Mean water fluxes across sections in the Mediterranean Sea, evaluated on the basis of water and salt budgets and of observed salinities

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ABSTRACT
On the basis of an earlier work on the surface water budget of various areas in the Mediterranean Sea, we propose a method of evaluation of the mean horizontal fluxes exchanged between these areas and of the mean vertical fluxes within a number of them. To this end, we consider, for each area, the water budget across the sea surface, together with the water and salt budgets in the surface and deep layers across the limits of the areas. In order to determine the fluxes, we introduce observed salinity values into the budget equations. The result obtained is in gross agreement with some published circulation patterns, but the lack of current measurements and calculations precludes a quantitative evaluation of the precision of the method proposed.


INTRODUCTION
As a result of oceanographic expeditions carried out in the Mediterranean, the geographical variations of temperature and salinity in this sea are relatively well known. The investigations of Allain and Furnestin (1969), Furnestin and Allain (1962), Lacombe and Tchernia (1960, 1972), Miller et al. (1970), Oren (1971) and Wust (1961) have been particularly useful to us, but there are many other available studies. Moreover, some authors, using the geostrophic approximation, have, at somewhat different periods proposed outlines of the circulation: Nielsen (1912, in Sverdrup et al., 1942, p. 649) and Ovchinnikov (1966). These outlines have been completed and verified in some regions by the study of the trajectory of a few drifting buoys. However, and despite the efforts exerted since the turn of the century, current measurements remain sparse, and we are still far from able to deduce fluxes across sections in the sea from such measurements.
In this work, a quantitative estimation of the mean water fluxes in different areas of the Mediterranean is proposed, on the basis of the water and salt budgets across the sea surface and various sections in the sea.

The spatial variations of the heat and water budgets across the surface of the Mediterranean Sea have been studied earlier (Bethoux, 1977), it has been shown that these could explain the general character of the thermohaline circulation. Subsequently, the exchanges of water across the Strait of Gibraltar and the strait of Sicily were evaluated (Bethoux, 1979). Due to the water deficit (evaporation, \( E > \) precipitation + runoff, \( P \)) the outflowing waters on these sills are more saline than the superficial inflowing waters. Locally, the salinity values are related to the water exchanges at the air-sea interface, and also to the horizontal and vertical mixing in the area considered. An evaluation of the mean fluxes across different sections in the Mediterranean Sea may thus be made by taking account of fluxes at certain straits, spatial variations of the water budget across the surface and local mean salinities. In order to formulate a numerical model of the circulation of the Mediterranean Sea, which would permit progress in many marine studies, an understanding of the respective roles played by air-sea interactions and currents on the local variation of salinity is necessary.

GENERAL CHARACTERISTICS OF THE CIRCULATION IN THE MEDITERRANEAN SEA

The schematic presentation in diagram 1, resumes the annual mean calculated values of the fluxes in the Strait of Gibraltar and in the strait of Sicily together with the resulting water deficit of the Eastern and Western basins. The respective mean deep salinity values at these straits are obtained from observations, whereas the mean salinity values of the surface waters (more variable than these of the deeper waters) have been calculated on the basis of the salt budget and different mean densities.

If we consider the Mediterranean Sea as a whole, or the Eastern basin alone, the deficit in water explains the variations of salinity observed at the different straits. In the case of the Western basin, the process is more complicated because of its central position.

Figure 1 presents the area and the mean annual water deficit \( (E - P) \) of the different sections of the Mediterranean Sea. The division into zones is based on meteorological (see Bunker, 1972) or geographical criteria. The areas with positive or weakly negative water budgets, such as the southern part of the Gulf of Lions (with the Rhone river), the Adriatic Sea (with the Po river) and the Aegean Sea (with the net outflow from the Black Sea), which are adjacent to strongly water-deficient areas, may play a role in some of the cyclonic gyres of the sea. Moreover, the net heat transfer across the sea surface (Bethoux, 1977) indicates that heat must be transported by the currents from the southern regions (with positive heat budget) towards the northern regions (with negative heat budget, the transfers towards the atmosphere being greater than the gain in solar energy). The Gulf of Sidra constitutes an exception to this latitudinal distribution, because of strong evaporation due to the proximity of the Sahara. The principal areas of negative heat budget across the sea surface, in addition to the Gulf of Sidra, are the Gulf of Lions, the Ionian and Cretan Seas and the Levantine basin. These coincide with zones of highly negative water budget because of the important effect of evaporation on both budgets. The effects of the water budget, amplified by that of the heat budget, give rise to a thermohaline circulation which is in gross agreement with the results of geostrophic calculations based on the spatial distribution of temperature and salinity. An example of the Mediterranean circulation is given in figure 2, where surface currents during winter are reproduced, as calculated by Ovchinnikov (1966).

Generally speaking, there is not a great deal of difference between summer and winter circulation. The flux-salinity relations in the different areas and across the limits specified in figure 1 will now be studied.

STUDY OF THE WESTERN BASIN

Strait of Gibraltar and Alboran Sea (area 1)

In the western sector of the strait, off Cape Spartel, Atlantic water (of mean calculated salinity 36.18°/oo) occupies the 0-150 m layer (Lacombe, Tchernia, 1972). In the eastern part of the strait, such a salinity value is

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Diagram 1

Mean annual values of fluxes and salinities in the Strait of Gibraltar and in the Strait of Sicily and resulting water deficit of the Western and Eastern basins.

<table>
<thead>
<tr>
<th>Fluxes</th>
<th>Salinities</th>
</tr>
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<tbody>
<tr>
<td>(53 \times 10^{12} \text{ m}^3/\text{year} )</td>
<td>(36.18°/\text{o} )</td>
</tr>
<tr>
<td>(39.8 \times 10^{12} \text{ m}^3/\text{year} )</td>
<td>(37.05°/\text{o} )</td>
</tr>
<tr>
<td>(50.5 \times 10^{12} \text{ m}^3/\text{year} )</td>
<td>(0.7 \times 10^{12} \text{ m}^3/\text{year} )</td>
</tr>
<tr>
<td>(38 \times 10^{12} \text{ m}^3/\text{year} )</td>
<td>(38.74°/\text{o} )</td>
</tr>
<tr>
<td>Strait of Gibraltar</td>
<td>Western basin</td>
</tr>
<tr>
<td>E - P</td>
<td>E - P</td>
</tr>
<tr>
<td>(1.8 \times 10^{12} \text{ m}^3/\text{year} )</td>
<td>(1.8 \times 10^{12} \text{ m}^3/\text{year} )</td>
</tr>
<tr>
<td>Eastern basin</td>
<td></td>
</tr>
</tbody>
</table>
only found in the 0-75 m layer. Below this level, salinities increase strongly with depth. Still further east, in the easternmost Alboran Sea, the salinity is even higher, with surface values around 36.7°/oo, while the deep waters are of salinity 38.4°/oo.

If it is initially supposed that there is no mixing between the Atlantic and the Mediterranean waters, it is possible to estimate the annual effect of the water deficit (E − P) on the inflowing water salinity. Writing the conservation of salt content in the surface layer, for

\[
V = 53 \times 10^{12} \text{ m}^3/\text{year}, \quad E - P = 0.4 \times 10^{11} \text{ m}^3/\text{year}, \quad S = 36.18°/oo, \quad \Delta S = S(E - P)/V = 0.03°/oo.
\]

Accordingly, in area 1, the variation of salinity of Atlantic waters (from 36.18 to around 36.7°/oo) cannot be explained solely by the water deficit; mixing between the two layers considered must therefore be taken into account.
Diagram 2

Horizontal and vertical fluxes and salinities in area 1.
Flux verticaux et horizontaux et salinités associées dans la zone 1.

\[
\begin{align*}
V_1 &= 53 \times 10^{12} \text{m}^3/\text{year} \\
S_1 &= 36.18^\circ/00 \\
\rho_1 &= 1.02679 \\
V_2 &= 50.5 \times 10^{12} \text{m}^3/\text{year} \\
S_2 &= 37.90^\circ/00 \\
\rho_2 &= 1.02865 \\
\end{align*}
\]

For area 1 (closed to the east by the Cape of Gata-Oran section), the horizontal and vertical fluxes, salinities and densities are summed up in diagram 2. Fluxes \(V_3, V_4, V_5, V_6\) and salinity \(S_3\) are initial unknowns, and their values (in brackets) are the proposed solutions resulting from the following method. On the basis of the water and salt budgets, it is possible to write the equations:

\[
\begin{align*}
V_3 - V_1 - V_2 &= (E - P) \\
\rho_1 S_1 V_1 &= \rho_2 S_2 V_2 \\
V_2 - V_4 &= V_5 - V_6 \\
\rho_2 S_2 V_2 - \rho_1 S_1 V_1 &= \rho_6 S_6 V_6 - \rho_5 S_5 V_5 \\
\end{align*}
\]

Figure 2 presents calculations of fluxes \(V_3, V_4, V_5\) and \(V_6\) as a function of the salinity \(S_3\). Owing to the spatial variability of \(S_3\), it is difficult to determine its mean value. From the hydrological data between \(1^\circ\) and \(2^\circ\) West reported by Lanoix (1974), and from his calculated surface fluxes, we adopt a \(S_3\) mean value of \(36.64^\circ/00\). So we obtain the different flux values:

\[
\begin{align*}
V_3 &= 51.72, \quad V_4 = 49.26, \\
V_5 &= 14.28 \quad \text{and} \quad V_6 = 13.04 \times 10^{12} \text{m}^3/\text{year},
\end{align*}
\]

as reported in diagram 2. It appears that vertical fluxes \(V_4\) and \(V_6\) are relatively large in comparison with the horizontal fluxes.

At the exit of area 1, we continue the study with the surface flux of \(51.72 \times 10^{12} \text{m}^3/\text{year}\) of a mean salinity \(36.64^\circ/00\). This water continues its path along the African coast towards the east and the strait of Sicily in area 2. There, the water deficit of \(0.19 \times 10^{12} \text{m}^3/\text{year}\) may produce a maximum variation in salinity of \(0.13^\circ/00\). This is not sufficient to explain the salinity increase of the surface waters from \(36.64^\circ/00\) to more than \(37^\circ/00\) in the strait of Sardinia, and suggests mixing with more saline waters. Allain (1964) gives some areas of ascending waters off the African coast, but from the data of Allain and Furnestin (1969), it is difficult to evaluate the amount of upwelling Intermediate water along this coast. According to the outlines of the circulation, we may suppose that the saline waters arrive principally from the north through the strait of Ivice. Moreover, a part of the Atlantic vein flows up along the coast of Sardinia and Corsica, while another vein penetrates the Tyrrenhian Sea. The values of the different fluxes in area 2 are unknown but will be deduced later from our knowledge of the fluxes and salinities in the other straits of the basin.

**Tyrrenhian Sea (area 3)**

The straits of Sardinia and Sicily are chosen as southern limits and the strait of Corsica as the northern limit of this sea. Fluxes and mean salinities in the Sicily strait have already been mentioned (diagram 1). The flux in the strait of Corsica has been determined earlier (Bethoux and Prieur, 1978). It is possible to determine the mean resulting flux between Sardinia and Tunisia and, from the salinity data of the three limiting straits, to give an evaluation of the vertical fluxes in Tyrrenhian Sea.

**Strait of Corsica (boundary between areas 3 and 4)**

Fluxes in the Nice-Calvi section have been calculated from *Hydrokor* hydrological cruise data (Calvi is on the
north-west coast of Corsica). We found a geostrophic surface flux of \( 37.8 \times 10^{12} \text{ m}^3/\text{year} \) off Nice in a NE-SW direction, and \( 17.3 \times 10^{12} \text{ m}^3/\text{year} \) off Calvi in a SW-NE direction. Fluxes in the canal of Corsica have been deduced: \( 20.5 \times 10^{12} \text{ m}^3/\text{year} \) flow northerly as a surface flux between 0 and 200 m, and \( 10.4 \times 10^{12} \text{ m}^3/\text{year} \) as an Intermediate water flux, both in the direction of the Gulf of Genoa. The measurements of Le Floch (1963), and those of Stocchino and Testoni (1969), give comparable values of mean fluxes in this strait; mean salinities for the surface and the Intermediate waters are respectively 38 and 38.55°/oo.

Strait of Sardinia (boundary between areas 2 and 3)

Here, the currents are complex (see, for example, Garzoli and Maillard, 1976). The surface flux of Atlantic origin can be divided into two branches. The southern branch (less saline) continues its run towards the Eastern basin, while the other penetrates the Tyrrhenian Sea. According to the data of Furnestin and Allain (1962), the mean salinity of the surface flux is about 37.10°/oo, and that of the Intermediate water is about 38.55°/oo. On the basis of the water and salt budgets in the Tyrrhenian Sea, it is possible to calculate the superficial \( V_s \) and Intermediate \( V_i \) fluxes for the strait of Sardinia.

\[
V_s - V_i = \text{water deficit in Tyrrhenian Sea} + \text{Water budget in Corsica strait} + \text{water budget in Sicily strait} = 0.17 + 30.9 + 1.8 = 32.87 \times 10^{12} \text{ m}^3/\text{year}.
\]

The salt budget in the Sicily strait is balanced, the salt budget in the Sardinian strait is equal to that of the Corsica strait. We may write:

\[
\rho_s S_s V_s - \rho_i S_i V_i = 1.213.55 \times 10^{12} \text{ kg}
\]

of salt, from which:

\[
V_s = 58.20 \times 10^{12} \text{ m}^3/\text{year};
\]

\[
V_i = 25.33 \times 10^{12} \text{ m}^3/\text{year}.
\]

Hydrological phenomena in the Tyrrhenian Sea

Part of the surface flux from the strait of Sardinia flows towards the strait of Sicily (\( 39.8 \times 10^{12} \text{ m}^3/\text{year} \)). The part, which penetrates into the Tyrrhenian Sea, is:

\[
V_{TT} = 58.20 - 39.80 = 18.40 \times 10^{12} \text{ m}^3/\text{year},
\]

with a mean salinity:

\[
S_{TT} = \frac{58.20 \times 37.10 - 39.8 \times 37.05}{18.40} = 37.21°/oo.
\]

The passage of water into the Tyrrhenian Sea is marked by a decrease in the salinity of the Intermediate waters (from 38.74 to 38.55°/oo) and by an increase of salinity of the surface waters (from 37.21 to 38°/oo at the Corsica strait). These salinity variations result from a mixing between the surface and Intermediate layers, on the one hand, and from the effect of the water deficit across the surface, on the other. On the basis of the previous data, the surface water budget in Tyrrhenian Sea is:

\[
-2.27 \times 10^{12} \text{ m}^3/\text{year} = \text{surface water budget in Tyrrhenian Sea}.
\]

The superficial salt budget is:

\[
-97.6 \times 10^{12} \text{ kg of salt}.
\]

The equilibrium of the water and salt budgets requires a net transport of water and salt from the Intermediate layer to the surface. Such transports involve upward and downward fluxes.

Taking into account the mean salinities and densities of the surface and Intermediate waters (respectively 37.60°/oo, 1.027 83 and 38.645°/oo, 1.02903), we calculated an upward flux \( V_u = 8.84 \times 10^{12} \text{ m}^3/\text{year} \) and a downward flux \( V_d = 6.57 \times 10^{12} \text{ m}^3/\text{year} \). The horizontal and vertical fluxes and salinities in the Tyrrhenian Sea (area 3) are summarized in diagram 3.

North-Western basin (areas 4,5 and 8)

Part of this basin is the seat of formation of deep water. Here, during the winter season, the surface water, mixing with Intermediate water, forms deep water which spreads into the deep layers. For the purposes of our study, it is

Diagram 3

<table>
<thead>
<tr>
<th>Strait of Corsica</th>
<th>Tyrrenhian Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.50</td>
<td>6.57 (vertical</td>
</tr>
<tr>
<td>38.00</td>
<td>37.60 fluxes)</td>
</tr>
<tr>
<td>10.40</td>
<td>8.84</td>
</tr>
<tr>
<td>38.55</td>
<td>38.64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strait of Sardinia</th>
<th>Strait of Sicily</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.40</td>
<td>39.8</td>
</tr>
<tr>
<td>37.21</td>
<td>37.05</td>
</tr>
<tr>
<td>37.10°/oo</td>
<td>38</td>
</tr>
<tr>
<td>38.55°/oo</td>
<td>38.74</td>
</tr>
</tbody>
</table>
necessary to evaluate the quantity of this water, which flows towards the Strait of Gibraltar after sinking. According to Wust (1961), it is principally the Intermediate water which flows over the sill of Gibraltar. However, due to mixing, this water cannot be traced further than the eastern Alboran Sea, so that most of the outflow at Gibraltar consists of deep water.

On an overall basis, the balance of the water budget in the Western basin implies that the Intermediate water passing the Sardinia and Corsica Straits vanishes. It may therefore be supposed that the deep flux entering the Alboran Sea (49.26 x 10^12 m^3/year) is composed of 10.4 (Strait of Corsica) + 25.33 (Strait of Sardinia) = 35.73 x 10^12 m^3/year of Intermediate water, together with 49.26 - 35.73 = 13.53 x 10^12 m^3/year of North-western surface water. The formation of deep water would then result in a mixing of 73% of Intermediate water (salinity 38.55 /oo) with 27% /oo of surface water. A mixing ratio of 2/3, 1/3 has been proposed by Minas (1979), on the basis of oxygen salinity diagrams for the Western Mediterranean. The balance of the salt budget requires the surface waters to have a salinity:

\[ S = \frac{49.26 \times 38.4 - 35.73 \times 38.55}{13.53} = 38.04 /oo. \]

This value supposes that the Intermediate water salinity remains unchanged between the Corsica and Sardinia straits and to the deep water formation zone. If this salinity decreases to about 38.50 /oo (instead of 38.55 /oo), the surface water salinity would be 38.14 /oo. Gascard (1978) observed a surface salinity value of 38.10 /oo during deep water formation. In order to simplify the next series of calculations, we adopt for this surface water salinity the value 38.04 /oo.

**Ligurian Sea (area 4), Gulf of Lions (area 5) and offshore area 8**

The fluxes in the strait of Corsica and the Nice-Calvi section are known. The Ligurian flow leaving area 4 and entering area 5 is:

37.80 (off Nice) - 0.04 (E - P) = 37.76 x 10^12 m^3/year,

and its mean salinity:

\[ S = \frac{37.8 \times 38}{37.76} = 38.04 /oo. \]

Due to the influx from the rivers (principally the Rhone), area 5 is at zero water budget, and therefore at constant salinity and flux. According to Figure 2, area 8 is divided into two parts by a line of divergence oriented NE-SW. Our present studies, of infra-red images from NOAA satellites indicates that a thermal front, located roughly from the northern part of the Balearic Islands at latitude 40°N, to longitude 6°E (south of Toulon) at latitude 42°N, often appears in the same zone. The NW part of zone 8 is in thermal continuity with the northern part of the Gulf of Lions, and the SE part with the southern part of the basin.

**Catalonia Sea (area 6) and central part of the Algero-Provençal basin**

According to the features of the circulation (Fig. 2), waters leaving the north of the Gulf of Lions (area 5) follow the Catalan coast: one vein passes through the canal of Ivice while another, closing a cyclonic gyre in the Catalonia Sea, finally joins the southern part of the Algero-Provençal cyclonic gyre. Taking into account the disappearance at the limits of areas 4, 5, 6 and 8 of 13.53 x 10^12 m^3/year of surface water (due to the formation of deep water), the flux entering the northern part of area 6 is: 37.76 - 13.53 = 24.23 x 10^12 m^3/year, and its salinity: 38.04 /oo.

Despite recent studies of the Catalonia Sea (Font and Miralles, 1978, Salat et al., 1978), the contribution of the water from the NW to the Atlantic flux (principally through the strait of Ivice) and the net flux across the Barcelona-Mallorca Island section have not been determined. Nevertheless, according to the data, it appears that the salinity of the 0-100 m layer, off Barcelona, varies from about 38.9 /oo in summer to about 38.2 /oo in winter. We thus adopt the mean annual value of 38.04 /oo for the salinity in the strait of Ivice, i.e. we maintain the salinity of the water entering area 6. Runoff and water from the Catalan rivers balance the evaporation of the coastal southward flux.

**Fluxes and salinities in the surface layer of the Western basin**

In Figure 4, we summarize the main features of the surface circulation in the Western basin and the known values of fluxes and salinities.

The salt and water budgets for areas 6, 2, 7 and 8 provide some relations between fluxes V_3, V_8, V_9 and the salinities S_3 and S_8, but these are not sufficient to solve the problem.

Figure 5 presents the variations of fluxes V_3, V_8 and V_9 as a function of salinity S_8, which seems the easiest accessible parameter. Nevertheless, because of its spatial and seasonal variability, it is difficult to determine a mean annual value of S_8. A rough estimate seems us to be about 37.4 /oo. For such salinity, fluxes V_3 and V_8 are rather great, respectively 18.3 and 11.6 x 10^12 m^3/year. Flux V_9 is only 5.9 x 10^12 m^3/year, but its salinity S_9 reaches the value of 38.3 /oo. The equilibrium is very sensitive to variations of flux or salinity in different zones of the basin.

**STUDY OF THE FLUXES IN THE EASTERN BASIN**

The calculated fluxes over the western sill of the Strait of Sicily are: surface incoming flux, 39.8 x 10^12 m^3/year; deep outgoing flux, 38 x 10^12 m^3/year. Their mean salinities are respectively 37.05 and 38.74 /oo, according to Morel (1971). The net flux dV = 1.8 x 10^12 m^3/year compensates an annual mean water deficit of 1.08 m which leads to an increase in mean salinity of 1.69 /oo at the basin outlet. However, as in the cause of the Western
basin, local salinities result from the cumulated effects of the water deficit and marine advection. Once again, a quantitative approach to the mean flux is attempted here, making use of the local values of salinity, the estimation of the water deficits and the direction of the main currents.

In Figure 1, the Eastern basin is divided into 13 zones (numbered 9 to 21) and their surface marine areas and the annual mean water deficit \( (E-P) \) are noted. Only the northern part of the Adriatic Sea presents a positive water budget, loss by evaporation being slightly less than river influx and precipitations. Despite the important flux of water from the Black Sea through the Bosphorus, area 16, which groups together the Aegean and Cretan Seas, still has an excess of evaporation and constitutes a concentration basin.

According to the outline of circulation proposed by Nielsen (see Sverdrup et al., 1942, p. 649), surface waters, after passing through the strait of Sicily, follow a cyclonic gyre along the coasts of the basin as well as in the Aegean and Adriatic Seas. The path of the incoming water can be traced up to the far end of the Levantine basin and up to the Cretan Sea by the presence of its salinity minimum (Lacombe et al., 1958). If it is supposed that the flux entering the basin \( (39.8 \times 10^{12} \text{m}^3/\text{year} \text{of salinity } 37.05/_{100} ) \) takes a direct course to the region of the Rhodes-Cyprus Islands, the deficit of water in areas 9 to 15 would lead to a mean salinity of \( 38.42/_{100} \). This is less than the actual local salinities which are around or greater than \( 39/_{100} \). Some proposed circulation patterns more recent than Nielsen's, such that of Ovchinnikov (Figure 2) or the current chart of the U.S. Naval Oceanographic Office (Pub. 700) show a measure of recycling and different phenomena of advection. In the Eastern basin, however, measurements or calculations of flux for those straits which could permit an evaluation of this phenomena do not to our knowledge exist. We are therefore obliged to formulate certain hypothesis based on hydrological facts.

**Strait of Sicily to the meridian of Malta (area 9) and NW part of area 10**

In area 9, the Levantine water filling the basin between the two sills (see Morel, 1971) shows a decrease in salinity, from \( 38.80 \text{ to } 38.74/_{100} \), while the surface water undergoes an increase in salinity, from \( 37.05/_{100} \) to about \( 37.30/_{100} \). Using the same method and equations as in the case of the Alboran Sea, we calculated the vertical and horizontal fluxes as a function of surface layer salinity. The results are presented in Figure 6, where it may be seen that, for a surface salinity of \( 37.32/_{100} \), the vertical fluxes are equal (about \( 1.5 \times 10^{12} \text{m}^3/\text{year} \)), while the horizontal fluxes amount to \( 39.8-0.23 = 39.57 \times 10^{12} \text{m}^3/\text{year} \) for the surface waters and \( 38.0 \times 10^{12} \text{m}^3/\text{year} \) for the Levantine water.

![Figure 4](image_url)

*Figure 4*  
Surface fluxes (upper number, in \( 10^{12} \text{m}^3/\text{year} \)) and salinities (in per mille, lower number) in the Western basin.

Flux de surface (nombre supérieur, en \( 10^{12} \text{m}^3/\text{an} \)) et salinités associées (en pour-mille, nombre inférieur) dans le bassin Occidental.
A flux of $39.57 \times 10^{12} \text{m}^3/\text{year}$, of mean salinity $37.32^\circ/\text{o}$, thus passes the meridian of Malta and enters the western part of area 10. In this zone, the hydrological data (Lacombe, Tchernia, 1960) show another salinity increase of surface waters, up to about $37.80^\circ/\text{o}$. The circulation pattern (see Fig. 2) points to a possible advection of NW Ionian Sea waters (of salinity $38.60^\circ/\text{o}$). The ratio of salinities (and densities) requires a surface flux of $24.07 \times 10^{12} \text{m}^3/\text{year}$ from the Ionian Sea through the NW part of area 10. Therefore, a flux of $39.57 + 24.07 = 63.64 \times 10^{12} \text{m}^3/\text{year}$, of salinity $37.80^\circ/\text{o}$, penetrates into area 10.

**Problem of the formation and flow of Adriatic and Levantine waters**

It is known (see for example, Lacombe and Tchernia, 1972) that the Levantine water, which leaves by the strait of Sicily in the form of deep water, is formed in the region of the Rhodes-Cyprus Islands, from surface waters of salinity near $39.10^\circ/\text{o}$. Furthermore, the Adriatic Sea is the seat of formation of dense waters (of salinity near $38.60^\circ/\text{o}$) which, after mixing with the Levantine waters, form the bottom waters filling the whole of the Eastern basin up to a certain depth.

The Eastern basin is in a stationary state of balanced budget in salt and water. This requires that all the Levantine and Adriatic waters formed each year should pass through the strait of Sicily. Thus, the outgoing flux of $38 \times 10^{12} \text{m}^3/\text{year}$, of salinity $38.80^\circ/\text{o}$ across the meridian of Malta, is the result of the mixing of these two waters. If we now suppose that the Levantine water conserves its original salinity of $39.10^\circ/\text{o}$ up to the Ionian Sea, the respective proportions of the deep flux off Malta are: $22.8 \times 10^{12} \text{m}^3/\text{year}$ of Adriatic water and $15.2 \times 10^{12} \text{m}^3$ of Levantine water. These are the values in our schematic circulation of the Eastern basin.

**Fluxes and salinities in the Eastern basin**

In areas 10 and 11, the water deficit ($0.62 \times 10^{12} \text{m}^3/\text{year}$), combined with a flux of $63.64 \times 10^{12} \text{m}^3/\text{year}$, of salinity $37.80^\circ/\text{o}$, results in a new flux of $63.02 \times 10^{12} \text{m}^3/\text{year}$ of mean salinity $38.17^\circ/\text{o}$. The problem now is to determine the respective fluxes leaving area 11 in the easterly and northerly directions. Not knowing the fluxes between Peloponnesos and Crete, we suppose this flux to be zero at the beginning. In these conditions, only the flux necessary to make up the water deficits of areas 12, 13, 14, 15 and 16, and the formation of the Levantine water, i.e. $15.83 \times 10^{12} \text{m}^3/\text{year}$, flows eastwards and towards the Aegean Sea. The salinity in the Aegean Sea should thus be $39.75^\circ/\text{o}$, which is greater than the real value. On the other hand, the flux leaving area 11 in the northerly direction, $63.02 - 15.83 = 47.19 \times 10^{12} \text{m}^3/\text{year}$, results in a salinity of $38.43^\circ/\text{o}$ in the South Adriatic Sea (area 19) and in area 21, which is too low.

To correct these salinity values, it is sufficient to increase slightly the eastward flux. This has the effect of decreasing the salinities in the Aegean Sea and then of making a flux pass through the SW straits of that sea, in the direction of the Adriatic, and leads to the valuations of fluxes and salinities presented in Figure 7. The mean salinities for the area south of Crete $(38.17^\circ/\text{o})$ and the Levantine basin $(38.82^\circ/\text{o})$ in area 14) appear to be still a little low. The simple outline proposed should be completed for this region by exchanges between areas 15 and 13, as well as between areas 17 and 11. However, in the absence of measured flux values at the limits of the Cretan Sea, between the Cyprus and Rhodes Islands and the coast, it appears to be unrealistic to attempt to establish a more detailed calculated circulation.

According to our study, an important point of the circulation in the Eastern basin seems to comprise the separation of the fluxes eastward and northward in the Ionian Sea. Oren (1971) employs the variations of the flux entering the strait of Sicily (which appear to be related to the atmospheric pressure variations) and so accounts for the important variation of salinity in the offshore waters of Israel. Zore-Armanda (1969), for her part, considers a summer-winter alteration in the importance of the respective surface fluxes in the Ionian Sea, which are directed eastward and northward. According to this author, and in agreement with the isohalines traced by Lacombe and Tchernia (1960), the flux entering the South of the Ionian Sea in summer would be directed principally towards the Adriatic Sea, leading to an increase in salinity in the East basin. In winter, the easterly components would be preponderant.

The conclusions drawn from the examination of our simplified mean circulation are therefore in gross agreement with the hydrological observations.

This flux-salinity method may similarly be applied to the northern part of the Aegean Sea and to the Sea of Marmara, taking into account the effect of the low salinity water issuing from the Black Sea. Supposing a null salt budget at the Bosphorus, and knowing the...
estimations of fluxes at this strait (Sverdrup et al., 1942, p. 650), as well as the water deficits and the variations of salinities, it is possible to deduce the horizontal and vertical fluxes in the Marmara and North Aegean Seas. These fluxes are, however, much lower than those of the general circulation and so have not been retained in our study.

CONCLUSION

Utilization of the spatial variations of salinity and water budget, together with knowledge of the fluxes at certain straits, thus allow us to propose a quantitative evaluation of the mean fluxes across a number of sections in the Mediterranean Sea. The obtained outlines show that some sectors are more sensitive than the others. An effort to measure the fluxes across the limits of these areas would help to improve our knowledge of the circulation, and its modelling. Thus, in the Western basin, apart from the Ligurian Sea, which has already been the subject of numerous hydrological measurements, the Catalonia Sea also appears to play an important role. In the Eastern basin, all measured flux values for the Aegean and Cretan Seas between the island of Cyprus and the coast would serve to verify the proposed circulation. In some areas (i.e., the Alboran and Tyrrhenian Seas, the strait of Sicily) variations of salinity in the surface and deeper layers allowed us to estimate the vertical fluxes, which are important for the nutrient concentration and its biological effects. More usually, the salinity increase of the surface layer, beyond the effect of the water deficit, results from vertical and horizontal advections related to past (amount of deep water formation) or present (effect of the water budget, wind and atmospheric pressure) climatic conditions. The proposed method shows the flux-salinity relation at the different straits of each basin which would permit a study of their variations and of their consequences. The data used being the annual means, they only give access to the annual mean circulation. If, however, the calculated circulation agrees with the reality, it seems possible to study the seasonal variations. The predominant effect being that of the advection phenomena, seasonal variations in salinity are probably related to seasonal variations in flux.

In the absence of detailed measured flux values in the Mediterranean, it would be daring to claim that the values given in this work are in total agreement with those in the actual sea. It thus appears necessary to question the dependence of the proposed schemes on the initial evaluations of fluxes in the straits or on spatial variations of the water budget. For example, the direct measurements of Lacombe and Chernia (1972) in the Strait of Gibraltar lead water and flux deficit values for the Mediterranean Sea which are about 30% lower than our estimations (incoming flux 38 x 10^12 m^3/year, E - P = 1.74 x 10^12 m^3/year). Assuming that the relative zonal variation of (E - P) should remain identical, since it is linked to meteorological conditions, and retaining the same hydrological facts and salinity data, we calculated the effects of 30% lower value of fluxes at the Strait of Gibraltar and in the strait of Sicily.

In the Eastern basin, except for the vertical fluxes (which remain very low: upward flux 0.16 and downward flux 1.01 x 10^12 m^3/year) in area 9, all the fluxes are to be lowered by the 30% factor. In the Western basin, as may be seen by comparing Figure 8 with Figure 4, the flux variations are not uniform, due to the vertical fluxes in the Alboran and Tyrrhenian Seas and to the fixed values of calculated fluxes to the north of Corsica. But the general pattern of the circulation remains unchanged.

Until some direct measurements of fluxes are available, it will not be possible to evaluate the precision of the calculated flux values. But perhaps the present work will permit other investigations, concerning for example nutrient budgets, which, in turn, will verify or improve our own results. Any information concerning the Mediterranean fluxes is of particular importance in climatology, pollution, biological and chemical studies.

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REFERENCES


Figure 8

Surface fluxes (in 10^12 m^3/year) in the Western basin, resulting from 30% lower fluxes in the Strait of Gibraltar and in the Strait of Sicily.
Flux de surface résultant (en 10^12 m^3/year) dans le bassin Occidental, pour des flux diminués de 30 % au détroit de Gibraltar et au canal de Sicile.
J. P. BETHOUX


