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An interpretation of the double T-S maxima in the Mediterranean outflow using chemical tracers

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ABSTRACT

TSD observations of the Mediterranean outflow into the N.E. Atlantic were supplemented by measurements of nitrate, silicate, and phosphate. Apart from the normal salinity maximum at 1200 m, the occurrence of a T-S maximum at a depth of about 700 m in the Atlantic has often been observed. The chemical data suggest that this upper maximum is due to the release of water from a relatively shallow depth in the Straits of Gibraltar.

1. Introduction

The flow through the Straits of Gibraltar has been described in terms of its T-S characteristics by Schott (1928) who also noted the seasonal variation in the depth of the boundary zone between the Eastward flowing Atlantic current at the surface and the Westerly movement of the deeper Mediterranean water. The changes in the depth of such a boundary due to internal tidal oscillations in the Straits has been discussed by Defant (1961). His theoretical treatment and use of observational data indicate vertical oscillations of amplitude as great as 100 m for a current boundary which generally lies at a depth of about 150 m. On leaving the Straits, the mixing and sinking of the Mediterranean water to a depth of 1200 m is well established, and recently Madelain (1970) has suggested a preferred flow path around the northern part of the Bay of Cadiz where the topographical features of that region will influence its route as it proceeds towards Cape St. Vincente.

The use of continuous bathysonde and TSD systems have revealed numerous occurrences of double maxima in the T-S profiles in the region to the West of Cape St. Vincente (Gieskes et al., 1970; Zenk 1970; Howe and Tait

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1973), where an upper maximum in temperature and salinity has been shown to exist at about 700 m. This feature has also been recorded farther afield by Cooper et al. (1962) in the Northern Atlantic and Zenk (1973) in the Western Atlantic. Siedler (1968) has suggested a process which involves tidal mixing in the Straits to produce two such preferred salinity maxima at different depths in the Atlantic.

The observations described here are part of a cruise which was planned, as near as possible, to coincide with the period at which the outflow from the Straits would have attained its maximum winter activity. During March 1973 a series of stations was made around Cape St. Vincente and into the Bay of Cadiz by R. R. S. Shackleton. In addition, one station was made, for comparison, to the East of the Straits in the Mediterranean itself. The physical data was supplemented with samples at standard depths for the determination of nitrate, silicate and phosphate. The relationships between these nutrients and the physical parameters are discussed and the results are used to identify the source of the upper maximum and to estimate the depth of the boundary zone within the Straits at the time of the release of this water into the Atlantic.

2. Observations

The 7 sections of closely spaced stations, including those at which chemical samples were obtained, are shown in Fig. 1. A TSD system was used which incorporated a Rosette water bottle array for the chemical sampling.

Samples for nutrients were filtered using membrane filters (0.45 µ) and stored
in deep freeze. A Technicon Auto-Analyser was used for the determination of the nutrient salts. Silicate and nitrate were analysed according to a method described by Brewer and Riley (1965, 1966) and phosphate by an automated modified version of Murphy and Riley's (1962) method. The SiO$_4$-Si, NO$_3$-N determinations were made in triplicate with a maximum error of 0.1 µg-at/l and the PO$_4$-P in duplicate with an error of 0.02 µg-at/l.

There was a significant correlation between the nutrient values and the main features in the T-S profiles. In particular the low values of the nutrients clearly corresponded with the presence of high salinity water at the different depths. This is illustrated in Fig. 2 where the detailed T-S profiles, reproduced from the original TSD records, can be compared with the nutrient profiles at two stations 73 and 95. Since it is expected that the nutrient concentrations should gradually increase with depth, it is clear that the decrease in nutrients at certain levels was associated with the intrusion of high salinity water.

These stations are part of sections V and VII respectively which show the
more general correlation between these parameters (Figs. 3 and 4). They also provide evidence of the variability of the water structure in this region with the high salinity Mediterranean mass confined to relatively shallow depths on the continental slope along section VII, whereas the aforementioned double maximum is well illustrated in section V.

The results of the water bottle cast at stn. 148 (see Fig. 1 inset) in the Mediterranean itself (35°57.8'N, 5°00'W) are shown in Fig. 5, which also includes the average profiles for the salinity and nutrients in this area of the Atlantic when the sporadic presence of the high salinity Mediterranean water at 600 and 800 m has been excluded.
Except for these depths the average Atlantic profiles were constructed by including all the data that was obtained in the chemical sampling. At 600 and 800 m however it was possible to detect a relatively high salinity (low nutrient) water mass in a variable state of admixture, and the relationship between the nutrients and the salinity was computed in the form of a regression equation at each depth. The values that are plotted at 600 and 800 m in the average profiles (Fig. 5) are therefore those which can be regarded as representative of the Atlantic in this region if the Mediterranean water influence were eliminated. The appropriate values were taken from the regression lines as a best estimate of these conditions and so represent the low salinity, high nutrient concentrations that normally prevail at these depths. A comparison between Figs. 2 and 5 therefore illustrates the distortion of the profiles, particularly between 600 and 800 m, when high salinity water is present.

The decrease in nutrient concentrations between 1000 and 1200 m can be regarded as normal since they will be related to the relatively high salinity water which is a permanent outflow feature at this level.

The low nutrient values associated with the upper maximum revealed an apparent contradiction in the normally accepted explanation of the outflow
process that occurs in the Straits. The high salinity water is usually expected to flow out over the sill from depths of 150–300 m and mix downwards to the 1200 m level. The results of this analysis certainly agree with such a well established process. However the range of nutrient values at the intermediate depths of 600–800 m were such that, in some cases, the resultant concentrations were less than those of both this apparent source and the layers in the Atlantic through which any mixing would occur. It is this result which is crucial to our interpretation of the upper maximum and will form the basis of the following discussion.

As mentioned previously the distortion in the profiles was analysed in terms of the nutrient-salinity relationships at 600 and 800 m. These are represented in Fig. 6 by the regression lines (solid) for nitrate-salinity, where the correlation coefficients were \(-0.84\) and \(-0.80\) respectively, and silicate-salinity with...
correlations of \(-0.78\) and \(-0.83\) respectively. The ‘goodness of fit’ of the regression lines for both nutrients was such that at 600 m, 94\% of the observations lie within one standard error of the estimate given by the regression equation, whereas at 800 m 100\% lie within one standard error. The regression equation was applied within the range of salinities that were actually observed at each depth. The lines, as shown, have therefore been drawn between salinity values which vary from 35.56°/oo to 36.59°/oo at 600 m, and from 35.69°/oo to 36.64°/oo at 800 m. The observations show that at these depths there was a relatively high salinity (low nutrient) water mass which in some cases was so anomalous in both its physical and chemical properties that the identification of its source might be attempted with some confidence.

3. Discussion

The source of the upper T-S maximum is of particular interest and so, for comparison, the salinity-nutrient relationship for stn. 148 has also been plotted in Fig. 6. The significant point in each regression line is the high salinity (low nutrient) value which has been labelled X and Y for convenient reference. They must represent the upper maximum in what can be regarded as its most original state. Several possible explanations for the existence of this water mass are discussed below and there is evidence to suggest that some of the previous ideas concerning its production are not quite consistent with these observations.

1. If water has passed through the Straits unmixed and descended to 600 or 800 m with little or no mixing to produce concentrations denoted by the points X and Y, then corresponding values should be identifiable at source. An extrapolation, where necessary, of the regression lines (Fig. 6) will intersect the Mediterranean profile (stn. 148) and provide the appropriate salinity-nutrient values. These were in fact observed in the Mediterranean column at depths of 100 m and 110 m respectively.

2. However the outflow process might be more complicated in that a certain amount of mixing within the column would occur as the water passed through the Straits, as well as with the deeper layers of the Atlantic during its descent. Firstly let us consider the mixing relationship which produces the values X, Y as the result of Mediterranean water descending through the Atlantic column. The mean values for the salinity-nutrient concentrations in the Atlantic from the surface to 600 and 800 m were computed and are plotted as A2 and A1 respectively. The corresponding mixing lines (broken) in Fig. 6 would then connect A2 and A1 to the source by way of the respective observed values X and Y. A point source for each can be determined from the intersections with the Mediterranean profile. The X values are related to those at a depth of 100 m in the Mediterranean whereas the Y values would be produced by water originating from a depth of 115 m, according to the silicate-salinity profiles, or 120 m if the nitrate-salinity relationship is used.
3. A further complication in the outflow process might be the degree of mixing within the Mediterranean column as it passes through the Straits and its effect on the resultant concentrations, which would then constitute the source. The main outflow is expected from depths between 150–300 m. The point M4 represents the average mixed conditions of this layer and since it lies well beyond the range determined by the suggested mixing lines (broken) it cannot be considered as a source. That is to say, water leaving the Straits with these salinity-nutrient characteristics and mixing down the Atlantic column with values such as A2 or A1 cannot produce the salinity-nutrient concentrations X, Y that were in fact observed. Similarly if complete tidal mixing of the column (0 to 300 m) within the Straits occurred, this would produce a salinity-nutrient composition represented by M3 which for the same reason does not comply with the source requirements. It seems that the only water mixture which can provide the correct source concentrations is that which is confined to the top 150 m in the Mediterranean. For example M2 and M1 are representative of complete mixing of the water column between 50–150 m and 0–150 m respectively. These values can be related by the mixing lines to the conditions in the Atlantic (A2, A1) and so produce the required concentrations in X and Y.

4. The construction of the mixing lines, which have been critical to the argument, depend on the values A2 and A1. These, as mentioned previously, include the concentrations in the surface layers of the Atlantic. It is reasonable to assume that the source water will have little or no contact with these layers as it sinks from the Straits. In fact the $\sigma_t$ profiles for the Mediterranean column increased from 27.10 at the surface to 28.83 at 200 m, whereas in the Atlantic values of 27.10 were not attained until the 400 m depth. Therefore the points A2 and A1 should probably be biased more towards conditions in the deeper layers of the Atlantic and so include greater nutrient concentrations. The resultant mixing lines (broken) would then show a greater slope and converge more closely to the 100 m depth in the Mediterranean profile. This would substantiate each of the results obtained in the above discussion which all indicate that the water in the upper maximum has originated from a relatively shallow depth in the Mediterranean.

Finally it should be mentioned that a similar application of the salinity-phosphate relationship was not as successful in the identification of the source water. The individual profiles and sections (Figs. 2–4) show that as an indication of high salinities in the Atlantic the correlation was comparable with that of the nitrate and silicate. However the general uniformity of the phosphate values with depth in the Mediterranean column compared with the increase in nitrate and silicate (Fig. 5), meant that the influence of the different layers could not be distinguished with any degree of certainty when using phosphate as a tracer.
4. Conclusion

The chemical observations suggest that the depth from which the water in the upper T-S maximum originates is relatively shallow. By considering various situations involving different degrees of mixing, both in the Straits and down the slope, the silicate-salinity and nitrate-salinity concentrations show that the source is above the normal boundary zone in the Straits and probably closely confined to the 100 m depth. There seems to be no other explanation for the low nutrient values that were observed in the upper maximum. At the time of release the boundary zone might be as shallow as 50 m and, allowing for some mixing, typical T-S values for the water leaving the Straits would be 14.2°C and 37‰. These are compatible with the observed values of 13°C and 36.6‰ in the T-S maxima at 600–800 m in the Bay of Cadiz. The vertical movement of the boundary zone in the Straits conforms with Defant's (1961) analysis, and the intermittent release of this upper water mass at specific times might well be controlled by a process similar to that described by Siedler (1968). But it seems that during such an event the mixing in the Straits is less than anticipated, with the outflow at the shallow depth maintaining its characteristics and preserving the stratification within the water column.

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