salty anomalies of 0.8 psu compared with

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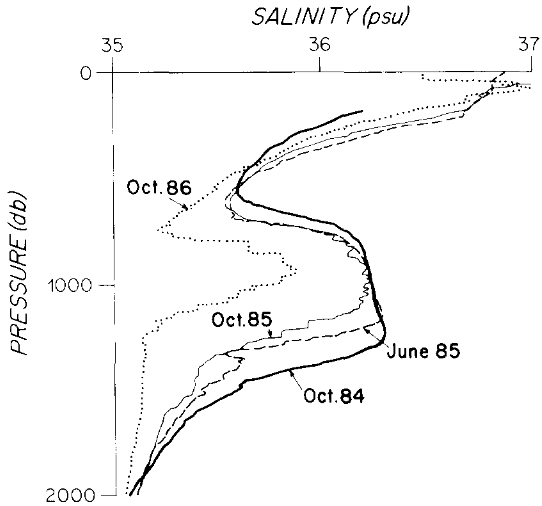

Fig. 1. Salinity profiles through the central region of a meddy showing the gradual decrease of its salinity anomaly with time over two years (psu is practical salinity unit). During this time the overall diameter decreased from 100 to 35 km. This meddy was continuously tracked with SOFAR floats southward from 32° N, 22° W to 22° N, 22° W at a mean velocity of 1.8 cm s^{-1} (see Armi et al., 1989 and Richardson et al., 1989).

background water (Fig. 1; see Armi and Zenk, 1984). Although the formation of a meddy has not been reported, they are thought to form from the overflow water near Cape St. Vincent, Portugal or from the very salty water which occurs off the coast of Portugal. Approximately 25% of the Mediterranean outflow is estimated to enter the Atlantic as these meddies which must be important to the ocean-wide salt distribution (Richardson et al., 1989). To further evaluate their importance we need better estimates of their numbers, distribution, velocity and lifetime.

Despite considerable recent effort studying meddies, their geographical distribution remains largely unknown because of the relatively sparse number of meddy observations. The purpose of this study of historical data in the eastern North Atlantic is to identify possible meddy observations and to learn more about their distribution and population. An earlier study of data from the National Oceanographic Date Center (NODC) in a smaller region in the Canary Basin (30–36° N, 20–30° W) found a few possible meddy observations which suggested that this approach could be fruitful over a larger region (Armi and Zenk, 1984).

2. METHODS

We searched through historical hydrographic stations for the tell-tale warm salty water of a meddy centred in the depth range 700–1300 m. Our criterion for a possible meddy observation was a layer of anomalously warm and salty water at least 0.4 psu saltier than the mean background value. This anomaly is about half that of a young, strong meddy (Armi and Zenk, 1984) and is representative of an off-centre cast in such a meddy or a near-centre cast in an older, weaker meddy.

Maps of the mean salt field near 800, 1000 and 1200 m as shown in the atlas published by Maillard (1986) were used together with the roughly 14000 stations which were the basis of the maps (Fig. 2). In the preparation of this atlas, mean salinity was calculated in each $2° \times 2°$ box, individual observations $> 2\sigma$ in salinity from the mean were eliminated, and the mean recalculated. Successive iterations were continued until consecutive values agreed to within 0.005 psu. The resulting grid of salinity values was smoothed and interpolated to obtain smooth distributions of salinity (Fig. 3). The stations previously identified as lying outside the band 2σ from the mean salinity were visually inspected to see whether or not they generally agreed with temperature and salinity profiles in known meddies. Those that did and had positive salt anomalies of at least 0.4 psu and a thickness of at least 200 m are listed in Table 1. We also checked station locations with cruise tracks to try and eliminate incorrect positions, and we checked that temperature–salinity (T–S) properties of the possible meddy observation stations generally agreed with background values above and below the depth of the salty Mediterranean layer. Other reported meddy observations are given in Table 2. Positive salt anomalies of 0.3 psu could be because of meddies, but we thought including them as possible meddy observations was risky because errors in station data, horizontal and vertical gradients in the mean salinity field, and other kinds of mesoscale fluctuations in the salt tongue could cause positive salinity anomalies of around this size. Salt anomalies of 0.3 psu which may or may not be meddy observations are given in Table 3. The region east of 10°W and south of 40°N was excluded from this study because of the salty outflow water and the large salinity gradient there.

The standard deviation of retained salinity values in $2° \times 2°$ bins is approximately 0.1 psu near 1000 m in the Canary Basin. Thus the criterion of 0.4 psu salinity anomaly for a possible meddy observation is four times the background fluctuations in salinity, after the large anomalies were removed. Katz (1970) and Joyce (1981) have reported abrupt jumps in salinity along the Mediterranean tongue of 0.15–0.20 psu in the vicinity of the Mid-Atlantic Ridge. Our criterion of a possible meddy observation is at least two times these values. Advection of the salinity field by time-dependent velocity fluctuations could cause salinity anomalies. Figure 3 suggests that to cause a 0.4-psu anomaly, water would have to be carried approximately 500 km perpendicular to the isohalines in the regions of strongest salinity gradient south of Cape St. Vincent, Portugal, and west of Cape

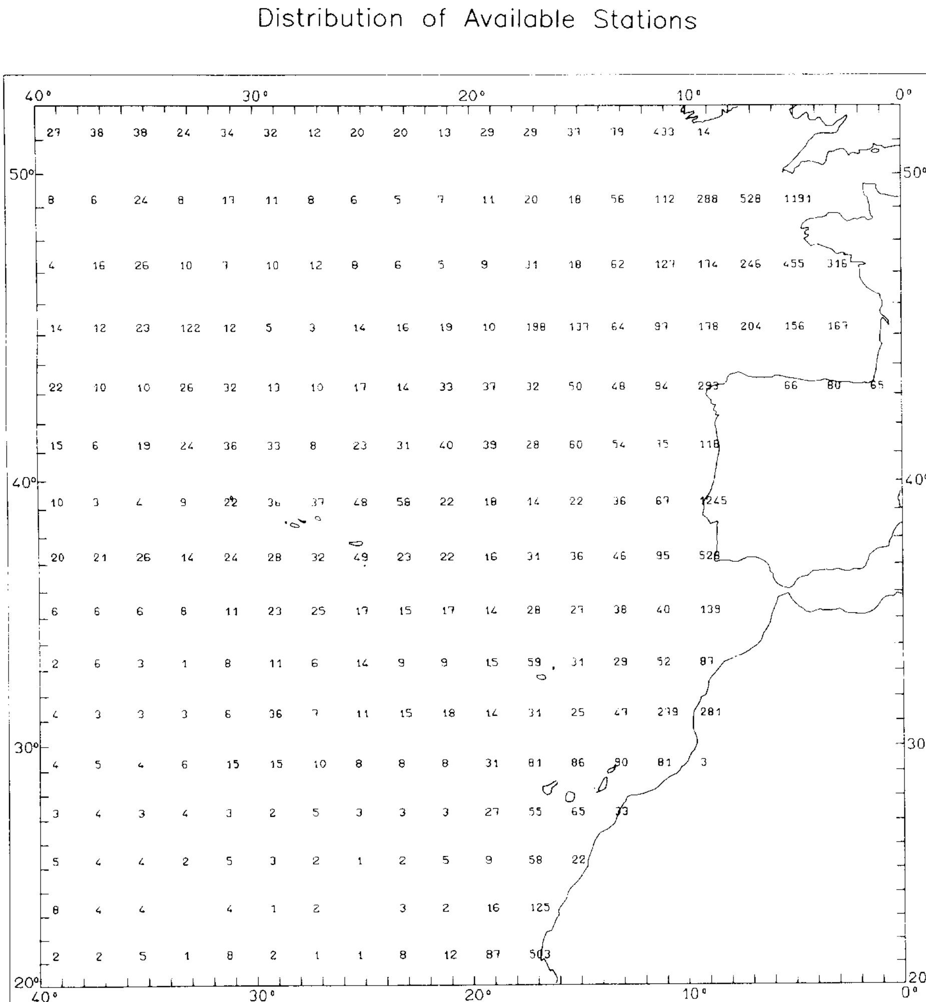

Fig. 2. Distribution of hydrographic stations used by Maillard (1986) to construct the mean salinity fields and to identify possible meddy observations. The data which consist of 13 551 stations made from 1903 to 1974 were available at the Banque Nationale de Données Océaniques in Brest.

Finisterre, Spain, or around 800 km southwestward along the axis of the Mediterranean tongue. We suspect that some of the 0.3-psu anomalies could be caused by time-dependent advections in the vicinity of the large salinity gradient regions.

The distribution of available stations is important because it influences the chance of observing a meddy. The 13 551 stations available at the Banque Nationale de Données Océaniques (BNDO) in Brest amount to an

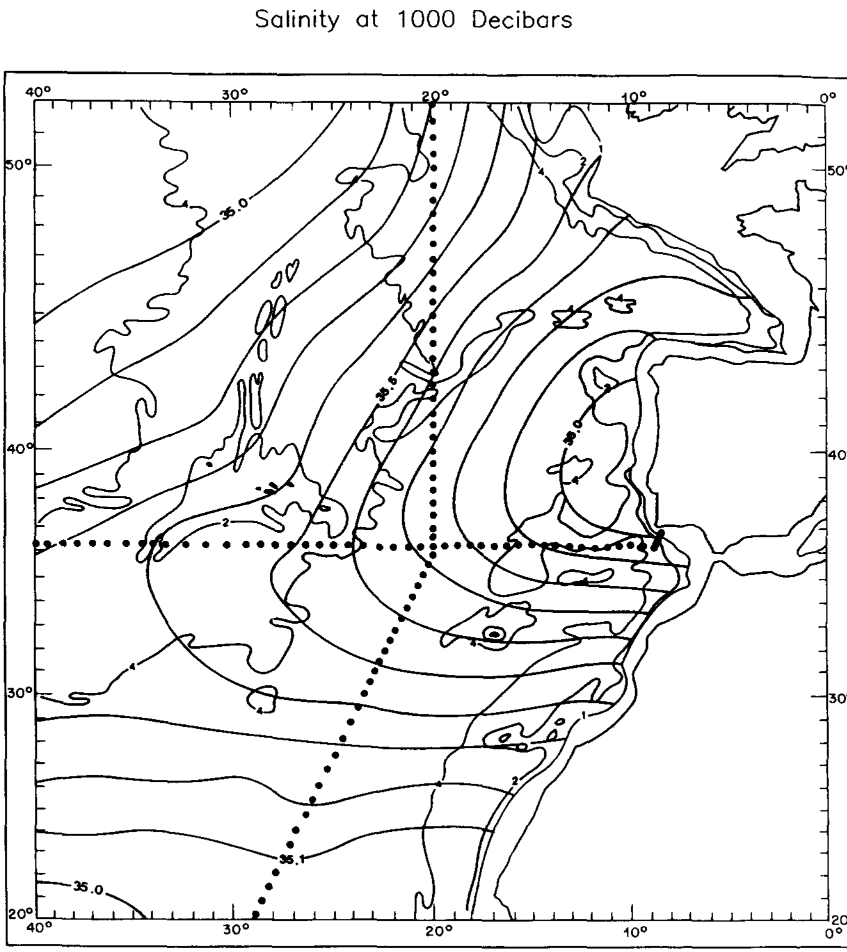

Fig. 3. Contours of the mean salinity field at a pressure of 1000 dbar as shown by Maillard (1986, fig. 104b). The general bathymetry of the region is added (values in hectometres). The saltiest region > 36.0 psu occurs as a bulge off the coast of Portugal. Since the Strait of Gibraltar is the origin of the high salinity water, it must flow northward along the coast. The main axis of the salt tongue extends from Portugal west-southwestward crossing 40 ° W near 33 ° N. The salinity at 800 and 1200 dbar is similar to 1000 dbar except for a slightly larger area encompassed by the 36.0-psu contour at 1200 dbar and smaller area at 800 dbar. The 35.5-psu contours at these three levels lie close to each other suggesting rather small vertical gradients in the mean salt distribution. Dots are station positions from two hydrographic sections referred to later in the text. The 20 ° W section was made aboard R/V Oceanus in August 1988; the 36 ° N section was made aboard R/V Atlantis II in July 1981.

average of 53 per 2° × 2° box. The stations are unevenly distributed with the highest density along the coast, in the Bay of Biscay and extending westward out to 18 ° W near 45 ° N. A lower density of stations extends from

TABLE 1

Possible meddy observations

Date			Latitude °N	Longitude °W	Salinity anomaly * (psu)	Maximum salinity (psu)
Year	Month	Day				
1922	06	23	43.53	24.75	0.4	35.57
1930	08	06	38.37	13.12	0.4	36.49
1931	06	05	37.07	18.80	0.4	36.15
1948	01	03	35.15	13.37	0.5	36.42
1949	10	27	40.67	26.27	0.6	36.02
1956	06	03	36.80	10.33	0.4	36.51
1057	10	29	37.13	10.32	0.5	36.51
1958	04	19	37.02	10.23	0.5	36.45
1958	09	11	45.12	15.93	0.4	35.99
1965	09	07	34.02	17.02	0.7	36.44
1965	10	01	31.50	14.45	0.6	36.22
1966	06	02	34.00	13.00	0.5	36.33
1967	03	10	36.00	24.50	0.4	35.91
1968	10	25	44.03	17.98	0.6	36.06
1970	08	02	35.00	10.00	0.6	36.65
1970	11	14	33.57	10.35	0.4	36.00
1970	11	22	33.48	23.33	0.6	36.13
1971	01	12	36.38	10.00	0.4	36.34
1971	01	21	29.95	28.00	0.5	36.05
1971	04	16	37.48	20.47	0.9	36.56
1971	05	18	36.50	14.77	0.4	36.30
1971	07	11	34.63	19.70	0.4	36.11
1971	07	19	37.48	21.48	0.4	36.08
1971	09	04	34.57	11.07	0.6	36.57
1971	09	17	44.00	17.98	0.6	36.06

* Note: salinity anomaly is largest value in the depth range 700–1300 m compared with the mean salinity field given by Maillard (1986).

this point through the Azores Islands. Two low data density regions occur, one centred near 47° N, 26° W, and the other southwest of a line joining the Canary and Azores Islands. The sparsity of stations in the southwest is unfortunate for this study because several meddies have been reported there. Without a higher data density this region will remain poorly studied.

3. RESULTS

3.1. Possible meddy observations

Twenty-five possible meddy observations were identified with salinity anomalies ranging from 0.4 to 0.9 psu (Figs. 4 and 5). Most of the meddy

TABLE 2

Summary of reported meddy observations

Date		Latitude °N	Longitude °W	Salinity anomaly * (psu)	Maximum salinity (psu)	Reference
Year	Month					
1965	Summer	29.50	17.00	0.6	–	Piip (1969); approx. position
1965	Summer	32.50	11.50	0.6	–	Piip (1969); approx. position
1976	06	36.00	30.00	0.6	36.42	Plakhin and Smirnov (1982)
1979	09	36.00	22.50	0.6	36.20	Plakhin and Smirnov (1982)
1981	06	31.00	26.65	0.9	36.35	Armi and Zenk (1984)
1981	06	30.83	22.63	0.8	36.28	Armi and Zenk (1984)
1981	06	33.00	21.47	0.6	36.17	Armi and Zenk (1984)
	–	33.00	29.50	0.4	35.88	Armi and Zenk (1984) (from NODC data 1914–1972)
	–	35.00	26.50	0.6	35.90	Armi and Zenk (1984) (from NODC data 1914–1972)
	–	33.50	23.30	0.6	36.16	Armi and Zenk (1984) (from NODC data 1914–1972)
1981	07	36.24	11.89	0.5	36.48	Roemmich and Wunsch (1985)
1982	04–05	36.00	20.67	0.5	36.20	Käse and Zenk (1987)
1982	04–05	33.00	23.17	–	–	Käse and Zenk (1987)
1982	04–05	31.50	22.58	–	–	Käse and Zenk (1987) (current meter mooring)
1982	05	33.00	22.00	–	–	Käse and Zenk (1987) (current meter mooring)
1982	05	35.00	23.00	–	–	Käse and Zenk (1987) (current meter mooring)
1983	01	25.67	27.83	0.9	36.14	Williams et al. (1986)
1983	03–04	26.53	29.10	0.8	35.96	Armi and Stommel (1983)
1984	10	31.97	21.80	0.8	36.30	Armi et al. (1989); Richardson et al. (1989)
1985	05	19.62	37.23	0.9	35.85	Yegorikhin et al. (1987)
1985	09	36.00	13.50	0.8	36.50	Zubin and Ozmidov (1987)
1985	11	33.92	24.08	1.1	36.56	Richardson et al. (1989)
1986	11	22.00	26.07	0.8	35.90	Richardson et al. (1989)
1988	08	25.40	25.98	1.0	36.26	Oceanus 202
1988	08	26.75	25.27	0.6	35.96	Oceanus 202
1988	08	37.00	20.01	0.4	36.16	Oceanus 202
	–	37.00	19.00	0.8	–	Elken (1987)
	–	32.80	12.08	0.6	36.50	Karlin et al. (1988)

* Note: salinity anomalies are from each reference or are estimated from the cited salinity and depth values compared with the mean salinity maps given by Maillard (1986). Some of these meddies have been shown on maps published by Richardson et al. (1989) and Kostianoy and Belkin (1989). Three possible meddies observed on Oceanus 202 in 1988 (M. McCartney, personal communication) are reported here for the first time.

TABLE 3

Stations with salinity anomalies of 0.3 psu

Date			Latitude °N	Longitude °W	Salinity anomaly (psu)	Maximum salinity (psu)
Year	Month	Day				
1906	02	05	34.77	11.09	0.3	36.09
1922	06	03	33.20	11.28	0.3	36.11
1930	06	16	42.68	09.82	0.3	36.24
1930	07	14	31.95	12.13	0.3	35.80
1930	07	25	29.48	16.55	0.3	35.82
1930	07	26	30.03	16.60	0.3	35.70
1930	07	27	31.07	17.27	0.3	35.86
1938	05	23	43.83	17.58	0.3	36.00
1957	08	15	39.80	23.62	0.3	35.88
1957	09	05	32.52	14.10	0.3	35.90
1958	03	23	43.82	22.62	0.3	35.70
1958	09	14	43.12	18.67	0.3	35.89
1958	10	31	40.20	24.35	0.3	35.74
1959	08	15	45.88	13.96	0.3	35.98
1960	01	25	41.71	25.80	0.3	35.66
1960	09	07	35.40	13.57	0.3	36.18
1965	02	12	45.03	15.80	0.3	35.97
1965	03	23	44.10	13.15	0.3	36.15
1965	09	05	36.68	16.08	0.3	35.74
1965	09	30	31.48	13.17	0.3	36.12
1967	03	25	40.00	16.00	0.3	36.19
1967	12	12	44.83	15.50	0.3	35.99
1970	06	30	44.70	09.45	0.3	36.11
1970	11	05	40.03	19.48	0.3	36.08
1970	11	29	38.52	18.25	0.3	36.11
1971	02	22	37.35	14.00	0.3	36.32
1971	02	23	38.70	20.48	0.3	36.00
1971	03	04	40.75	14.01	0.3	36.24
1971	03	22	44.38	20.46	0.3	35.67
1971	07	13	35.00	17.07	0.3	36.13
1971	09	05	37.83	11.00	0.3	36.51
1971	09	29	40.67	22.43	0.3	35.89
1972	05	03	44.52	15.55	0.3	35.99
1972	05	04	44.50	11.35	0.3	36.09
1972	10	29	44.44	09.89	0.3	36.12
1979	10	03	46.90	15.54	0.3	35.85

observations are clustered in a triangular region whose corners are Cape St. Vincent, Portugal, the Azores and Canary Islands. This area has relatively high data density and several confirmed sightings of meddies. What is really

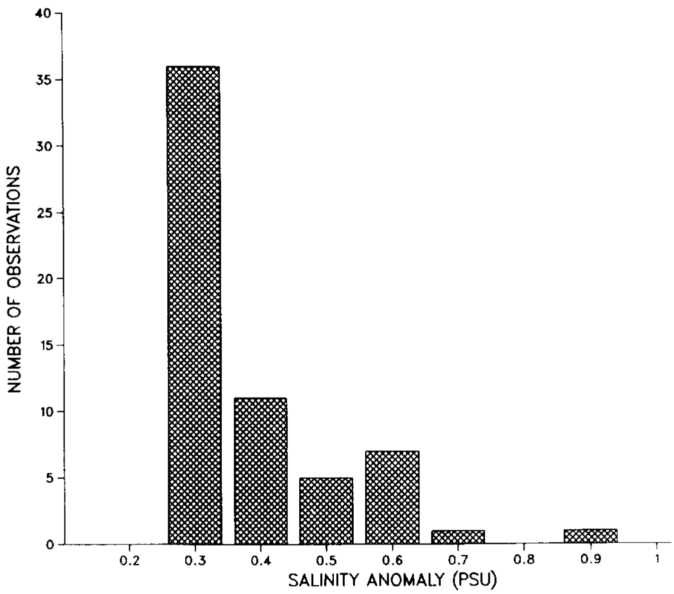

Fig. 4. Histogram of the number of positive salinity anomalies as a function of the size of the anomaly.

new here are the five meddy observations located to the north of this cluster in an area where meddies have never been reported before. Until now all reported meddy sightings have been south of the latitude of Cape St. Vincent, ~ 37° N. The five northern meddies are centred off Cape Finisterre, Spain near 44° N. Three have anomalies of 0.6 psu, two of 0.4 psu. The salinity–depth profiles of the three meddy observations near 43° N, 18° W (Fig. 6) are consistent with profiles from confirmed meddies reported in the southern region, and nothing obviously wrong could be found with the northern meddy data.

Schauer (1989) described observations of salty eddies in the northern region, but these are weaker, deeper, and rotate cyclonically, opposite to the reported meddies. Schauer's eddies, located near 47° N, 20° W, are typically 75 km in diameter, have cyclonic rotation and a maximum salinity anomaly near 1600 dbar of 0.3 psu, smaller than our threshold for a possible meddy observation. One of the eddies she lists is close in space and time to one of our 0.3-psu anomalies; all the rest of her observations are more recent than the data considered here.

No meddy observations were found west of 30° W. Between 40 and 50° N, the density of stations is probably adequate to observe meddies had they been there, but south of 40° N, the station density is very low and the chance of observing a meddy, assuming they are present there, is slight especially if they are small from decay.

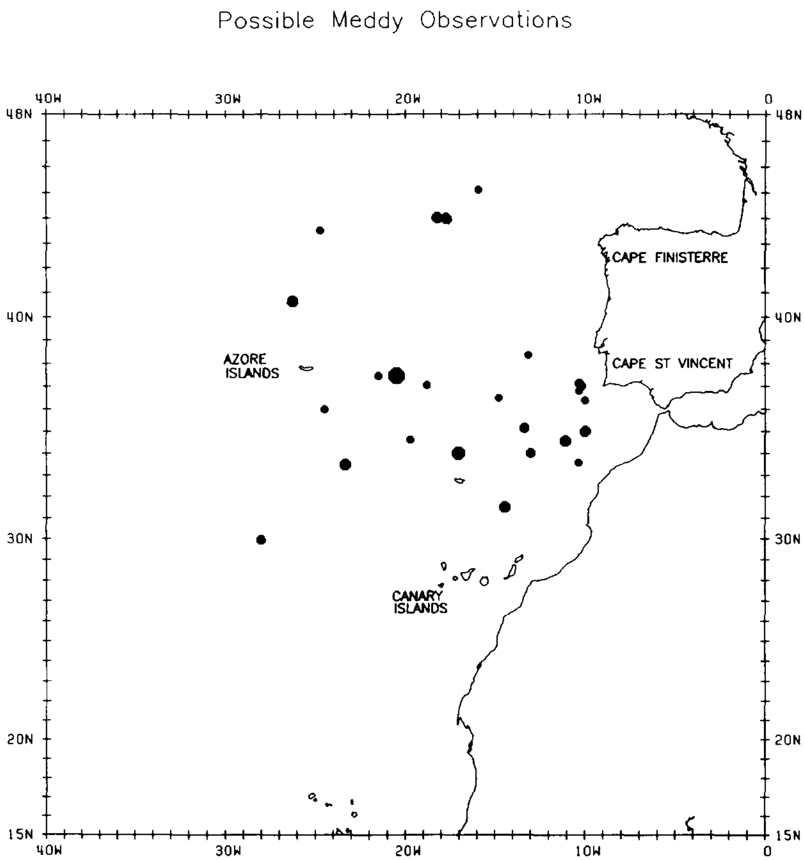

Fig. 5. Plot of 25 possible meddy observations with a positive salt anomaly of at least 0.4 psu (see Table 1). The diameter of each dot is proportional to the magnitude of the salt anomaly. The region east of 10° W, south of 40° N was excluded from the study.

The number of stations per meddy observation north of 40° N is about twice that south of 40° N. Summing values in 4° × 4° boxes that contained at least one meddy observation suggests that around 115 stations per meddy observation occur in the north and 62 in the south. The percentage of meddy observations in 4° × 4° boxes ranges up to 5% which is the same approximate size as reported by Armi and Zenk (1984) and Käse and Zenk (1987). The percentage averaged over all the boxes containing meddy observations is 1.8%. If we interpret this number as the percentage area occupied by meddies and assume that an average meddy diameter encompassing the 0.4 psu anomaly is 50 km, then we estimate that roughly 19 meddies could coexist. This number depends heavily on the assumed average size and assumed threshold salinity anomaly. For example if we included all 0.3-psu anomalies as meddy observations our estimate would increase to 37 med-

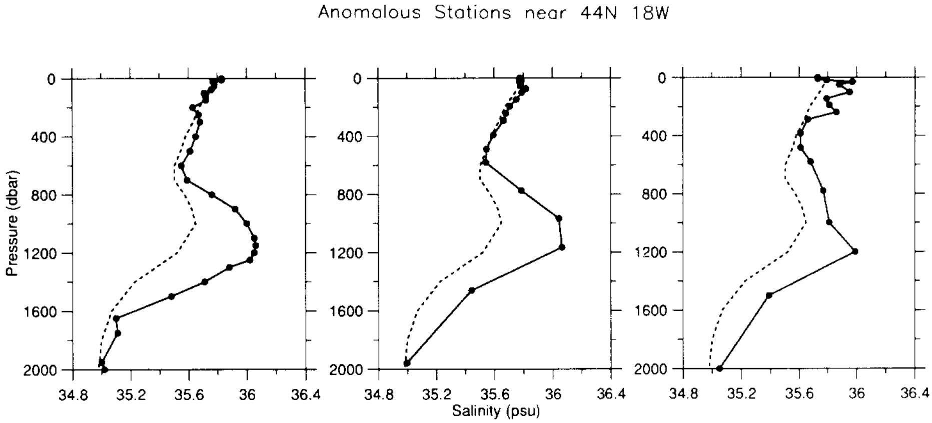

Fig. 6. Vertical profile of salinity in three possible meddy observations located near 44° N, 18° W. The background profile of mean salinity for this location from Maillard (1986) is added as a dashed line. The apparent positive salinity anomaly of ~ 0.2 psu in the middle and right-hand profiles between 1500 and 2000 dbar could be due to a lack of samples between these pressures as can be seen by comparing these profiles with the left-hand profile which has a higher vertical resolution.

dies. Increasing the average diameter to 77 km to equal the average size of meddies reported by Armi and Zenk (1984) would reduce the original estimate to eight meddies. Decreasing it to 45 km, the two-year average diameter of the 0.4-psu salinity anomaly of the well-studied meddy shown in Fig. 1 implies a population of 24 meddies. We favour the smaller diameter in our estimate because it represents a partially decayed meddy.

3.2. Reported meddy sightings

Many recently reported meddies do not appear in the BNDO historical data. In order to obtain the best picture of the distribution of meddies we have combined our meddy observations with 28 other reports of them (Table 2, Fig. 7). Reported meddies tend to have larger salt anomalies ranging up to a maximum of 1.1 psu; five reports are of 0.9 psu or greater. This is probably due to choosing a station located near the meddy centre to calculate the anomaly. Most reports of the sightings are recent, all but two in the last eight years. The reported sightings coincide with our southern cluster but extend it southwestward to near 20° N, 37° W. None of the reported meddies confirm our northern observations which must remain undocumented until a meddy is well surveyed there.

Most of the historical and reported meddy sightings fall within an oval shaped area roughly 1500 km wide extending roughly 3000 km southwestward from Cape St. Vincent, encompassing 3.5×10^6 km^2 (Fig. 8). Most

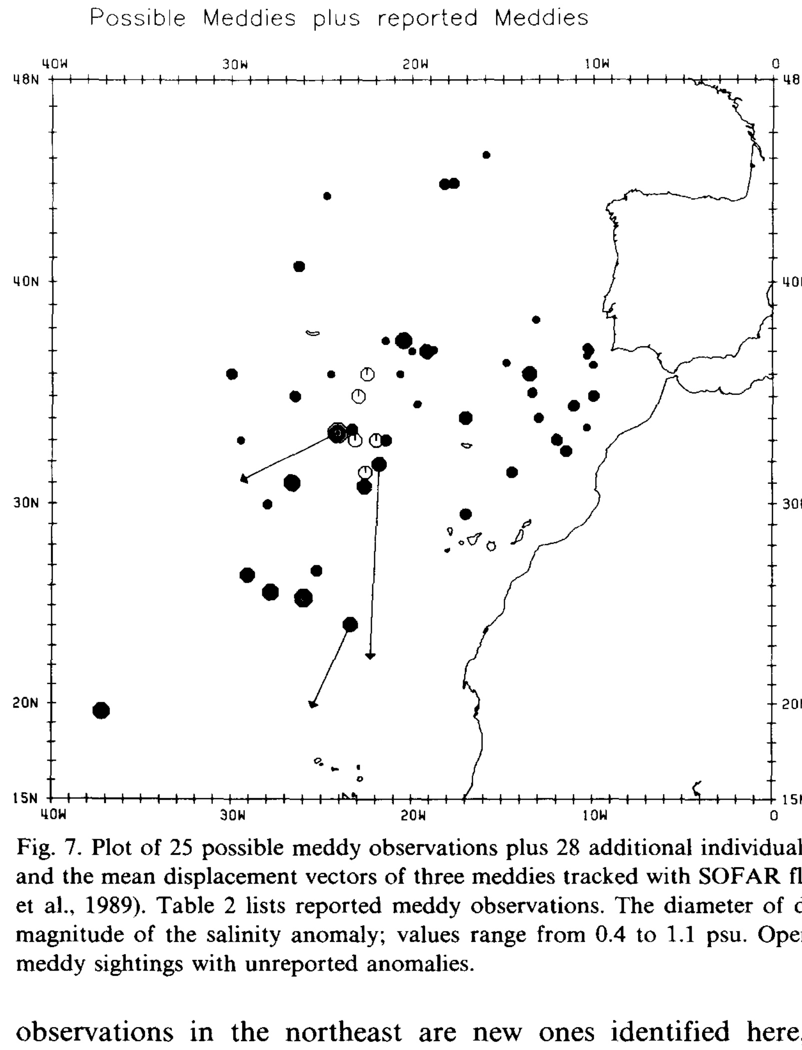

Fig. 7. Plot of 25 possible meddy observations plus 28 additional individual meddy sightings and the mean displacement vectors of three meddies tracked with SOFAR floats (Richardson et al., 1989). Table 2 lists reported meddy observations. The diameter of dots indicates the magnitude of the salinity anomaly; values range from 0.4 to 1.1 psu. Open circles indicate meddy sightings with unreported anomalies.

observations in the northeast are new ones identified here, most in the southwest are reports of recent measurements not in the historical data. The implied mean track of meddies extends southwestward from Cape St. Vincent east of the Mid-Atlantic Ridge (Fig. 9) and crossing 20°N near 35°W, far south of the implied axis of the Mediterranean tongue seen in Fig. 3. Thus the general path of meddies cuts across a sharp gradient in the mean salinity field. The southwesternmost meddy has such a large anomaly, 0.9 psu, because it drifted into a background of decreasing mean salinity. The three meddies tracked by sound fixing and ranging (SOFAR) floats (Richardson et al., 1989) drifted with a mean velocity of 1.5 cm s^{-1} toward 199° (averaged over 3.4 years of meddy tracking) which agrees with the overall distribution of meddies and which implies long lives for the southwestern ones.

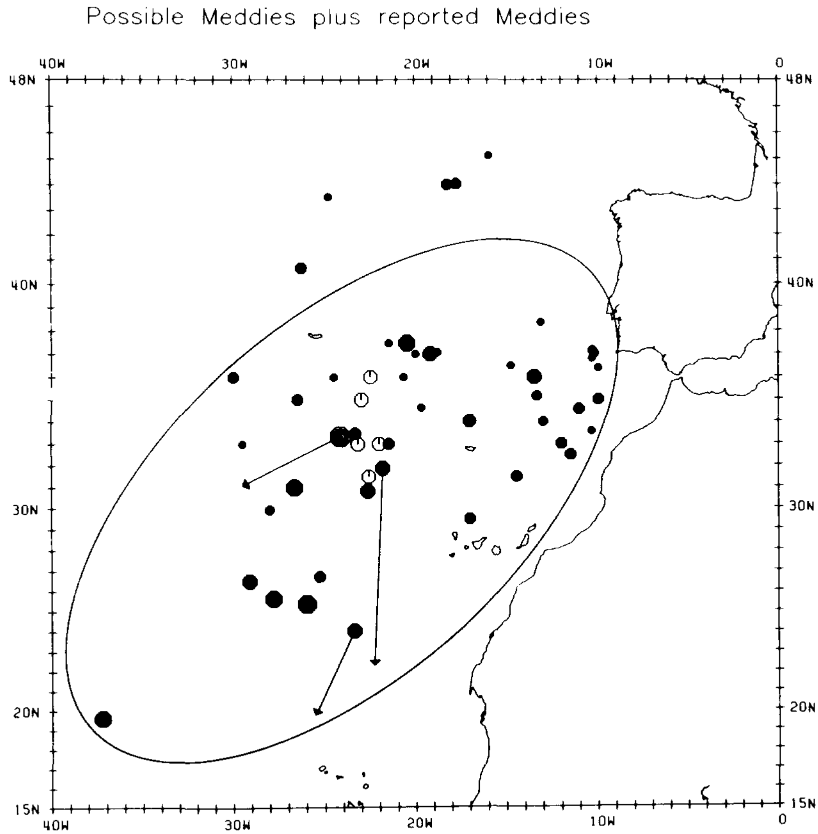

Fig. 8. Summary of all meddy observations and an oval that encompasses the observations south of 40° N. The oval is approximately 1500 km wide, extends ~ 3000 km southwest from Cape St. Vincent, Portugal, and shows the mean track of meddies.

If the normal path of meddies is southwestward, how did the northern ones end up there? The two most obvious possibilities seem to be: (1) they formed near Cape St. Vincent and drifted northwestward possibly in a northward branch of the Azores Current (Käse et al., 1986); or (2) they formed along the coast of Portugal perhaps as far north as Cape Finisterre, Spain, and then drifted westward. This latter possibility seems less at variance with the implied southwestward path of the majority of southern meddies.

3.3. 0.3-psu anomalies

Thirty-six anomalies of 0.3 psu were identified (Table 3, Fig. 10). They seem to be clustered in two groups, one northwest and west of Portugal and extending out to the Azores Islands (38–47° N, 9–26° W) and the second

Possible Meddies plus reported Meddies

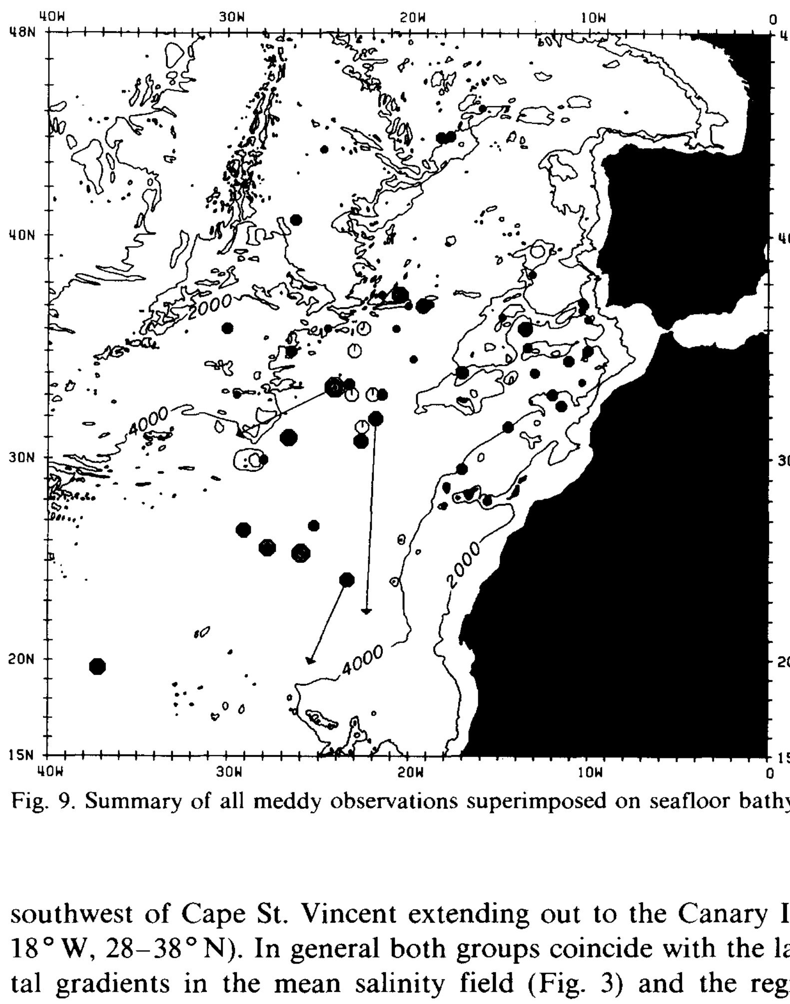

Fig. 9. Summary of all meddy observations superimposed on seafloor bathymetry.

southwest of Cape St. Vincent extending out to the Canary Islands (coast–18° W, 28–38° N). In general both groups coincide with the largest horizontal gradients in the mean salinity field (Fig. 3) and the region of highest station density (Fig. 2). The number of stations per 0.3-psu anomaly is about equal in the two groups. Thus there is an equal chance of encountering a 0.3-psu anomaly in both groups, unlike the meddy observations. The region north of 38° N contains relatively few meddy observations (six total) but an abundance of 0.3-psu anomalies (23 total). In contrast the region south of 38° N contains most of the meddy observations (20 total) but fewer 0.3-psu anomalies (13 total). Thus the southern region has a larger percentage of large anomalies ($\geqslant$ 0.4 psu) compared with the northern region. Maybe this is a reflection of the Mediterranean source water having a larger salinity near Cape St. Vincent, the presumed origin of meddies in the southern region, compared with the water farther north along the coast of the Iberian peninsula, the possible origin of meddies in the northern region.

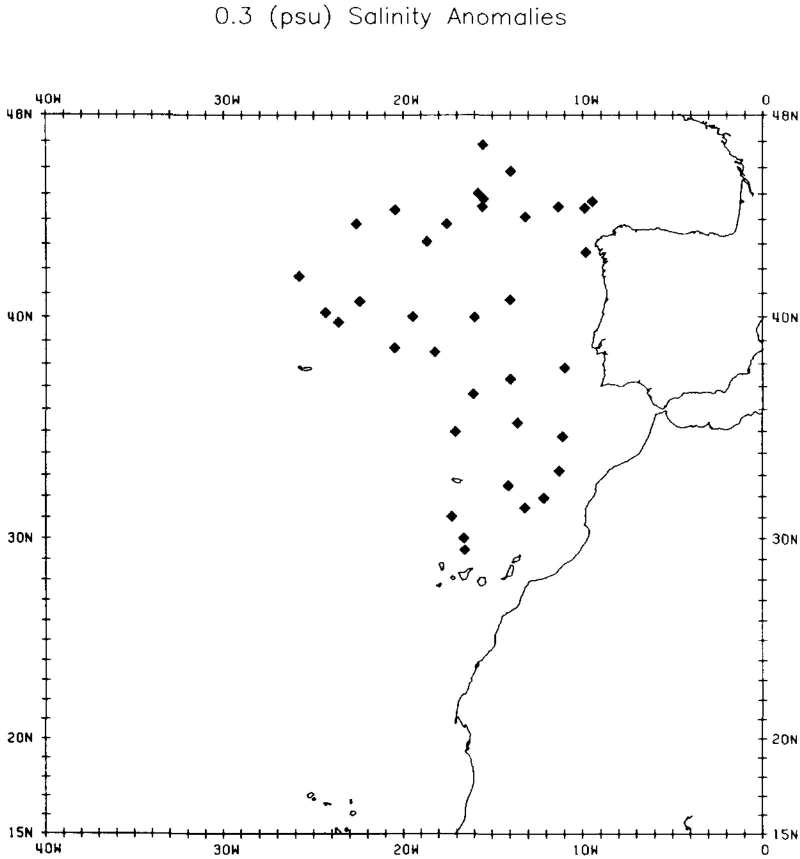

Fig. 10. Plot of 36 observations with a positive salt anomaly of 0.3 psu.

Could these anomalies be meddies—decayed or weak ones or stations near their edge? Without further proof we cannot rule this out, but we think the 0.3-psu anomalies could be something else, so we have not included them with the meddy observations. That the 0.3-psu anomalies match the highest salinity gradient regions located on the north and south sides of the main Mediterranean water tongue suggests that their occurrence could be due to the gradient region coupled with time-dependent velocity fluctuations. One can imagine that velocity fluctuations could advect high-salinity water normal to mean salinity contours giving rise to anomalous blobs of salty water different from the discrete cells of rapidly rotating Mediterranean water in meddies. Figure 3 suggests water would have to be carried around 350 km across isohalines to cause a 0.3-psu anomaly in these regions. On the other hand the 0.3-psu anomalies might be weaker brethren of meddies. Schauer's (1989) salty eddies in the northern region could be similar to some of the anomalies identified here, although her eddy had a deeper salinity anomaly. Käse et al. (1989) discuss some salty eddies west of the Iberian peninsula and their possible formation by baroclinic instability, but these also have a weaker anomaly reaching 0.2 psu. Further work on these features is needed to reveal what they are and what their relationship is to meddies.

3.4. Inferred trajectories

The movement of individual meddies was inferred from possible meddy observations plus 0.3-psu salinity anomalies. Individual observations $\geqslant 0.3$ psu were connected into series by linking nearest neighbours and favouring the slowest implied velocities. Distances between points > 250 km and times between sightings > 6 months were omitted. The results (Fig. 11) reveal four inferred trajectories, all during 1970–1971, the years of the greatest numbers of observations. Three trajectories have a generally southwestward mean velocity with speeds of 1–3 km day^{-1}, in agreement with meddies tracked continuously by floats. The inferred movement of one meddy (A) near

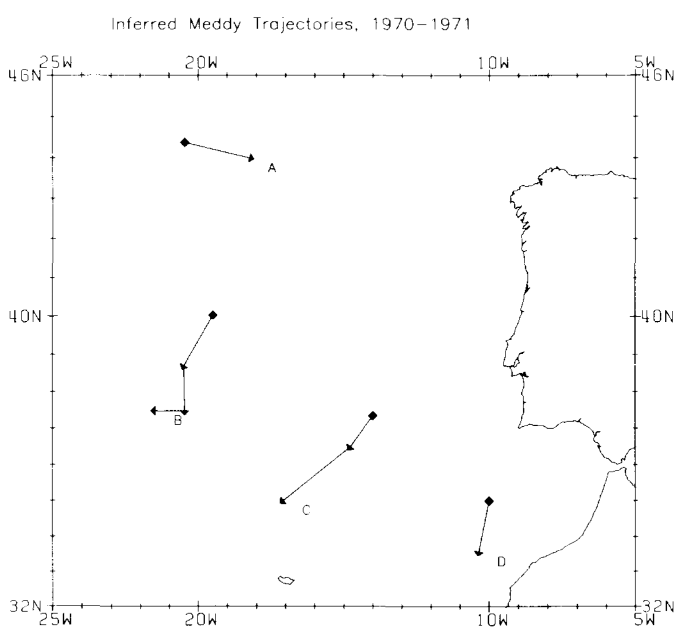

Fig. 11. Inferred meddy trajectories, 1970–1971. Individual observations of possible meddies and 0.3-psu salinity anomalies were combined by linking nearest neighbours and favouring the slowest implied velocities. The four inferred meddy trajectories contain six possible meddy observations of at least 0.4 psu (at least one per trajectory) and five salinity anomalies of 0.3 psu.

20° N, 44° W, based on only two observations, was eastward which seems unrealistic. Of the six possible meddy observations ($\geqslant$ 0.4 psu) used to construct these series, two were repeated observations of the same meddies. An additional four possible meddy observations implies that a minimum of seven to eight meddies coexisted during 1970.

If we restrict ourselves to just possible meddy observations, then we are left with only two trajectories—D, and the end of B (Fig. 11). Increasing the maximum allowable difference in location and time requires numerous subjective decisions about which points to connect. Linking individual observations could lead to false trajectories especially considering the inclusion of 0.3-psu anomalies and the sparse data. For these reasons the inferred trajectories should be viewed with considerable caution. Taken at face value, however, the three trajectories between 34–40° N do imply a southwestward meddy velocity in the northern region, consistent with that in the south.

3.5. Meddies in synoptic sections

A somewhat different perspective on meddies and their relationship to the Mediterranean salt tongue is gained by examining high-resolution (vertical and horizontal) synoptic sections with a conductivity, temperature, depth (CTD) profiler (locations on Fig. 3). Observed variations of depth-averaged salinity between 4° and 12° potential temperatures and salinity at 1000 dbars are well correlated (Fig. 12). This demonstrates that the salinity variations on a single isobaric surface reflect those on a broad enough range of pressures as to significantly affect the average salt content of the full depth Mediterranean salt tongue, i.e. the fluctuations have a thick vertical scale. Another visualization of this is given in Fig. 13, the observed salinity field along the 20° W meridional section.

Three stations on the 20° W section fit the meddy criterion of salinity values at least 0.4 psu higher than the local average value from the atlas (Table 2). Two of these lie south of the main body of the tongue along 20° W, the third in the tongue. The southernmost feature lies mostly above 1000 dbar with maximum salinity exceeding 36.2 psu, near 800 dbar, an anomaly of 1.0 psu, while the middle feature is more nearly centred at 1000 dbar, showing as a strong anomaly there (Fig. 13).

The third station along 20° W that fits our meddy criterion is of a different character, for it falls right in the middle of the Mediterranean salt tongue rather than on its southern flank. This station is quite high in salinity in an absolute sense, but its location in the middle of the tongue causes it to just barely meet the meddy criterion. There are two not quite so salty features adjacent, which do not meet the criterion, again because their salinity is compared with the relatively high values of the axis of the average

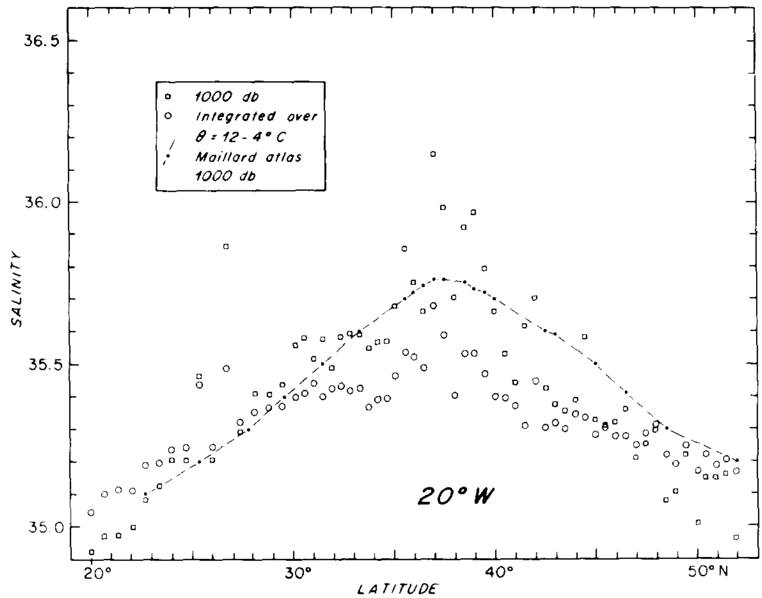

Fig. 12. Distributions of salinity along the 20° W section (location Fig. 3). The squares are the values at 1000 dbar (2 dbar sampled CTD data averaged over a 20-dbar interval, to smooth slightly and make more analogous to the interpolated hydrographic data used in the atlas). The circles are the depth-averaged salinity over the potential temperature range encompassing the bulk of the Mediterranean salt tongue (4°–12° C). The connected dots show the salinity distribution at 1000 dbar along the track line from the atlas (Fig. 3 here).

tongue. The core of the tongue, defined, say, by the 35.6-psu contour in Fig. 13, is made up of a large area that almost meets the meddy criterion.

While the third meddy observation along 20° W is narrow, like a classic meddy, we cannot be sure that it is not attached to the main body of the Mediterranean salt tongue lying to the east. The 1000-dbar salinity distribution along 36° N (Fig. 14, seven years earlier than the 20° W section) shows this salinity level, 36.1 psu, in the tongue only 300 km to the east. Given the patchiness of the tongue along both sections, the 36.1 salinity surface could be highly convoluted, and the 20° W third meddy could represent an extrusion from the main tongue. The pinching-off of such an open ocean extrusion could produce a meddy as suggested by Käse and Zenk (1987). However, several meddies (Table 2) have a higher salinity than the Mediterranean tongue, more similar to the salinity near Cape St. Vincent, suggesting that meddies form near there.

Four stations along the 36° N section (Figs. 14 and 15) satisfy the meddy criterion, but three of them are east of the 10° W boundary of our study and in the region of large salinity gradients in the outflow off Cape St. Vincent. The fourth station, number 92 near 12° W, meets the meddy criterion with

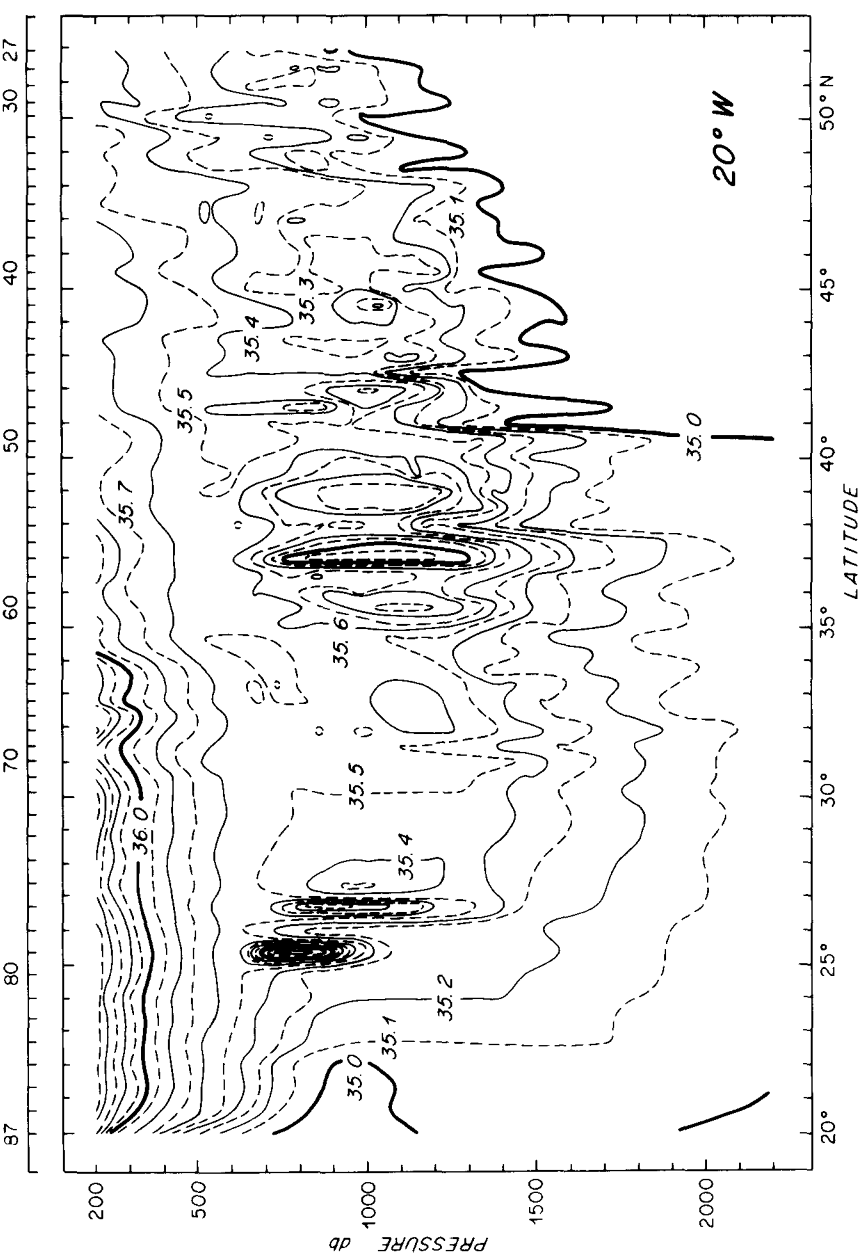

Fig. 13. Distribution of salinity between 200 and 2200 dbar along the 20° W section (location Fig. 3). Contour interval of 0.1 psu. Stations 57, 77, and 79 satisfy the local salinity anomaly ⩾ 0.4 psu meddy criterion.

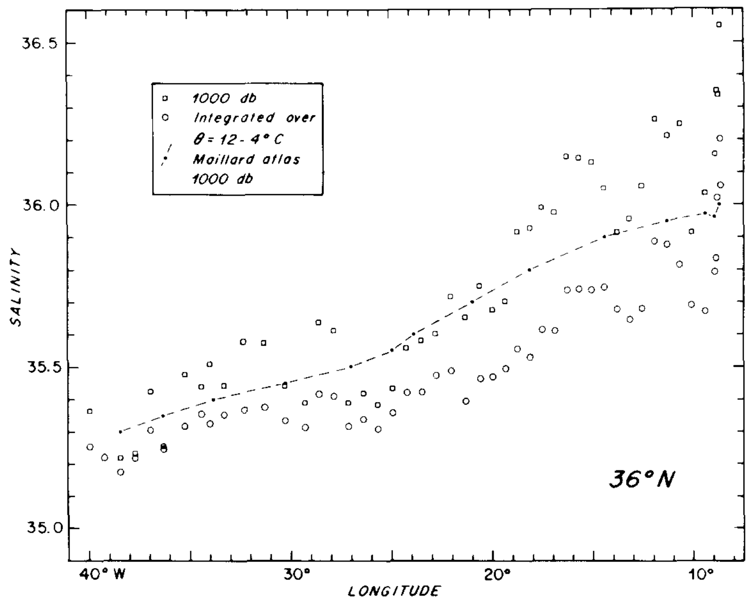

Fig. 14. As Fig. 12, but for 36 ° N section (location Fig. 3).

an anomaly of 0.5 psu. Between 10 ° W and 18 ° W the tongue appears as a series of near meddies, much like it appears along 20 ° W between 35 ° N and 40 ° N (Figs. 12 and 13).

Possibilities of climatological shifts in the structure of the Mediterranean salt tongue are suggested by differences between the synoptic and the atlas average salinity distributions. Along 20 ° W at 1000 dbar (Fig. 12, 1988 data) the synoptic section shows only slightly higher salinity levels on the south side of the tongue which could be interpreted as a southward displacement of about 100 km. But on the north side of the tongue a more dramatic difference is seen: the synoptic section salinity distribution is systematically fresh by about 0.2–0.3 psu corresponding to a southward shift of 300–400 km. Since the centre of the tongue falls at the same latitude in the synoptic section as in the atlas average, the synoptic tongue is thus showing a sharper northern side than the atlas, and a weaker southern side. Along 36 ° N at 1000 dbar (Fig. 14, 1981 data) the synoptic section shows a more salty tongue east of 20 ° W, a fair match with the average between 20 ° W and 25 ° W, and a tendency towards higher salinity west of 25 ° W. In the west this higher salinity could be interpreted as a westward shift of isohalines by roughly 500 km. Such shifts of the basic pattern of salinity in the Mediterranean salt tongue could impact on our accounting of meddies.

Adopting a slightly different approach to the definition of a meddy could result in a significant change in the number of meddies identified. Figure 16

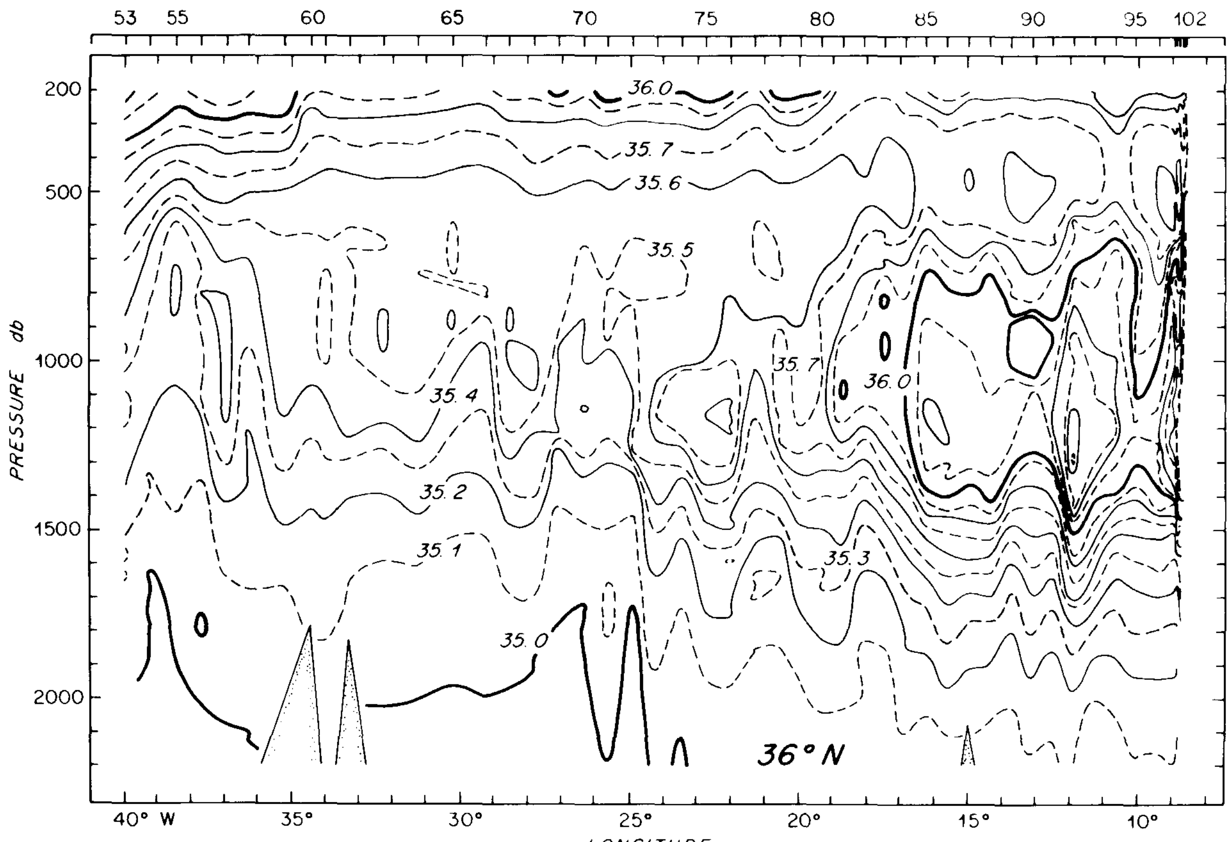

Fig. 15. As Fig. 13, but for the 36° N section. Stations 92, 97, 98 and 99 satisfy the local salinity anomaly $\geqslant 0.4$ psu meddy criterion. The eastern three fall in the Mediterranean Outflow off Cape St. Vincent, and show anomalously saline because of the smearing of thin outflow in the averaging (2° × 2° boxes) of atlas values. This causes the average salt level of the outflow to be less than that of any given synoptic crossing.

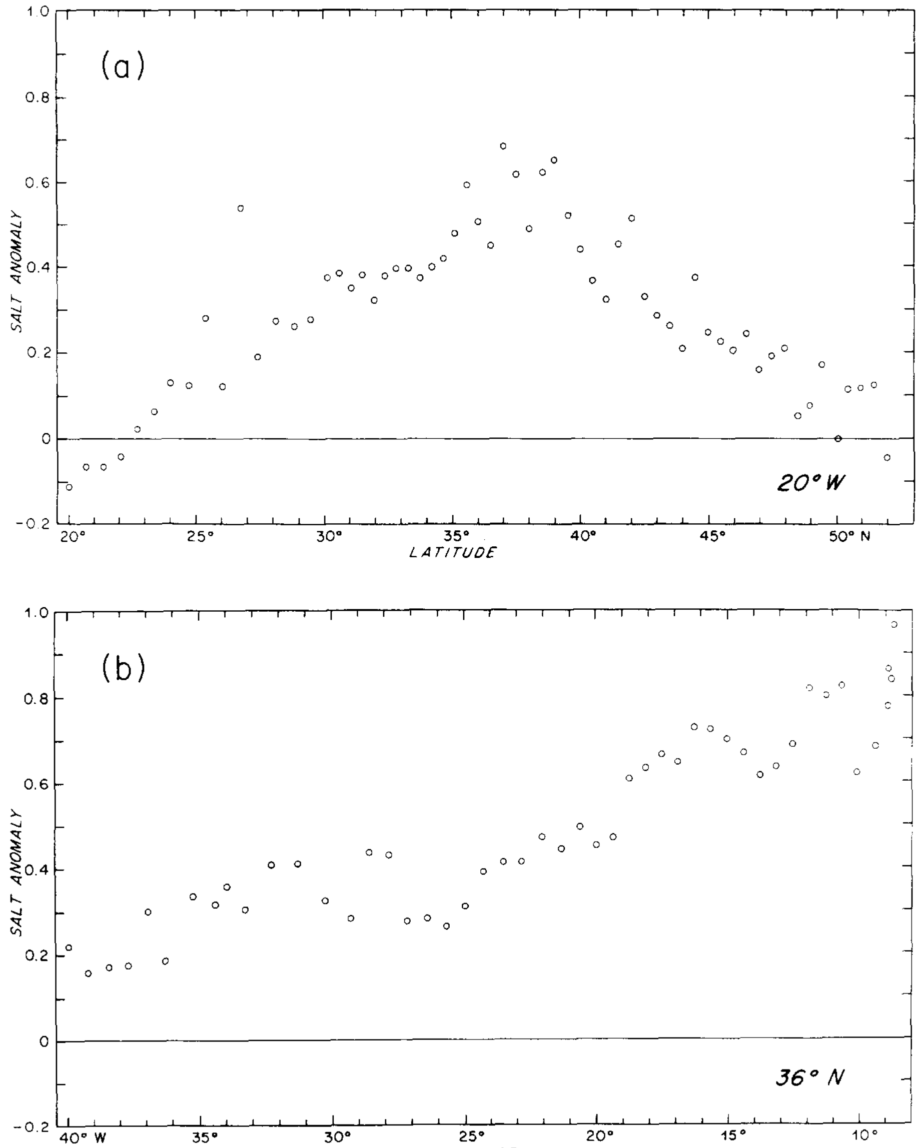

Fig. 16. Distribution of salinity anomaly along the 20° W and 36° N section (location Fig. 3). The anomaly is defined by the differences between the observed salinity at a potential density and the western North Atlantic average salinity at the same density computed from the Armi and Bray (1982) algorithm.

shows the distributions of salinity anomaly at 1000 dbar along the 20° W and 36° N sections defined by subtracting a regional average salinity from the observed salinity at the same density rather than the local average salinity at the same pressure level. For the purpose of illustration and because it is available as a spline fit functional (Armi and Bray, 1982), we have used the western North Atlantic average. This system, using an arbitrary anomaly of 0.5 psu as the selection criterion, identifies nine potential meddies at 1000 dbar along 20° W (Fig. 16a), with seven of them falling in the core of the tongue, one to the north and one to the south. This approach emphasizes the absolute salinity of the water and its anomaly relative to the average ocean as opposed to the anomaly of salinity based upon a locally defined average value. With such an approach, the main body of the tongue could be considered a cluster of meddies possessing nearly identical characteristics to the separate and isolated features identified as meddies by the local anomaly approach. Thus, along 36° N (Fig. 16b) the entire region east of 19° W, the strong tongue, shows as > 0.5 psu anomalies in three main patches: one at the overflow at the eastern boundary, one at 11° W and one at 15–16° W.

4. SUMMARY AND CONCLUSIONS

A search of historical hydrographic data has led to the identification of 25 possible meddy observations, each with at least a 0.4-psu salinity anomaly at the Mediterranean water level. Twenty of these are located in a region extending southwestward from Cape St. Vincent, Portugal; the remaining five are in the north near 44° N where meddies have never been reported before. These northern meddies need confirmation by detailed in situ measurements. The observations imply that meddies are found over a significantly larger area than previously reported. Previous reported meddy sightings were included in this study to show their general distribution especially in the southwestern region where historical station density is very low. Setting aside the five northern ones, the observations fall within a large, oval 1500 km by 3000 km orientated with its major axis in the southwest direction. Meddies could also exist outside this area yet have remained undiscovered from lack of stations or because of small anomalies. However, no 0.3-psu anomalies were found west of the oval suggesting that decayed meddies are not found there or are very small. We expect the number of meddy sightings to increase in the southwestern region and also in the northern region as more stations are made and as oceanographers realize that meddies are common features. Based on the possible meddy observations, we estimate that a population of around 20 meddies could coexist, each one having an assumed mean diameter of 50 km.

Thirty-six anomalies of 0.3 psu were identified in regions of high data density and large horizontal gradients of the mean salinity field. Although these could be meddy observations, we think it more likely that they are caused by less organized time-dependent velocity fluctuations carrying salty water across mean isohalines. Assuming that 0.3-psu anomalies are observations of meddies doubles the estimated meddy population. Combining individual anomalies $\geqslant 0.3$ psu reveals four inferred meddy trajectories during 1970–1971 which generally agree with meddies tracked continuously with floats.

The examination of two CTD sections raises some issues about the interpretation of salinity anomalies as possible meddy observations. In particular the salt tongue itself might be the source of some meddies. A detailed two-dimensional CTD survey of the high salinity tongue could help resolve this issue. A second issue is the effect of large-scale shifts of the salt tongue compared with the mean salinity distribution obtained from historical data.

None of the three possible meddy observations identified by Armi and Zenk (1984) in NODC data were found in the present work which suggests that further study of NODC data could identify more meddy observations.

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