COMITÉ D'OCÉANOGRAPHIE PHYSIQUE

Président : Prof. LACOMBE (France)

PHYSICAL OCEANOGRAPHY OF THE MEDITERRANEAN SEA : A DISCOURSE

by Arthur R. MILLER

SUMMARY

A progress report is given on the results from four recent cruises of the Woods Hole Oceanographic Institution in the Mediterranean Sea. These cruises include " Chain " 7 june 1960, 11 stations; "Chain" 21 october-november 1961, 137 stations; "Atlantis" 263 february-march 1961, 138 stations, and " Atlantis " 275, february-march 1962, 119 stations.

The purpose of these cruises was to determine and observe the areas, during the most probable times of formation, where deep and bottom waters may have their origin. Areas of concentration were the Ligurian Sea, the Adriatic Sea, and the Cretan Sea. Hydrographic sections were also made throughout the Mediterranean from the Alboran Sea to the Sea of Marmora.

Precise temperature and salinity characteristics for the various deep water masses were obtained. Evaporation and net radiation measurements were carried out aboard ship. Drift bottles were set out. Samples were taken for phosphate and nitrogen analyses and dissolved oxygen was determined.

INTRODUCTION

When one estimates the quantity of water in the World Ocean in terms of its temperature and salt content such as Montgomery has done (fig. 1), it is remarkable that most of ocean water is made up of a certain type of very cold water with a definite salt content. Its uniformity leads one to believe that it has existed in this state for a very long time. If one can point a finger to its origin or origins it necessarily must point to the Polar regions. These are the heat sinks of the water world.

Although one may conclude that this water is very old, it cannot be assumed that the process by which it originated has ceased. It continues year after year. The question may follow-how fast and in what quantities is this water made? These are problems of vertical circulation. Similarly we must consider how long can a given parcel stay at the surface to be affected by those changes occurring at the interface. The energy exchanges which govern the state of a parcel of water and modify its condition at or near the surface create what may be called « new » water. Once the water leaves the surface environment it begins to " age " until it is once more returned to the surface. The process of creating new water must be very small in terms of the entire volume of the ocean.

If the process of making new deep water is a continuing one, what phenomenon of nature controls its spectacular uniformity? It is true that when we look at the possible places of origin, in terms of size, these places are mere faucets of small capacity in comparison with the enormous basins of the world. As far as the Atlantic Ocean is concerned there is the heat sink near Greenland where water must leave the surface for deep depths since its high salinity once cooled does not permit it to remain. In the Southern Ocean, namely, the Weddell Sea, we have another heat sink where the surface water is cooled past its freezing point and its brine squeezed out of the sea ice to take part in the forming of deep bottom water. It is generally assumed that this phenomenon takes place near the coastal shelf where the newly formed water can sink to the floor of the ocean. We are not completely tied to this hypothesis, for, if sea ice can be formed considerable distances away from the shelf, its brine has to sink where it is, rather than be transported in an unstable condition laterally.

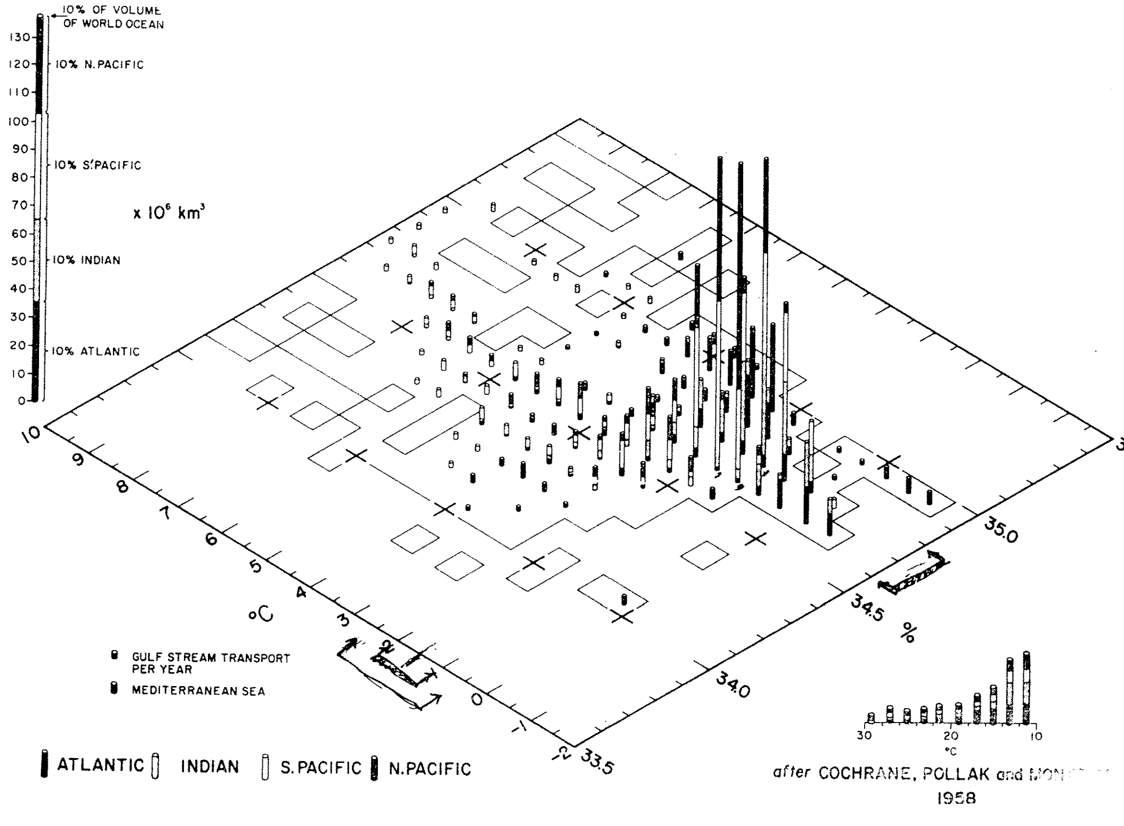

FIG. 1. — *Temperature, salinity, volume diagram of the World Ocean.* (After COCHRANE POLLAK and MONTGOMERY, 1958 : graphic presentation through courtesy of H. Stommel).

What is the volume of production of these unique masses of water? What is the mechanism of this production? And how do these masses sink to the floor of the ocean? What is the compensation for this vertical downward transport? And, in turn, what is the significance of vertical movement to lateral transport?

The Mediterranean has in itself a strong influence on the Atlantic Ocean. WÜST has shown the spreading or " Ausbreitung " of the Mediterranean water clear across the North Atlantic diluted as it goes westward but nevertheless strong enough to be detected in continuity. In order to produce this great volume of water, is it made up in large quantities seasonally — or is this great influence merely a show of time long past? These are some of the reasons why my colleagues, TCHERNIA, CHARNOCK and myself and others have gone to the Mediterranean for some enlightenment. Vertical circulation in the Mediterranean is active if only for its small density ranges.

I am not going to give estimates on rate of production. Although we are hopeful, methods are still rudimentary and there are other facets to this problem remaining untouched. Let us say that modern techniques point to ways and means of attempting to solve this problem — rate of production. What I will give you now is in the way of a progress report on some cruises in Mediterranean waters. These were mostly concerned with the winter time to re-discover key areas already pointed out by other investigators. We tried to observe as closely and practically as we could, with our present instrumentation, the means in which water of the Atlantic arriving in the Mediterranean is transformed into saltier water, sinking at depths and to the bottom, finally finding its way out of the Straits of Gibraltar to influence the entire North Atlantic.

General description.

I will not dwell on the history of the Mediterranean. There is much in the literature on that subject. For the most part Mediterranean efforts have been confined to local areas. Only recently Dr WUST has written a paper in which he uses data for the past 50 years — and he comes up with a total of a little more than 500 stations in that 50 years time. From these stations he has deduced a seasonal circulatory pattern based on data taken before 1956.

It is worthwhile to note matters of technique in surveying the Mediterranean. Here we have an inland sea whose general range of salinity and temperature, aside from the superficial areas, is very narrow indeed. We might say that the deep water temperature and mid water temperature may range between 12,7° C to perhaps 14,5° C. Also its salinity range may be between 38, 4 ‰ to 39, 0 ‰. Any observations beyond this range are close to the surface or matters for local interest. So one can easily see, when taking samples of Mediterranean water in this limited range, the techniques required are rather stringent. Noise in the data due to rougher techniques of yesteryear are almost as variable as the observations. Thus, extreme care and certainty is required in modern observations.

It is only recently that we are now depending upon methods of salinometry which use a device giving one confidence in being able to estimate the value known as salinity to as much as 0,003 ‰ accuracy. — In contrast to possible errors using silver nitrate titration of 0,05 ‰. So this tenfold improvement in technique in observing the salt content requires another look at that ocean with limited range of values, the Mediterranean.

In 1961 we proceeded to the Mediterranean with the " Atlantis " equipped with a modern salinometer and occupied 138 stations in the Western Mediterranean (fig. 2). In 1962 we also occupied winter stations throughout the entire Mediterranean. In 1961 in the fall we obtained a number of observations in the Eastern Mediterranean. Closely allied with the planning of these cruises were my colleagues, TCHERNIA and CHARNOCK, as well as my associates, MUNNS and DENSMORE. With the guidance of TCHERNIA, who has done considerable work in the Mediterranean, we were able to concentrate our work on certain significant areas which we considered to be potentially active in the interaction between the air and sea with subsequent production of deep and bottom waters.

Essential features of Mediterranean circulation are worthy of mention. First of all, the source of supply of water in the Mediterranean is primarily the water entering through the Straits of Gibraltar from the Atlantic. Minor influence comes from certain rivers and run-off areas such as the area surrounding the Adriatic Sea, the Nile and the inflow through the Straits of Dardanelles. In general, one can say that the Mediterranean Sea is mostly North Atlantic water modified by its environment.

We can give a rough picture — not a real picture since it is oversimplified — of the general circulation. Think of it this way. The North Atlantic water, the surface North Atlantic water — an important factor in the quality of the Mediterranean water masses — enters through the Straits of Gibraltar, more or less follows the shores of North Africa and, sometimes, spreads out over the surface, some of it going up to the northern part around Corsica and the Tyrrhenian Sea

That is not all. The remaining North Atlantic water at the surface, now very much changed, continues eastward and reaches the eastern shores and travels north. All this time, in its eastward migration, it is undergoing the evaporative and cooling processes and " enjoying " the Mediterranean sun. So it is also absorbing heat through solar radiation, more or less unimpeded by cloud interference. As it goes north from the southern portion it becomes, in the wintertime, influenced by cooling. The very high salt water in the eastern area comes into the Aegean Sea and is cooled there by air masses coming across Turkey. In the Cretan Sea we have another source of deep water which I will mention later on.

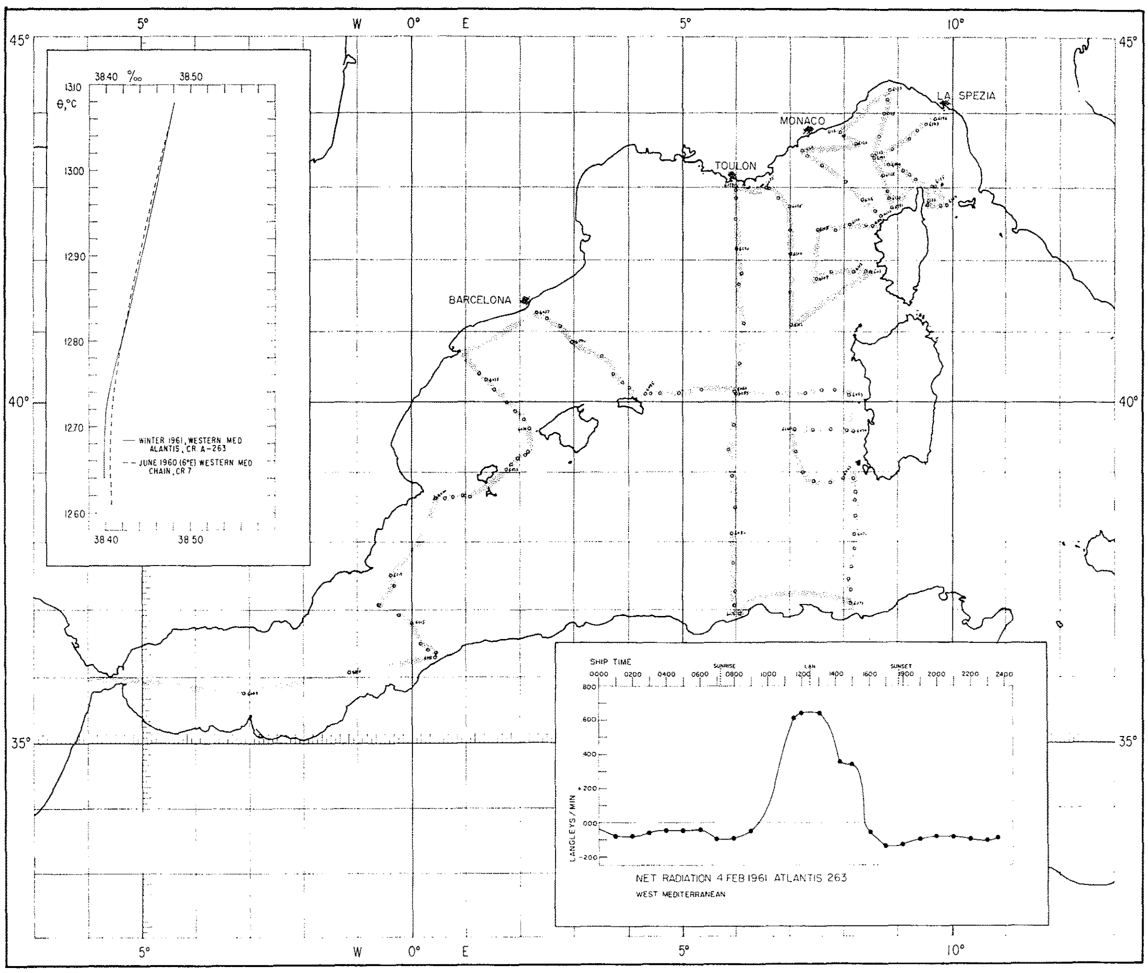

FIG. 2. — *Hydrographic stations occupied in the Western Mediterranean during " Atlantis " cruise 263.*

where it becomes modified by the evaporating and cooling effect of dry polar air masses from the continent of Europe. Subsequent to this modification it sinks, producing a definite water type in the deep Western Sea.

North Atlantic water also passes through the Straits of Sicily, continues eastward, moves about in the Eastern Mediterranean, some of it going to the north and into the Adriatic where, again, it is affected by the continental air masses flowing over the water. It is cooled, sinks, and pours out sporadically over the sill of the Straits of Otranto to form the deep water mass in the Eastern Mediterranean.

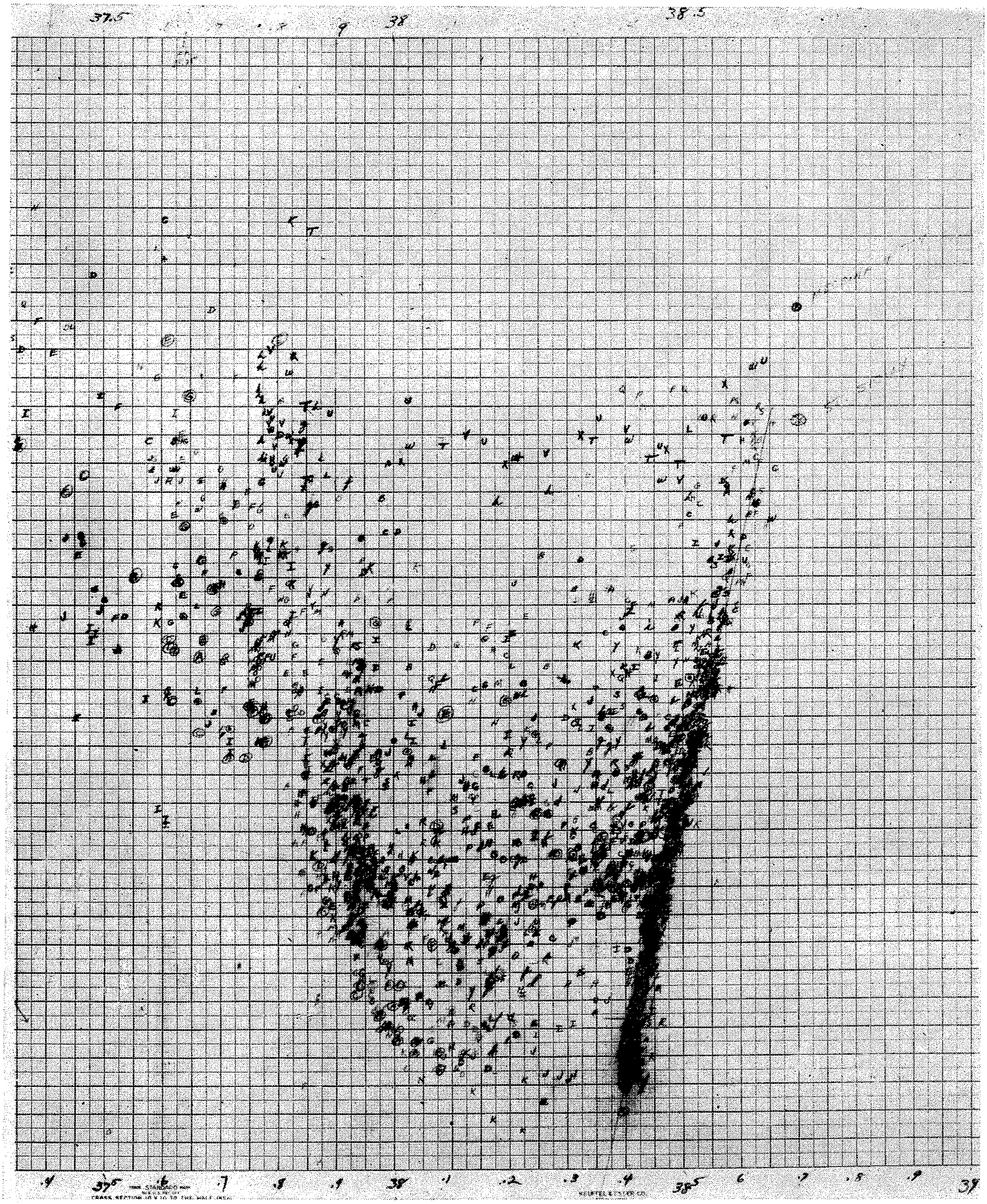

FIG. 3. — *Working T/S diagram of "Atlantis" cruise* 263. T = Θ, potential temperature.

In this oversimplified circulatory scheme, the water must leave. It leaves the Straits of Gibraltar over the bathymetric sill creating an artificial sill for the incoming water. From there it spreads out to the North Atlantic Ocean.

We have made attempts to measure the energy exchanges at the interface by observing solar radiation and net radiation, by making tests of evaporation using local surface water in an evaporating pan swinging in an exposed position, estimating from the gain in salinity the loss of water sometimes on an hourly basis. Other factors concerned here were the air temperature, humidity and wind.

A cooperative drift bottle effort was made with the French Hydrographic Service. In 1961 we seeded about 1 500 bottles, ballasted and containing plastic " flotteurs ". We have received about 12 % return — normal return from flotteurs alone is about 3 %.

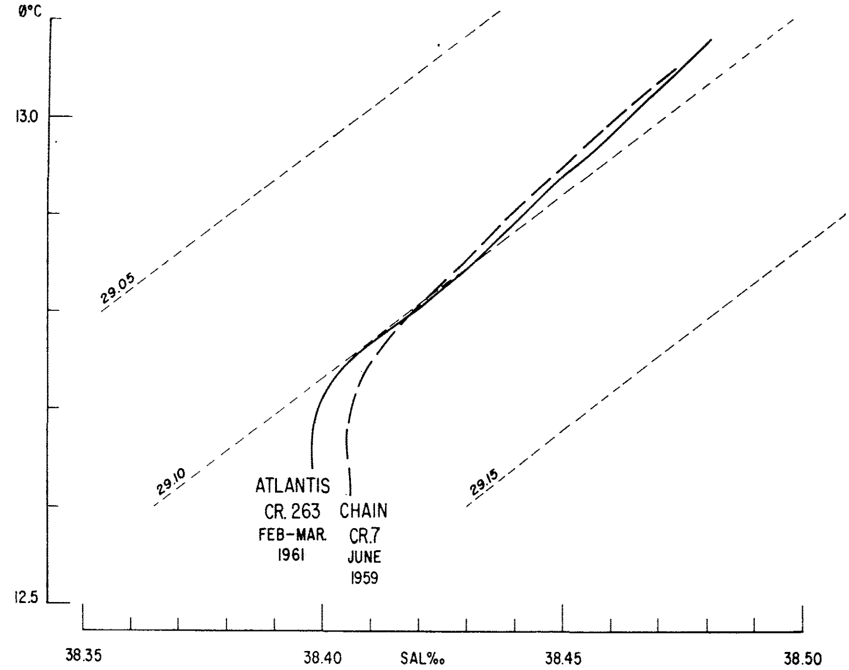

FIG. 4, — *Θ/S diagram for cruises " Atlantis " 263 and " Chain " 7.*

In the study of vertical circulation it is somewhat questionable as to what you observe. For instance, vertical movement. — How do you observe water that is falling? At our present stage of techniques we can only observe this kind of circulation in an indirect manner and must deduce it in various ways.

With regard to the results of these cruises and what they signify in terms of vertical circulation it is best that one take a look at the results of applying the T/S correlation to the data. A rough T/S diagram (fig. 3) was constructed with temperature expressed potentially. The adiabatic effects due to pressure were removed, the points representing water as it would exist if it were brought to the surface or if it had originated at the surface.

One can see in the Western Mediterranean T/S relationship a very definite lineup of the deep water in a straight line. The superficial waters remain spread throughout a much greater range. You will notice that this line is very tight and narrowly confined in the presentation. Blowing up this portion of the diagram where most of the observations are concentrated we were able to produce a characteristic T/S line which describes the water of the Western Mediterranean for the winter of 1961. This next diagram (fig. 4) shows the results from using a statistical treatment for every one hundredth of a degree centigrade. One can see that it is not truly a straight line. In the very coldest water we have a sharp bend at this scale. Also on this diagram are the results of another season diametrically opposed in time, June, " Chain " 7, in the Western Mediterranean. One can see that in June the bottom water is colder and slightly saltier. I point out the fact that " Atlantis " 263 shows a significant stretch of observations completely neutral

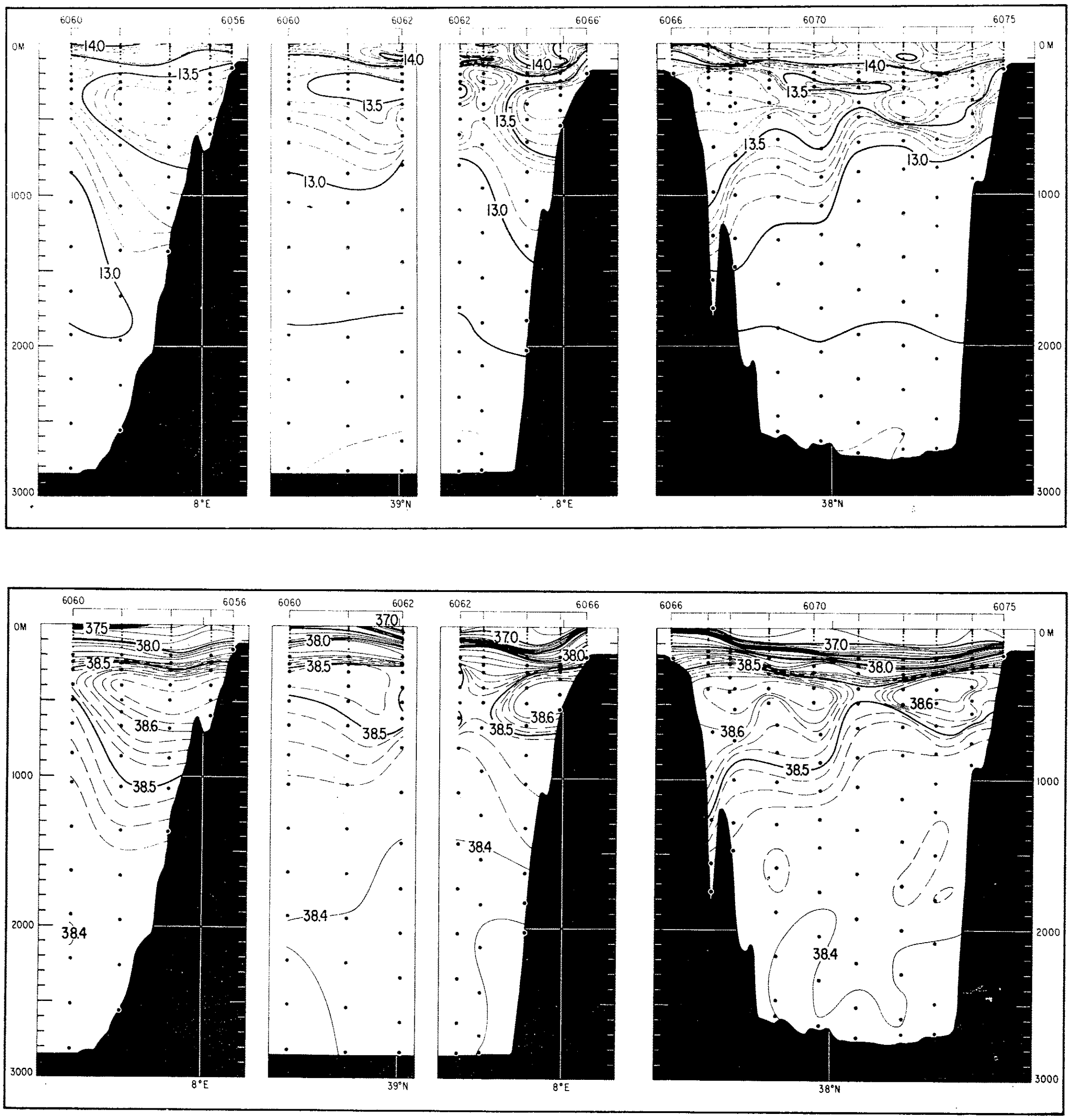

FIG. 5. — *Temperature and salinity profile from Sardinia to North Africa* (right) *and off west coast of Sardinia.*

in potential stability. You will notice that the T/S curve for " Chain " 7 is completely stable in all its parts. These two T/S curves taken at opposite seasons show that there probably is a pronounced seasonal change in Western Mediterranean deep water.

I will show, now, some profiles, cross sections taken during the '61 winter cruise. The first diagram (fig. 5) shows the passages, north to south, or, west to east, from Sardinia to

North Africa. Also, from Toulon to North Africa (fig. 6). The easternmost of these shows very clearly the Levantine Intermediate Water crowding to the right downstream yet tonguing in the central portion, that tongue appearing in the Toulon section. This is also apparent in the temperature of the intermediate water. On the surface as one goes east the water was warmed to over 14°. If I may jump to the end product of this Western Mediterranean circulatory system I'd like to point to station 6087 where there is a connection between the surface and the deep water but not a through connection. It would appear that water is sliding downhill, so to speak,

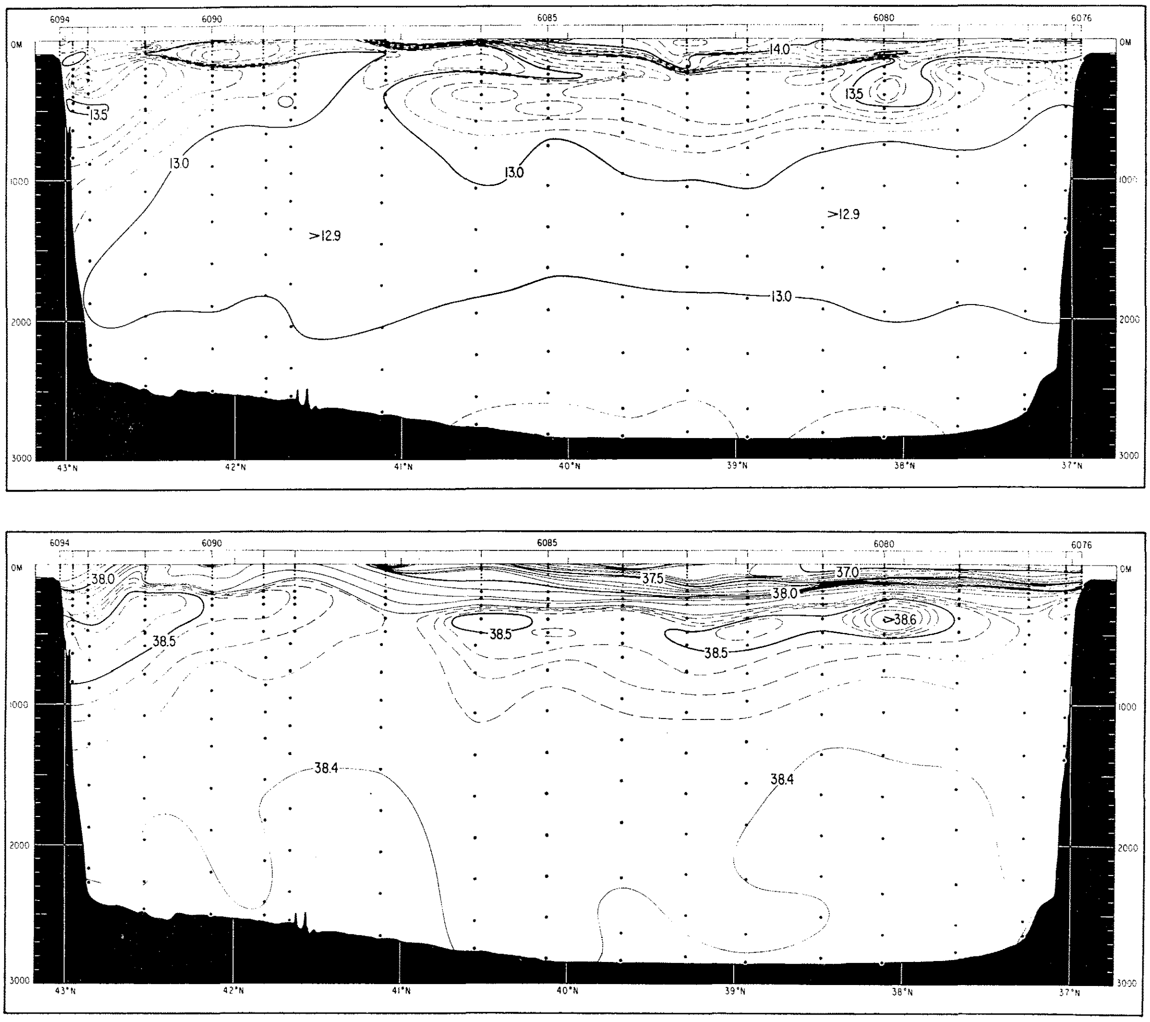

FIG. 6. — *Temperature and salinity profile Toulon to North Africa.*

and eroding the intermediate layer. This cold water tongues toward the south. If we follow the Levantine Intermediate water and surface water to the end product of deep western Mediterranean water we can see that this area near station 6087 is the most likely spot for a vertical breakthrough.

There were no significant outbreaks of polar air masses, continental air masses, approaching the Northern Mediterranean during this cruise. It was relatively quiet. Yet we show a sign of change and possible sinking. Other slides permit us to trace the Levantine Intermediate

Water (fig. 7, 8) up the coast of Sardinia and Corsica — weakening along the way. These next sections (fig. 9) show cross sections between Corsica and the French Riviera across the Ligurian Sea. We see that the central part is définitely not Levantine water but something else. The

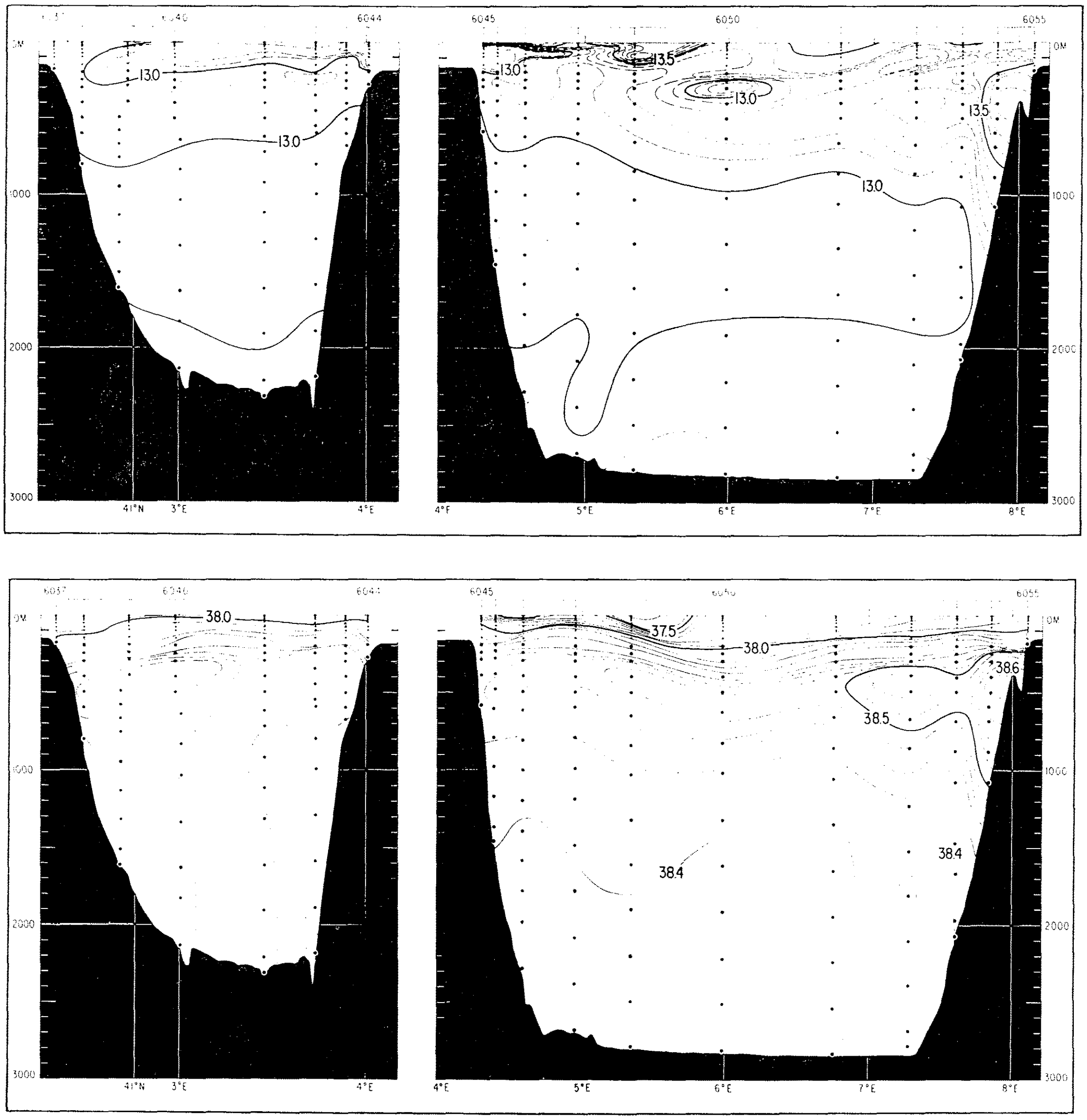

FIG. 7. — *Temperature and salinity profile Spanish mainland to Minorca, Minorca to Sardinia.*

Intermediate water hugs the coast of Corsica, goes around in a circular fashion to the east past the tip of Corsica towards the Italian Riviera, following the coast to the French Riviera and along the southern coast of France to the west. It is somewhat strengthened by water passing through the straits near the Island of Elba.

Sections were made in the Ligurian Sea in the geographical form of spokes of a wheel (fig. 10). It would appear that the most probable origin of deep water was off center from the hub of this wheel and to the southwest of this center. As we follow the Levantine water to the west, and to the coast of Spain, we must consider the influence of the Rhône and the Gulf

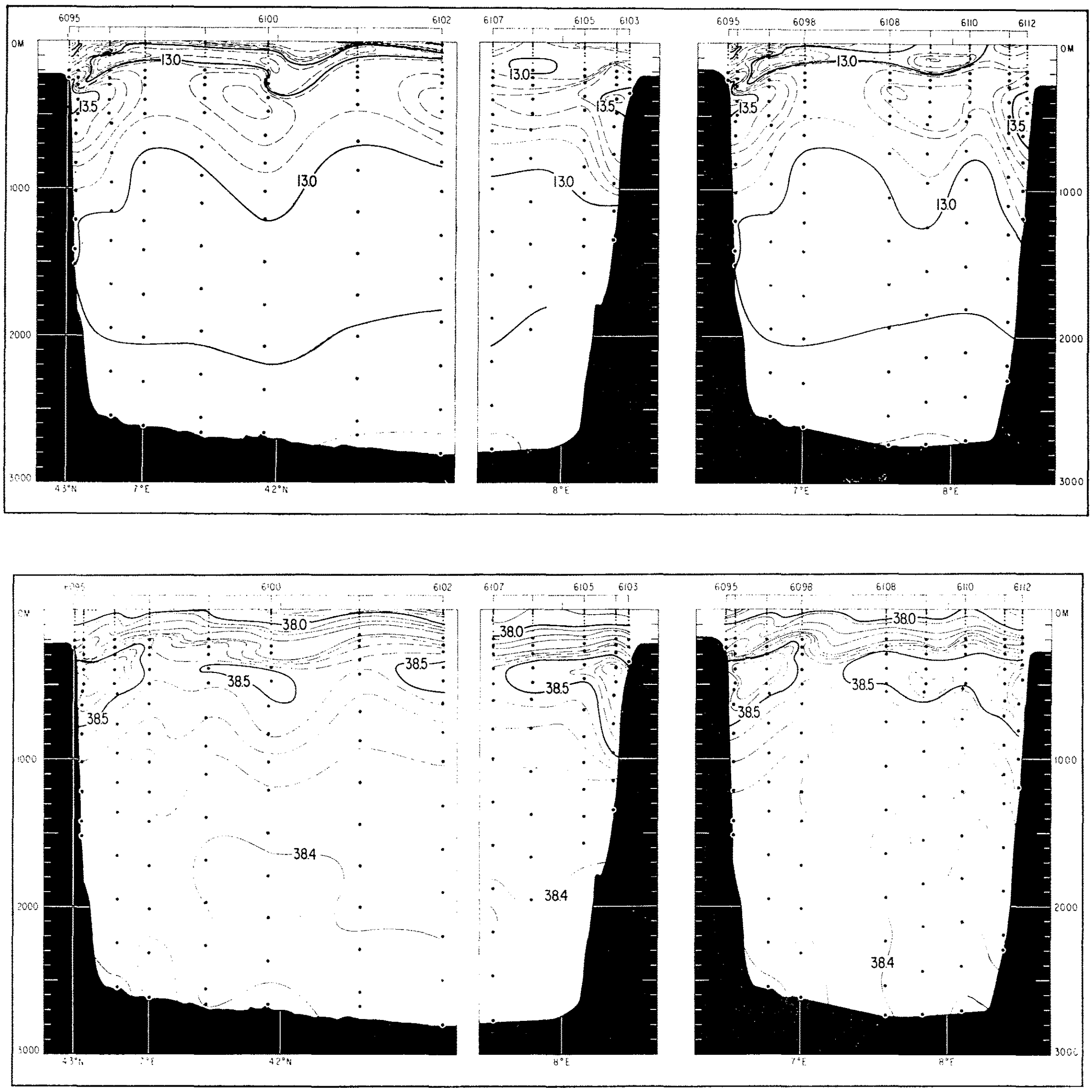

FIG. 8. — *Temperature and salinity profiles west coast of Corsica, French Riviera to Corsica.*

of Lion. There is a cold water influence from this region, but too stable and fresh to condition the water for sinking. There is one unexplained portion (fig. 11) and that is the deep cold water near the Balearic Islands. Its continuity seems to be lacking in the remaining sections. The cold water in the Toulon section can be traced and followed back along the African coast. Where it goes from there is anybody's guess.

Since there were no notable continental air outbreaks this season, we find that perhaps there is another explanation for this apparent sinking of water masses. It is necessary to look at the circulation at the surface. The next slide (fig. 12) shows in a graphical form the places where drift bottles were set out in groups of ten. Then the following slide (fig. 13) shows the

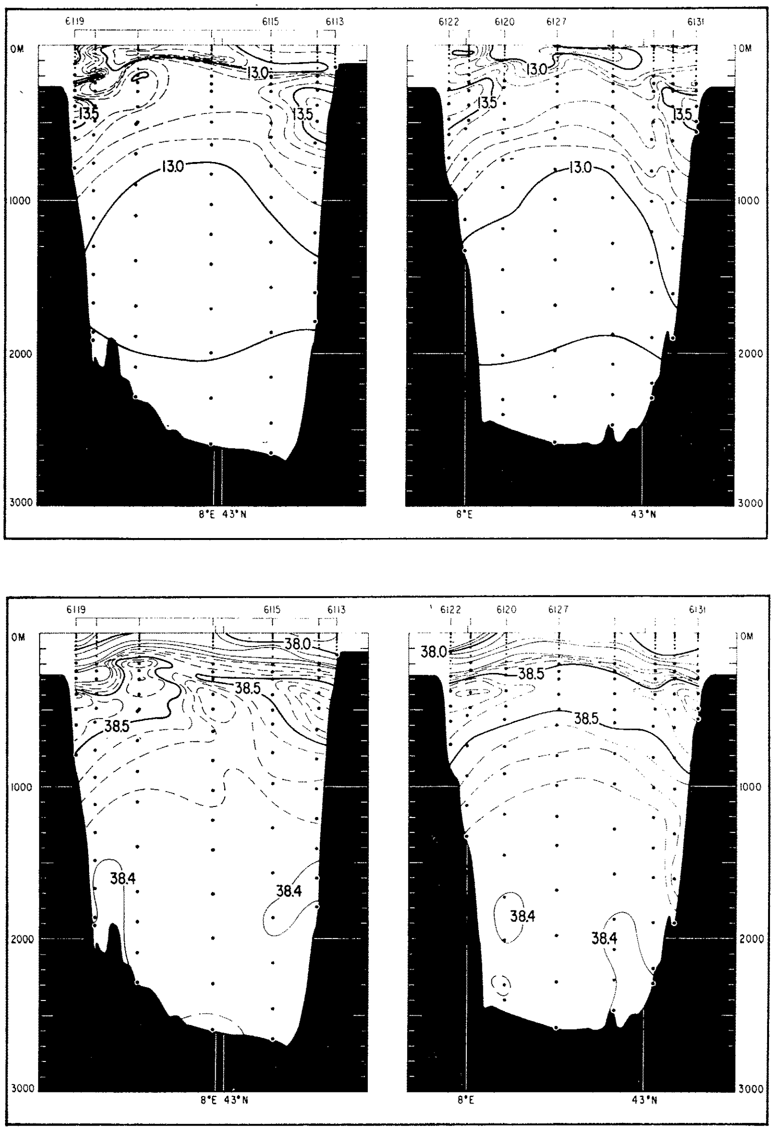

Fig. 9. — *Temperature and salinity profiles across SW Ligurian Sea.*

places where they were recovered. Most significant is the fact that bottles from the Ligurian Sea area were recovered rather rapidly from both shores, indicating a circular surface current regime where water recirculates back into the area. This water seems to be moving around in a counterclockwise direction circulating about the hub of the « wheel » we used as a pattern for investigation. If one considered how long a sample of water could remain on the surface, here is one place where a sample of water can return again and again to be cooled and cooled some more from evaporation and radiative cooling. In this way it is possible that even in quiet winters such as this one, deep water, or waters having the same density of deep water, can be formed.

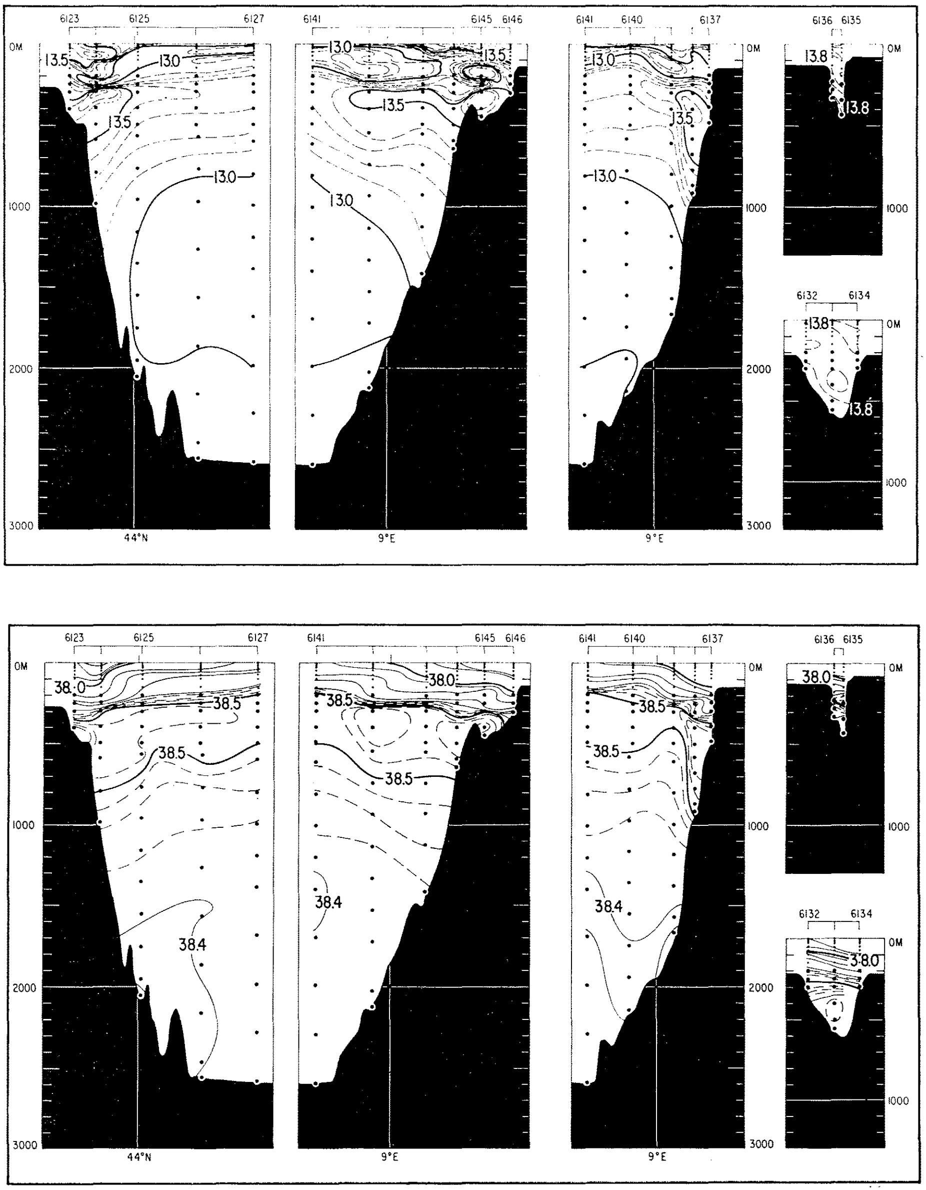

FIG. 10. — *Temperature and salinity profiles of the Ligurian "wheel".*

I have only cursorily examined and discussed this important area of the Mediterranean. Now I wish to point up general features of the entire circulation that have aroused our interest, raised some questions and given us some answers.

The next slide (fig. 14) takes into account all the recent Woods Hole cruises to the Mediterranean. It only used those portions of observations in which a definite straight line grouping occured in the T/S relation. These lines represent the T/S character of the deeper Mediterranean water from the west to the deep waters of the Sea of Marmora. Since this diagram is aimed at the deep circulation I will only point out the scale which is rather large and the fact that these cruises are compatible with each other. In certain cases they show significant differences. You can see that the waters of the western Mediterranean are significantly characteristic from one year to the other. — these cruises were both taken in the winter time. The Gulf of Lyon water is somewhat fresher than the general Western Mediterranean while the Tyrrhenian and Ligurian Seas is saltier. The high salinity scale of Western Mediterranean water extends towards the lines describing the Eastern Mediterranean.

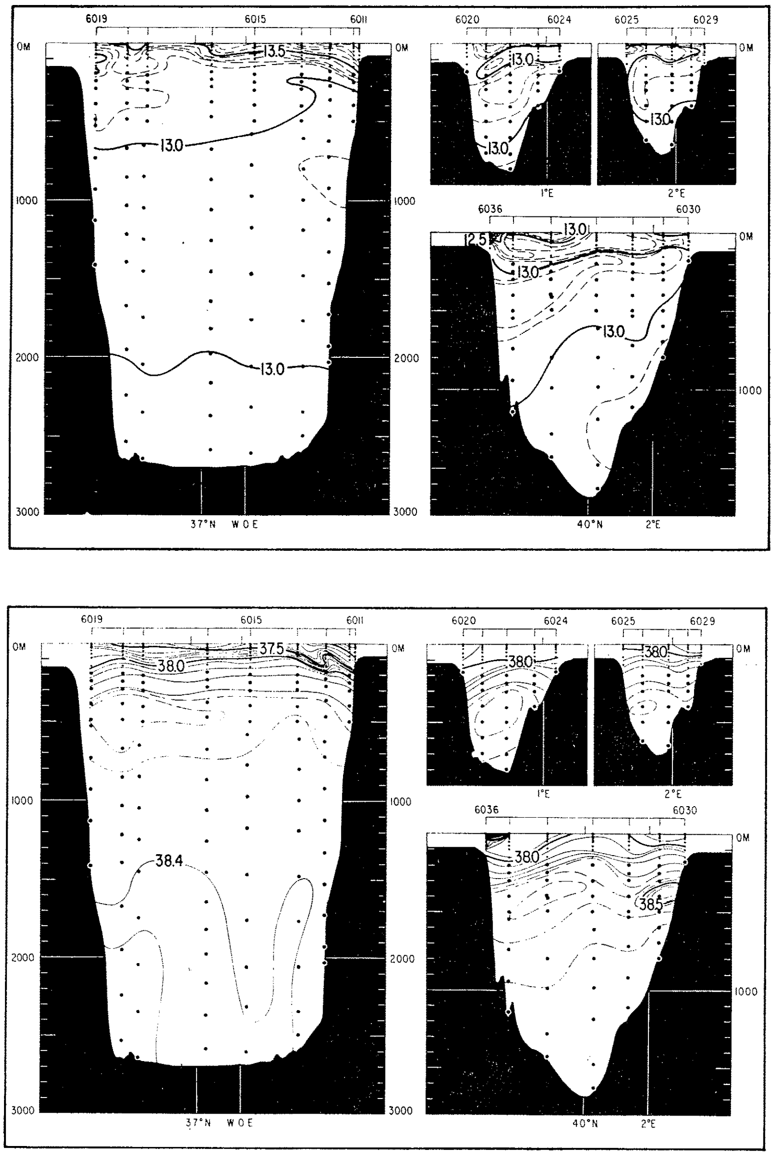

FIG. 11. — *Temperature and salinity profiles of Balearic channels, NW to Spanish mainland, and across Alboran Sea* (left).

The " Chain " 21 cruise in the Eastern Mediterranean was done in the fall, October and November, around the Cretan Sea and also in the far Eastern Mediterranean. The lines from " Chain " 21 and " Atlantis " 275 show that the Ionin Seas and Eastern Mediterranean Sea are identical in their TS properties.

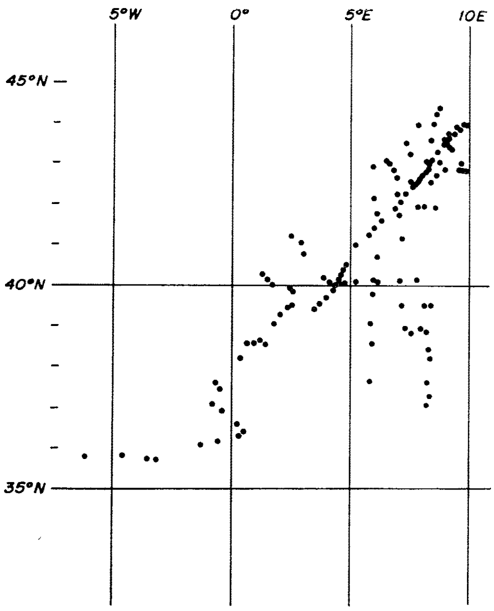

FIG. 12. — *Geographical positions where bottles were set adrift.*

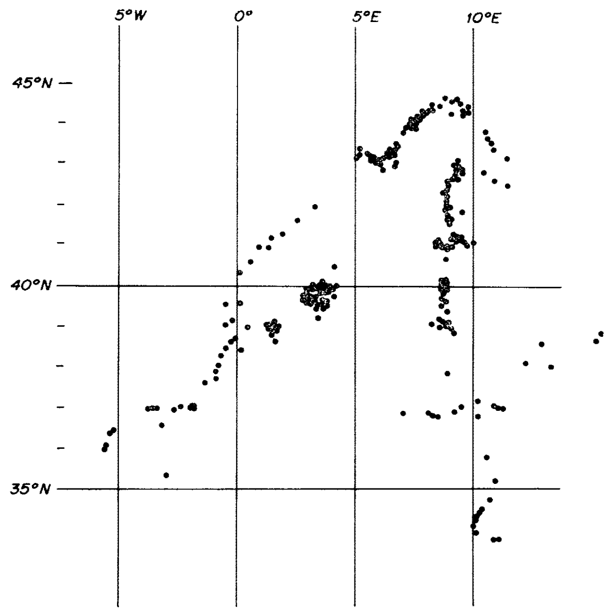

FIG. 13. — *Geographical positions where bottles were recovered.*

It is evident that the coldest water in the Ionian Sea has its origin in the Adriatic. This agrees with findings of others, Pollack among them. The other end of the T/S scale describing the deep eastern waters originates in the Cretan Sea. This is rather significant because in the 1948 cruise of " Atlantis ", POLLACK refuted the Cretan Sea as being a source for deep water. It is easy to see why this can escape observation. The actual observation of Cretan Sea deep water, during " Atlantis " 275 outside its environment, was fortuitous.

The deepest water source was found in the Adriatic behind the sill of the Straits of Otranto. At this particular season in 1962 it was just about ready to spill over and enter the Ionian Basin if it had not already done so.

Near surface waters from the Adriatic probably exert a strong influence on what is called the Levantine Intermediate water when it finally reaches the Western Mediterranean.

In October, we found water in the east as saline as 39,2 ‰. This is somewhat fresher than the findings of " *Calypso* " in 1956 and the " Atlantis " in 1948, where considerable amounts of water were found in the neighborhood of 39,4 ‰. Curiously, we found only one small patch of water at 39,0 ‰ in the winter of 1962. Higher values were absent. The conclusion might be that violent wintertime stirring in the Cretan Sea must necessarily mix and cool high salinity water to make dense water, eventually to pool and puddle in the deep basins of the Cretan Sea.

The water which describes the other portion of the Eastern Mediterranean was found at a depth of 1 000 meters in the Cretan Sea and actually observed outside the Caso Straits falling to a depth of 1 400 meters. Its influence seemed to have quickly dissipated but nevertheless shows itself as a source of supply.

As to the evaporation effects that can produce the very saline water I must say that we measured differences in the evaporating pan which rather surprised us since it gave rates on the average which could increase the salt content 0,15 ‰ per hour. From our radiation measurements we find that the available net radiation was in the order of 60 gm calories/cm²/day. If

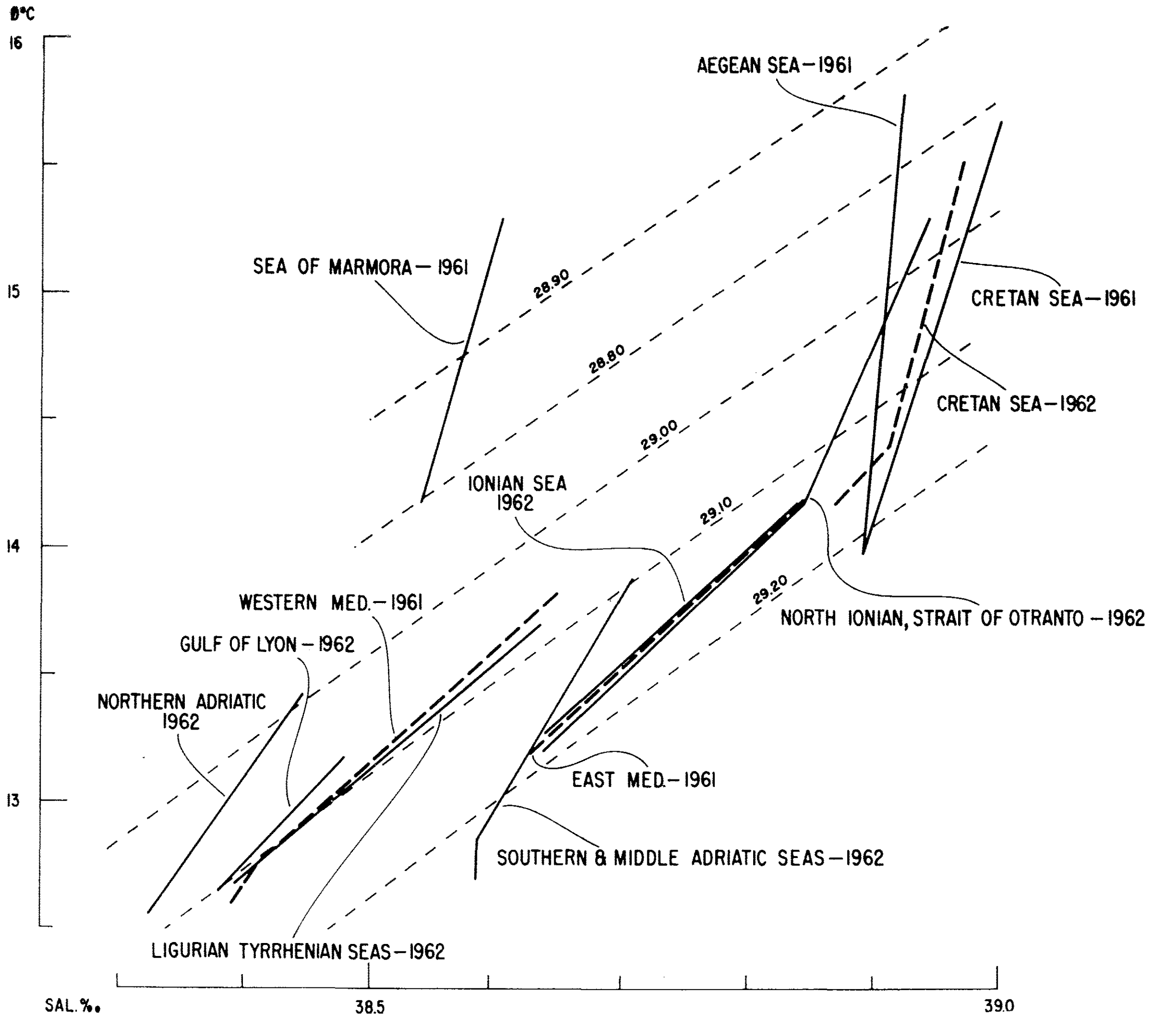

FIG. 14. — *Θ/S diagram of observations taken during cruises "Atlantis" 263, 275 and "Chain" 21.*

one thinks about parcels of surface water being affected by evaporation and radiation, it is difficult to keep the water at the surface in order to have it warm up sufficiently. The rate of evaporation seems to be far in excess of what the heating can provide. It may be necessary to assume that sinking occurs rather rapidly and surface parcels are replaced many times in order to balance out the effects of evaporative cooling and absorption of solar radiation.

Woods Hole Oceanographic Institution.