Mediterranean Circulation

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Outline

What is a mediterranean basin?
- Geography: semi-enclosed sea, Strait of Gibraltar
- Buoyancy Loss, Net Evaporation
- How is water balance maintained?

2-layer exchange through Strait of Gibraltar
- Mass and Salt conservation
- Estimating the exchange

Deep Water Formation
- Every basin has deep water, where is it formed?
- Wintertime buoyancy loss and deep water formation process

Overturning Circulation
- What sets its size?
- Hydraulic control limits amount of flow through Strait of Gibraltar
- Configuration of Strait determines saltiness of Mediterranean

Mediterranean has all the elements of an ocean
- Deep water formation, Overturning Circulation
- Time for Climate Change in the Mediterranean is shorter than for Ocean
- Can we understand how Mediterranean circulation processes are changing?

Mediterranean Circulation and the Strait of Gibraltar

A mediterranean basin is a semi-enclosed sea connected to the open ocean by a narrow strait. Over the basin, there is a net buoyancy loss, generally due to excess evaporation. By excess evaporation, we mean Evaporation - Precipitation - River Runoff, so the net evaporation represents the overall freshwater budget for the the basin. The Strait of Gibraltar is the only marine connection between the Mediterranean Sea and the global ocean. The Strait of Gibraltar connecting the Mediterranean Sea to the Atlantic Ocean has played a central role in oceanography for centuries (Deacon, 1971). The Mediterranean is the classic example of a semi-enclosed sea and the Strait of Gibraltar is the classic example of a narrow and shallow strait connecting two large basins.

Mythology says that Hercules opened up the Strait of Gibraltar: when he reached the end of the Mediterranean on his labour to gather the apples from the Hesperides he tore out the land and piled it up into the pillars of Hercules allowing the water to pour into the Mediterranean. In fact, the Mediterranean Sea was nearly dry 6 million years ago after Africa ran into Eurasia (Hsu, 1983; Blanc, 2000). And when the Strait of Gibraltar formed, there was a sudden inflow of Atlantic water to fill the Sea. For many centuries, there was a puzzle about the water balance for the Mediterranean for all the waters appeared to be entering the Sea: surface inflows through the Strait of Gibraltar and Bosporus, all the rivers (Nile, Rhone, etc) flowing in. It was realised that there was much too much inflow to be balanced by evaporation. Where did all the water go? Marsigli's (1681) experiments in Bosporus suggested there must be a deep outflow of water through the Strait of Gibraltar into the Atlantic. Finally, just before the Challenger expedition, Carpenter and Jeffreys (1870) observed this undercurrent by deploying a parachute drogue at 300 m depth beneath a small boat south of Gibraltar.

After the observation of the undercurrent, the key issue became to quantify the exchange: how much was coming in and going out through the Strait. It was generally accepted that there was a surface inflow and a deep outflow, but how big were they? For the strait connecting the semi-enclosed sea to the ocean, there is usually a two-layer exchange through the strait. The primary reason for a two-layer exchange is that mass and salt must be conserved for the semi-enclosed sea: the sea is neither filling up or draining down on average so the inflow through the connecting strait must basically equal the outflow; but the outflowing water is saltier than the inflowing water so there must be more inflow to the basin to balance both the outflow and the evaporation over the basin and to balance the overall salt budget.

Knudsen is generally given credit for first quantifying the exchange between two basins connected by a strait through the development of what we now call the Knudsen relations:

$$\text{for Mediterranean Sea} \begin{cases} \text{Mass Conservation} & Q_A + Q_M = E \text{ where E is the net Evaporation} \\ \text{Salt Conservation} & Q_A S_A + Q_M S_M = 0 \end{cases}$$

$$Q_A = -Q_M \frac{S_M}{S_A} \text{ from salt conservation}$$

$$-Q_M \frac{S_M}{S_A} + Q_M = E \quad \text{or} \quad -Q_M(S_M - S_A) = S_A E$$

$$\left.\begin{aligned} Q_M &= \frac{-S_A}{S_M - S_A} * E \\ \text{and } Q_A &= \frac{S_M}{S_M - S_A} * E \end{aligned}\right\} \text{Knudsen relations}$$

The power of this technique is that measurements merely of the upper-layer Atlantic salinity and of the lower-layer Mediterranean salinity combined with an estimate of the net evaporation over the Mediterranean basin allow one to determine the fluxes.

Knudsen actually applied the relations to the Baltic Sea which is a basin where there is a net source of fresh water from river runoff and precipitation that exceeds evaporation. Nielsen (1912) is generally given credit for being the first to apply the Knudsen relations to his measurements in the Strait of Gibraltar. But in fact Buchanan did it first in the 1880s before there was even a proper definition of salinity.

The modern classic estimate of the exchange through the Strait of Gibraltar was presented by Lacombe and Richez (1982). They used a net evaporation rate of 80 cm year^{-1} (multiplied by 2.5 x 10^{12}m^2 surface area yields E = 0.55 x 10^5m^{3}s^{-1})

and S_A = 36.15‰
S_M = 37.9‰

to estimate
$$Q_M = \frac{-36.15}{1.75} \ x \ 0.55 \ x \ 10^5 m^3 s^{-1} \ = \ -1.14 \ x \ 10^6 m^3 s^{-1}$$

$$Q_A = \frac{37.9}{1.75} \ x \ 0.55 \ x \ 10^5 m^3 s^{-1} \ = \ +1.19 \ x \ 10^6 m^3 s^{-1}$$

Note that because the salinity difference is small compared with the salinity, a small net evaporation leads to a substantial exchange, a factor of 20 larger than the net evaporation.

One problem with this method is the uncertainty in the actual size of the net evaporation. A secondary problem is deciding upon representative values of S_A and S_M in a time varying environment.

Lacombe and Richez also set out to actually measure the Gibraltar exchange during the 1960s. Their primitive current measurements made by lowering a current meter from an anchored ship repeatedly over a tidal cycle yielded inflow and outflow transports of

$$Q_A = 1.20 \text{ x } 10^6 m^3 s^{-1}$$
$$Q_M = -1.15 \text{ x } 10^6 m^3 s^{-1}$$

not surprisingly the same as determined from the Knudsen relations since there are options for adjusting E, S_A and S_M to yield any reasonable transports between 0.5 and 2 x 10^6m^{3}s^{-1} .

Deep Water Formation

Discussions of thermohaline circulation generally start with a consideration of where and why deep water formation occurs. Because the deep water is by definition very dense (it has to be to be at the bottom), formation of dense deep water must occur where the surface waters reach high density either because of low temperature or of high salinity. As soon as surface waters achieve a high density (low enough temperature), they quickly sink; dense waters cannot hang around on the surface above lighter waters. Thus, the dense water formation and its injection into the deep ocean occurs on short time scales and small spatial scales.

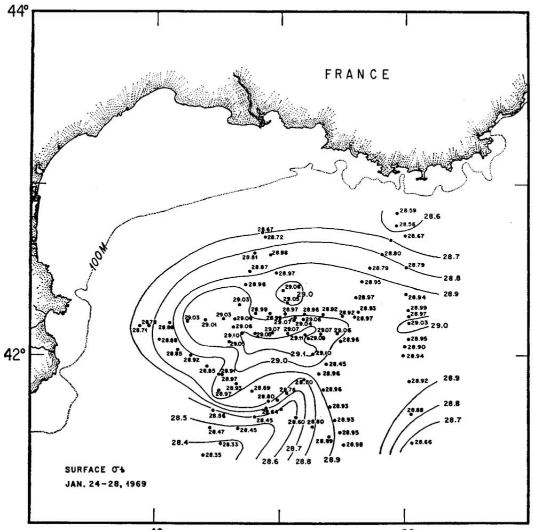
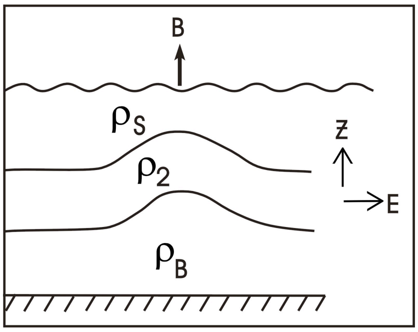


Figure 1 Density (sigma-t) at the surface before onset of the Mistral

The deep water formation occurs in small patches, of order 10 km across, sometimes called chimneys. It is observed to occur in late winter (February or March in the Northern Hemisphere) when the surface density achieves maximum values due to wintertime heat loss and evaporation increasing the salinity. There is usually some form of preconditioning whereby deep waters are a bit closer to the surface in a particular area, due to an eddy perhaps, and the deep water formation then occurs in this area.

Stommel(1972)

The natural places to look for deep water formation are in the extreme latitudes, where the surface waters are coldest and where the winter conditions are extreme. And, of course, the coldest conditions to make the densest waters are in wintertime so you can imagine how difficult it is to observe the formation process of deep water for the global ocean. Fortunately one can observe the deep water formation process in any semi-enclosed basin such as the Mediterranean because its deep water must be formed somewhere within the basin. In fact, our best knowledge of deep water formation comes from the Mediterranean where western Mediterranean deep water is formed just south of France.



Formation takes place when the buoyancy loss is large enough to increase the density of the water column to the deep water density:

$$B = \int g\big(\rho(z) - \rho_B\big)dz$$

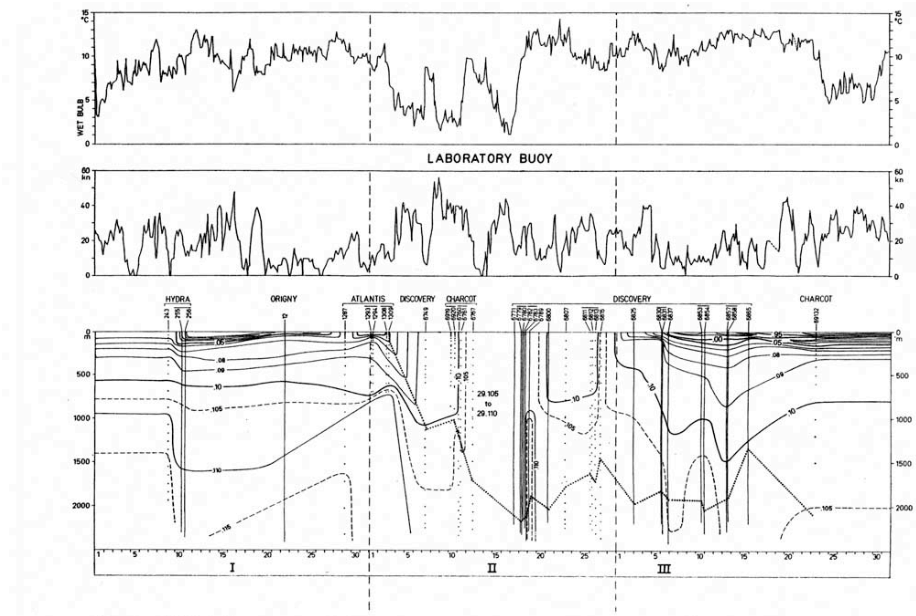


Figure 3a Welt-bulb air temperature and wind velocity recorded at the Laboratory Buoy (42° 15′ N, 5° 30′ E) and time-depth section of sigma-theta in the center of the dense patch. Dotted line shows bottom of mixed layer as indicated by transition in water mass properties (Figure 4)

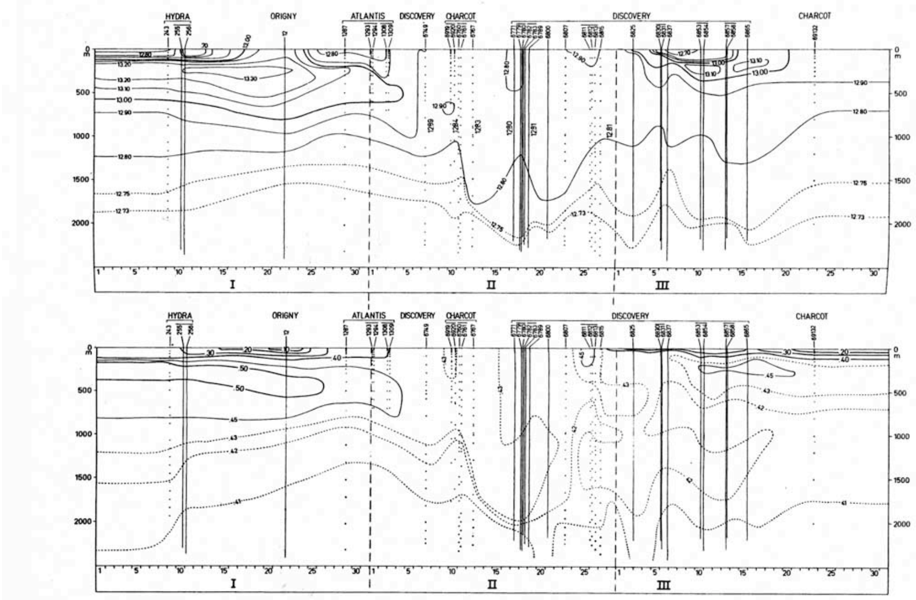


Figure 3b Potential temperature on the time-depth section in the center of the dense patch

Figure 3c Salinity on the time-depth section in the center of the dense patch

Stommel (1972)

As buoyancy is lost to the atmosphere over winter, the surface density, ρ_S, is increased until it equals ρ_2 and new formation of ρ_2 water begins. If buoyancy loss, B, continues so that ρ_2 is increased to ρ_B, then deep convection to the bottom begins.

Deep water formation need not take place every winter, in fact it has been found to be sporadic in the Mediterranean and in the Labrador Sea, probably dependent on the severity of the winter but also related to the properties of the waters present at the surface.

Differences between Mediterranean and Estuarine Basins

Mediterranean basins where evaporation exceeds precipitation and river inflows usually have a vigorous deep water circulation with plenty of oxygen. The Mediterranean Sea is the archetypical example. Mediterranean basins with a net buoyancy loss must convert less dense inflowing waters into more dense deep waters, so they naturally have active vertical mixing processes as the surface waters become denser and denser until they convect downward. As a result the deep waters in Mediterranean basins are well ventilated and have high oxygen. In contrast, estuarine basins, which have a positive water balance where river inflow and precipitation exceed evaporation, usually have stagnant deep water. These basins with the constant input of fresh, less dense river waters have no inherent mixing due to buoyancy effects and must rely on winds (or tides) to provide the mixing mechanisms. Wind mixing seldom penetrates more than 100 m below the sea surface, so the deep waters in estuarine basins tend to be stagnant. Estuarine basins can have just a thin fresh layer of surface waters flowing to the sea with the stagnant, anoxic deep waters separated from the relatively thin fresh surface layer by a sharp halocline. Large-scale examples of Estuarine Basins are the Baltic Sea or the Black Sea.

Dynamical Models for Two-Layer Exchange Flows

What should the size of the flow through the Strait of Gibraltar be? The Strait is a narrow and shallow connection which surely restricts the exchange between the Atlantic and Mediterranean. It is a bottleneck! How much flow can go through the Strait? If the salinity difference between, the Atlantic and Mediterranean is reduced while the evaporation stays the same, the Knudsen relations tell us that the inflow and outflow become larger and larger:

$$|Q_A| + |Q_M| \quad \propto \quad \frac{E}{S_M - S_A}$$

the smaller the salinity contrast, the larger the exchange. But hydraulic theory indicates that the size of the exchange is proportional to the salinity (or density) contrast between the two basins:

$$|Q_A| + |Q_M| \quad \propto \quad \sqrt{S_M - S_A}$$

the larger the salinity difference the greater the exchange. When both statements are true, that is Mass and Salt are conserved for the Mediterranean basin and the flow through the Strait is hydraulically controlled and achieves its maximum possible value then the salinity difference can be estimated from the evaporation:

$$S_M - S_A \quad \propto \quad E^{\frac{2}{3}}$$

where the proportionality factors are a combination of the width and depth of the strait, gravity and the physical properties of seawater. The Strait then controls the salinity difference between the basins, that is the salinity excess of the Mediterranean Sea above the salinity of the Atlantic Ocean.

This is the two-layer equivalent of the hydraulically controlled flow over a dam where we can determine theoretically the maximum flow for the reservoir height above the dam. In the past 15 years much effort has been put into developing analytical two-layer hydraulic control models and applying them to the Strait of Gibraltar. These hydraulic control models conserve mass and salt as in the Knudsen equations. But they also conserve Bernoulli potential in the upper layer and in the lower layer. These hydraulic control models are able to predict the maximum amount of water that can get through the Strait of Gibraltar given only the density (or salinity) contrast between Atlantic and Mediterranean Water and the physical configuration of the Strait, that is its width and depth. With knowledge of the net evaporation over the Mediterranean Sea, these models can predict the salinity or density excess of Mediterranean Water over Atlantic Water as well as the size of the exchange between the Atlantic and Mediterranean through the Strait. These predictions are in reasonable agreement (15%) with actual measurements of the exchange flows (Bryden and Kinder, 1991).

Mediterranean Circulation in a Changing Climate

Since the salinity difference is determined by the configuration of the connecting strait and by the net evaporation over the basin, it is possible to predict how the salinity will change if the net evaporation changes over the basin. A case in point is the Mediterranean where river diversion projects for irrigation in Egypt and Russia have effectively increased the net evaporation over the Mediterranean by about 10% in the last 50 years. As a result, we predict that the salinity of the Mediterranean will increase over time by about 0.13‰ due to this anthropogenic change in the water budget (Rohling and Bryden, 1992). Indeed there is evidence that the salinity of the Mediterranean deep waters is changing, with a gradual increase in the salinity of western Mediterranean deep water and a recent catastrophic change in the deep water formation in the eastern Mediterranean which suddenly switched its location about 1990 from the Adriatic to the Aegean with an increase in deep water salinity of more than 0.1‰.

The Mediterranean Sea has all the elements of an Ocean including deep water formation and an overturning circulation. Can we understand how the Mediterranean circulation will change in a changing climate? Increasing CO2 in the atmosphere is expected to increase the net evaporation over subtropical regions including the Mediterranean Sea. Are we already seeing changes in salinity caused by the increase in evaporation? How will the overturning be modified? Will we be able to observe the change in the overturning by measuring the Gibraltar exchange?

Additional Reading:

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