Budgets of the Mediterranean Sea. Their dependance on the local climate and on the characteristics of the Atlantic waters

Mediterranean Sea
Budgets
Flows
Climate
Modelling
Méditerranée
Bilans
Flux
Climat
Modèle

J. P. Bethoux
Laboratoire de Physique et Chimie marines-ERA CNRS
Station marine. 06230 Villefranche-sur-mer, France.

Received 18/8/78, in revised form 7/12/78, accepted 18/12/78.

ABSTRACT

In the study of the physical oceanography of the Mediterranean Sea many efforts have been made to determine the flux of waters through the Strait of Gibraltar on the basis of measurements or calculations. Our own earlier studies of the heat and water budgets of the Mediterranean, together with the results obtained by other authors enable us to suggest a physical model of its behaviour which is conditioned by its climate and by the characteristics of the Atlantic water. This model is verified by calculating actual flows through the Strait and the water deficit of the sea. The results are compared to those obtained by other methods. The model may also be used for the investigation of the effects of climatic changes on the hydrological parameters of the Mediterranean.

Oceanol. Acta, 1979, **2**, 2, 157-163.

RÉSUMÉ

Bilans en Méditerranée, leur dépendance du climat local et des caractéristiques des eaux atlantiques

L'étude des flux d'eaux atlantiques et méditerranéennes à travers le détroit de Gibraltar a fait l'objet de nombreux travaux. En complément à la mesure ou au calcul de courants différents auteurs font intervenir les bilans en eau, en sel ou encore en énergie potentielle entre la Méditerranée et l'Atlantique. Ayant précédemment étudié le bilan thermique et le bilan en eau de la Méditerranée nous utilisons nos résultats, ainsi que ceux d'autres auteurs, pour présenter un modèle global de fonctionnement de cette mer soumise à l'action du climat et à l'influence des eaux atlantiques. Ce modèle peut permettre de calculer les effets de variations du climat sur les caractéristiques hydrologiques de cette mer. En nous limitant aux conditions climatiques actuelles nous appliquons ce modèle au calcul des flux à travers le détroit de Gibraltar, ainsi qu'à la détermination du déficit en eau de cette mer et de ses deux grands bassins, oriental et occidental. Les résultats sont comparés à ceux obtenus par d'autres méthodes.

Oceanol. Acta, 1979, **2**, 2, 157-163.

INTRODUCTION

Much of work has been done on the physical oceanography of the Mediterranean Sea (see, for example, Sverdrup *et al.*, 1942; Defant, 1961); and many efforts have been made to determine the flux of water through the Strait of Gibraltar, either by measurement of currents over the sill (e. g. Lacombe, 1971) or by evaluation of evaporation and precipitation, and of the resulting deficit of the Mediterranean (e. g. Tixeront, 1970). The results obtained by the various authors are by no means identical. Thus for example, extreme values of 1.3 m (Schott, 1915, cited by Wust, 1959) and 0.56 m (Carter, 1956, cited by Lacombe, 1971) have been reported for the annual mean water deficit of the Mediterranean. The water and salt budgets of the Mediterranean characterize the hydrological functioning of this concentration basin, which many authors (e. g. Lacombe, Tchernia, 1972) have related qualitatively to the climate. Proposing a new method, Kullenberg (1953) has suggested a relationship between the flux through the Strait of Gibraltar and the vertical profiles of density on either side of the sill. This author has made use of the salt and potential energy budgets across the Strait which are considered later in the present report. Some results of our own previous study on the heat budget of the Mediterranean (Bethoux, 1977) are presented below. By evaluating the thermal advection across the Strait of Gibraltar, and knowing the solar flux, we may obtain a new estimation of the thermal transfers to the atmosphere and thus of the water height evaporated. There a double relation appears between the heat and water budgets, firstly through thermal advection and secondly through evaporation, which permits a quantitative estimate of the effect of climate. In order to describe the functioning of the Mediterranean, its salt and potential energy budgets of the sea, and their various interactions with the heat and water budgets have also been studied. A summary of these different mechanisms is presented in the form of a model.

HEAT, WATER, SALT AND POTENTIAL ENERGY BUDGETS

The *heat budget* of the entire Mediterranean involves the gains and losses of heat by the sea, as a result of solar radiation absorbed by the water $Q_s(1-A)$ (where A is the mean albedo); marine advection Q_a; and heat transfers to the atmosphere by back radiation Q_n, by conduction Q_c, and by latent heat of evaporation Q_e. If $Q(t)$ denotes the change in heat content of the waters during the time interval in question, the equation of the heat balance may be written:

$$Q_s(1-A)+Q_a+Q_n+Q_c+Q_e=Q(t). \quad (1)$$

The constancy of the mean annual temperature corresponds to the thermal equilibrium, and is reflected by a zero mean annual value of the term $Q(t)$. For the Mediterranean considered as whole, the advection term Q_a is reduced to the difference between the quantities of heat conveyed by the water flows exchanged at the Strait of Gibraltar. Assuming, despite salinity differences, that the densities ρ and specific heat C_p of the inflow V_e (at a mean temperature T_e) and of the outflow V_s (at a mean temperature T_s) are equal, we may write the thermodynamic equation:

$$Q_a=\rho C_p(V_e T_e-V_s T_s) = -\{Q_s(1-A)+Q_n+Q_c+Q_e\}. \quad (1')$$

The *water budget* of the Mediterranean consists of the net flow dV, which is the difference between the flows V_e and V_s through the Strait of Gibraltar and which offsets the net loss of water, the evaporation E exceeding the water gain P due to runoff from rivers and from land to the sea, precipitation and also net flow from the Black Sea. Thus,

$$dV=V_e-V_s=E-P. \quad (2)$$

This constitutes the equation of conservation of volume, and, with the density, the equation of conservation of mass.

Similarly, the *salt budget* expresses the conservation of that concentration variable. If S_e and S_s are the respective mean salinities of the inflow and outflow through the Strait of Gibraltar, since the densities vary only slightly, by using the same approximation as above, the salt balance may be written:

$$V_e S_e=V_s S_s. \quad (3)$$

To the heat, water and salt budgets can be added a *potential energy budget* relative to the outflow at a depth of between about 150 and 300 m over the Gibraltar sill. Owing to its character as a concentration basin, the only waters flowing out of the Mediterranean are of greater density than the Atlantic waters present at the same depth, west of the sill. This density difference constitutes a potential energy whose conversion into kinetic energy is reflected by a current, and hence by the outflow. According to the principle of conservation, the kinetic energy must be equal to the potential energy, and may therefore be calculated from the vertical density profiles on either side of the Gibraltar sill. In a manner similar to that adopted by Kullenberg (1953), and neglecting frictional effects, we may write:

$$V_s^2=k(\sigma t_{Medi}-\sigma t_{Atl}). \quad (4)$$

We shall show below that the coefficient k is dependent on the geometry of the strait in question. The σt of the outflowing Mediterranean waters may be related to their temperature T_s and salinity S_s by an equation of state. In the numerical application given below, we use the simplified form suggested by Mamayev (1964) so that:

$$\sigma t_{Medi}=\sigma t_s=28.152-0.0735\,T_s-0.00469\,T_s^2 + (0.802-0.002\,T_s)(S_s-35) \quad (5)$$

Each of the equations 1′, 2, 3, 4 and 5 involves the use of terms common to other equations, denoting certain interactions which we have examined previously (Bethoux, 1977). They provide an understanding of the internal dynamics of this sea and explain some of its characteristics.

FORMULATION OF THE MEDITERRANEAN SEA MODEL

If we consider the Mediterranean as a whole, its stationary state may be modelled by the system of five equations (1′, 2, 3, 4 and 5), in which only two physical parameters of the sea itself are involved: the morphology of the Strait of Gibraltar (coefficient k) and the area of the basin (included in the water loss per unit surface). The other parameters depend either on the characteristics of the Atlantic waters or on the climatic conditions over the Mediterranean, which constitute the external forcing agent.

With the characteristics of the Atlantic waters, T_e and S_e, assumed to be given boundary conditions, the system of equations (1′, 2, 3, 4, 5) connects the heat advection Q_a, the water loss E-P, the characteristics of the Mediterranean waters T_s, S_s and the water flows through the Gibraltar strait, V_s and V_e. The choice of the unknowns allows for two different studies.

In the first case, the effects of the present climate, i. e. the heat advection Q_a and the water loss E-P, are known and we may calculate the values of the outflowing water characteristics T_s, S_s, and the flows V_s and V_e. It is also possible to examine the effects of climatic changes on the hydrological parameters of the Mediterranean (one example, concerning such an effect during the last Ice Age, may be found in Bethoux, 1978).

In the second case, relative to the study of the present stationary state, the characteristics T_s and S_s are known and it is interesting to derive, from the suggested system of equations, the values of thermal advection Q_a, flows V_s and V_e, and water loss E-P. We tend to favour this second approach, and obtain the mean annual values of terms which are difficult to measure. The credibility of the model is tested by comparing the calculated values of the flows to those previously published. We also compare the water loss values obtained from the waters characteristics at the Strait of Gibraltar used in the model with values derived from our heat budget (evaporation height) and precipitation studies at the surface of the sea. Solution of the system of equations requires, however knowledge of the coefficient k in (4) at the Strait of Gibraltar (and also in the Sicilian-Tunisian strait to formulate a submodel of the Eastern basin).

Evaluation of coefficient k and inflow and outflow at the Strait of Gibraltar, together with the water loss and average annual advection of the sea as a whole

Two hydrological stations located on either side of the Strait, one in the Atlantic, the other in the Mediterranean, exhibit different vertical density profiles. At each level z, below the motionless isobaric interface ($z=0$), and discounting friction, Kullenberg (1953) calculates the pressure difference due to the density difference $d\sigma t(z)$ and the resulting mean current. The outflow is obtained by multiplying the velocity at each level z by the width of the strait $l(z)$. Thus, the outflow

$$V_{s(m^3/sec)}=(2g\times 10^{-3})^{0.5}\int_0^Z \sqrt{z}\sqrt{d\sigma t(z)}\,l(z)\,dz$$

$$=(2g\times 10^{-3})^{0.5}\int_0^Z \sqrt{z}\sqrt{\sigma t(z)}\,dA(z), \qquad (6)$$

where Z is the level of the sill below the mean interface ($z=0$), and $dA(z)$ the minimum cross-section of the Strait corresponding to the thickness z.

Using the same expression, Kullenberg also calculates the inflow V_e, and thus determines the depth of the motionless isobaric interface by considering the salt balance. But the evaluation of an annual average value of V_e necessitates consideration of climatic effects (wind, atmospheric pressure) and tidal influences (see Lacombe, 1971). The formulation of our own model does not require such a complete calculation, so, in the next application, we restrict our study to the outflow V_s; this involves an inaccuracy in determining the interface depth which we deduce from the vertical profiles of σt. Furthermore, owing to the shape of the function $d\sigma t(z)$, it may be possible to change $d\sigma t(z)$ by its mean value $d\overline{\sigma t}$. In this case, and provided that the level $z=0$ is well chosen, it may be seen that the integral is only function of the geometry of the strait and coefficient k also which may be expressed as a function of the depth Z and of the minimum cross-section A (for a triangular or rectangular shape of the cross-section of the strait, the coefficient k is function of ZA^2).

After studying the flows in different seasons and years, Kullenberg published a mean outflow value of $V_s=1.79\times 10^6$ m³/sec (without frictional effect).

In a later publication, Whitehead *et al.* (1974), with the same frictionless method, completed Kullenberg's study by taking into account the effect of the rotation parameter f on the flows in a strait. This author considers two large basins (in our case the Atlantic and the Mediterranean) connected by a rectangular channel, of width 2 L, which is occupied by a two-layer system. The relation proposed by Whitehead for the calculation of the flow in the Strait of Gibraltar is:

$$Q_{m^3/sec}=0.5\sqrt{g'}\,H^{3/2}\,L\left\{1-\frac{L^2}{3x_0^2}\right\}, \qquad (7)$$

where x_0 Rossby radius of deformation $=0.5\,(g'H/f^2)^{0.5}$;
$g'=[(\rho_2-\rho_1)/\rho_2]\,g\simeq 10^{-3}\,d\sigma t\,g$;
$f=2\omega\sin\varphi=0.85\times 10^{-4}$ at Gibraltar;

H is the depth of the sill; and L is the half width of the strait at the interface depth.

This equation is only used if $L^2<3x_0^2$, which is verified at the Strait of Gibraltar. Taking $g'=2\times 10^{-2}$ m/sec², H=286 m, 2 L=7 10³ m (the width of the 100 m depth contour at the sill, which we find too weak), Whitehead calculates an outflow $Q=1.16\times 10^6$ m³/sec.

In our own calculation of the outflow through the strait, we set the mean depth of the sill at about 300 m (Kullenberg established it at 320 m and Frassetto, 1960, measured a minimum sill depth at 284 m). If we assume first that the interface is at a mean depth of 150 m and the thickness of the outflow Z to be equal to H/2, the relation (7) may be written:

$$Q=V_s=(2gZ10^{-3}d\sigma t)^{0.5}\,ZL\left(1-\frac{L^2}{3x_0^2}\right)\text{m}^3/\text{sec}. \qquad (8)$$

If the product ZL is similar to the cross-section A, we find again the equ. (6) from Kullenberg, modified by the addition of the Coriolis corrective factor. The strait width 2 L, function of the depth, is given by Kullenberg's graphic, $d\sigma t$ is calculated from hydrological density profiles. However, owing to mixing between the two superimposed layers, both $d\sigma t$ and the depth of the boundary surface separating the in and outflowing layers vary with the location of the stations and with time. We employed the density profiles obtained during the MOP-Espadon survey in September 1960 at stations C_2 (Gibraltar radial), B_2 (Tarifa radial) and A_4 (off Cape Spartel). Between the pairs of stations, by applying Whitehead's formula (7), we obtained:

C_2/A_4, $d\bar{\sigma}t = 0.59$ (80-300 m), $L = 6 \times 10^3$ m,

$Z = 220$ m, $V_s = 1.65 \times 10^6$ m^3/sec;

B_2/A_4, $d\bar{\sigma}t = 0.68$ (90-300 m), $L = 5.8 \times 10^3$ m,

$Z = 210$ m, $V_s = 1.60 \times 10^6$ m^3/sec.

We also considered $d\sigma t$ between station C_2 and the stations of profile III MOP-Calypso (September-October 1965) in the Atlantic:

$d\bar{\sigma}t = 1.86$ (150-300 m), $L = 4.65 \times 10^3$ m,

$Z = 150$ m, $V_s = 1.58 \times 10^6$ m^3/sec.

In the three cases examined, despite the geographical variation of both $d\bar{\sigma}t$ and the mean depth of the interface, similar outflow values were obtained, the corrective term $L^2/3x_0^2$ in (7) remaining small before the unity. The mean value of the calculated outflow.

$V_s = 1.60 \times 10^6$ m^3/sec,

is lower than Kullenberg's result

1.79×10^6 m^3/sec,

higher than Boyum's measured flow in 1965

1.5×10^6 m^3/sec,

and significantly greater than the mean outflow 1.14×10^6 m^3/sec proposed by Lacombe (1971) on basis of measurements in September 1960 and May-June 1961.

In the absence of current measurements of adequate duration throughout the water column, we must accept the calculated values. Furthermore, if we consider only those stations which are relatively far from the sill, $d\bar{\sigma}t$ has a value close to 1.9, the mean depth of the interface is about 150 m, the half-width is smaller than x_0 and the Coriolis corrective factor is negligible. It is then possible to use the equation (4) with a k coefficient which depends only on the geometric dimensions of the strait: $k = 2g \times 10^{-3} Z^3 L^2 = 1.4 \times 10^{12}$ m^6/sec. Using this coefficient k and the system of five equations, in which the characteristics of the Atlantic and Mediterranean waters are the given conditions ($T_e \simeq 15.4$°C; $S_e \simeq 36.2$ ‰; $T_s \simeq 13$°C; $S_s \simeq 37.9$ ‰; $d\bar{\sigma}t \simeq 1.86$), it is possible to obtain the following values:

outflow:

$V_s = 1.60 \times 10^6$ m^3/sec or 50.5×10^{12} m^3/year;

inflow:

$V_e = 1.68 \times 10^6$ m^3/sec or 53×10^{12} m^3/year;

net flow:

$dV = 8 \times 10^4$ m^3/sec or 2.5×10^{12} m^3/year;

thermal advection:

$Q_a = 2.16$ 10^{13} J/sec or 68×10^{19} J/year.

In order obtain the water loss and thermal advection of the Mediterranean proper account must be taken of exchanges with the Black Sea. According to Möller (see Defant, 1961), the net flow in favour of the Mediterranean amounts to some 20.5×10^{10} m^3/year, while the salt budget appears to be balanced. Considering this net flow as a river runoff and applying our previous estimates of the heat flow $-1\ 10^{19}$ J/year, we thus obtain for the Mediterranean, the values:

water loss:

E-P $= 2.5 \times 10^{12}$ m^3/year or per unit area 1 m/year;

thermal advection:

$Q_a = 67\ 10^{19}$ J/year or 27 kJ.cm^{-2}.year^{-1}.

It would appear possible to improve these evaluations, mainly through a more complete calculation of the flows in the Strait of Gibraltar, taking into account the inflow and the effect of turbulent circulation.

Application of the model to the study of exchanges between the Eastern and Western basins

Consideration of the heat, water, salt and potential energy budgets through the Sicilian-Tunisian strait permits us to write, for the Eastern basin, a system of equations equivalent to that presented above for the Mediterranean as a whole. By using the known hydrological characteristics of the waters we may determine the mean annual flows at this strait, and the water loss and thermal advection of the Eastern basin. Then, taking account of the results obtained for the entire Mediterranean, we may determine the water loss and thermal advection of the Western basin.

Owing to the complex morphology of the Sicilian-Tunisian strait, however, and the limited number of oceanographic measurements taken in this zone, calculation of the outflow by a method similar to the one employed at Gibraltar provides merely an approximation; the latter is nonetheless of interest in the absence of direct measurements of average flows at this strait.

Hydrological data taken at stations 6637 (or 6643) and 6641 of the LOP-Calypso survey (Morel, 1971) permit calculation of the vertical profile of the density differences on either side of the main western sill of the strait (11°35'E, 37°23'N), between the depths of 75 and 430 m. The depth of 75 m corresponds to the iso-haline 37.50 ‰, and hence to the lower boundary of the inflow, while 430 m constitutes the maximum sill depth. The difference in σt, which has an average value of 0.23 between 80 and 300 m, is zero below 300 m, so that the calculation is limited by these depths. The half-width L of the strait at the interface depth (80 m) is about 7.5×10^3 m, and is thus larger than $x_0 = 4.7 \times 10^3$.

In this case, owing to the effect of the Coriolis force, the entire width of the Strait is not taken up by the outflow, which is calculated by Whitehead's second formula:

$$V_s = 2(3f)^{-1} g \times 10^{-3} d\sigma t Z^2, \quad (9)$$

for

$Z = 220$ m, $d\overline{\sigma}t = 0.23$, $f = 0.88\ 10^{-4}$,
$V_s = 0.83\ 10^6\ m^3/sec$.

We also estimated the flow passing over the second sill (11°05'E, 37°30'N) located at a depth of 350 m. Between stations 6636 and 6642, and at depths between 60 and 220 m, $d\overline{\sigma}t$ value is 0.16. The half-width L remains greater than x_0 and the equation (9) gives an outflow: $V_s = 0.38\ 10^6\ m^3/sec$.

The total outflow through the Sicilian-Tunisian strait is:

$V_s = 0.83 + 0.38 = 1.21\ 10^6\ m^3/sec$.

Applying this value to equations 1', 2 and 3, and knowing the mean annual value waters characteristics on either side of the strait

$T_s \simeq 14.1°C$; $T_e \simeq 16.2°C$; $dS/S_e \simeq 4.7\%$,

we obtain the following values at the strait:
outflow:

$V_s = 1.21 \times 10^6\ m^3/sec$ or $38\ 10^{12}\ m^3/year$;

inflow:

$V_e = 1.27 \times 10^6\ m^3/sec$ or $39.8 \times 10^{12}\ m^3/year$;

net flow:

$dV = 6 \times 10^4\ m^3/sec$ or $1.8 \times 10^{12}\ m^3/year$;

thermal advection:

$Q_a = 1.36 \times 10^{13}$ J/sec or $43\ 10^{19}$ J/year.

Our value of V_e agrees with the calculation of the geostrophic flow by Garzoli and Maillard (1976) who, using hydrological stations established in March 1965 and in July 1966, proposed a mean value $V_e = 1.20 \times 10^6\ m^3/sec$.

By considering the water and heat flow through the Dardanelles and the Bosphorus, we obtain the following values for the Eastern basin:
water loss:

$E - P = 1.8 \times 10^{12}\ m^3/year$ or 1.08 m/year;

advection:

$Q_a = 42 \times 10^{19}$ J/year or $25\ kJ.cm^{-2}.year^{-1}$.

Finally, using the overall results obtained for the Mediterranean and for the Eastern basin, we may calculate the following values for the Western basin:
water loss:

$E - P = 0.84$ m/year;

advection:

$Q_a = 31\ kJ.cm^{-2}.year^{-1}$.

Consideration of thermal advection in the Strait of Gibraltar and in the Sicilian-Tunisian strait suggests that advection in the Eastern basin mainly comes from the Atlantic water flow, whilst advection in the Western basin principally results from the Intermediate water flowing from the Eastern basin.

COMPARISON OF WATER LOSS ESTIMATES

We have previously investigated (Bethoux, 1977) the different terms of the average annual heat and water budgets of the Mediterranean as a whole and of its two main basins, and this provides us with another estimate of the water losses. We first give the values obtained for the terms of these budgets in the following table and then explain briefly the methods employed. Recordings of solar radiation, Q_s, at certain meteorological stations were supplemented by calculations at other localities, where cloud cover values are known. Taking account of the albedo of the sea, A, which we measured in the northern part of the Western basin from the Bouée Laboratoire "Borha 1" (42°47'N, 5°35'E) and which accounts for an annual average reduction of nearly 7% of the incident solar radiation, we obtain the value of solar radiation absorbed by the waters, which is the term $Q_s(1-A)$ that appears in the first line of the table. The accuracy is about 5%.

Thermal advection Q_a was estimated from the temperature of the waters over the sills and from flow calculations resulting from the water budgets. Owing to the relative weakness of this term in relation to solar radiation (about 3%), the inaccuracy in its determination

Table
Annual value of the different terms of the heat and water budgets of the Mediterranean and of its two main basins.
Valeur annuelle des différents termes des bilans en chaleur et en eau de la Méditerranée et de ses deux grands bassins.

	Mediterranean	Eastern b.	Western b.
Solar radiation $Q_s(1-A)$	615 $kJ.cm^{-2}$/year	635 $kJ.cm^{-2}$/year	580 $kJ.cm^{-2}$/year
Advection Q_a	20 "	20 "	20 "
Back radiation Q_n	216 "	217 "	215 "
Conduction Q_c	42 "	43 "	41 "
Evaporation Q_e	377 "	395 "	344 "
Evaporation height E	1.54 m	1.61 m	1.40 m
Water gain P	0.59 m	0.59 m	0.60 m
Water loss E-P	0.95 m	1.02 m	0.80 m

has a very slight effect on the knowledge of the total energy gain of the sea: absorbed solar radiation and marine advection.

Since back-radiation was calculated from surface temperature, cloud and humidity data, the heat balance equation gave us the sum of the heat transfers by evaporation and by conduction. The Bowen ratio permits separate determination of these two terms, heat transfer by conduction alone accounting for about one tenth of the transfer by evaporation.

The evaporated water height derived from the heat budget is one of the terms of the water budget, which we supplemented by analysing the water gains of the sea as a result of precipitation and runoff from the rivers, the term P. Runoff from rivers into the Mediterranean has been estimated by Tixeront (1970). To determine rainfall at sea, we applied to its entire area the observation made at "Borha 1" that the height of rainfall at sea is approximately half (between 0.48 and 0.52) of that recorded at the bordering coastal meteorological stations. We thus calculate 0.31, 0.29 and 0,33 m for the Mediterranean as a whole, and for its Eastern and Western basins respectively. Knowledge of water gains by the sea and loss by evaporation permits calculation of the water loss of the basin in question, which appears in the final line of the table.

By analysing the flows (sections 3.1 and 3.2 above), we obtained the following values for the water losses: 1.00, 1.08 and 0.84 m for the Mediterranean as a whole, and for its Eastern and Western basins respectively. The differences between these two calculations may be attributed to inaccuracy in flow calculations and in the evaluation of the evaporation height E (hence Q_e) and water gains P.

For the entire Mediterranean, an increase of 0.05 m in evaporation corresponds to a variation of the energy amount of 12 kJ.cm^{-2}, which at all events remains smaller than the uncertainty in solar radiation (5%), back-radiation (about 10%) or thermal advection. We wish, nevertheless, to point out that while the annual evaporated water height of 1.54 m agrees with Bunker's estimate (1972) obtained by the bulk aerodynamic method, it is higher than all previous estimates made by other authors. Similarly, we calculated back radiation by using Laevastu's formula (1970), and the result obtained is significantly lower than that which would be acquired by Berliand formula (1960). An inaccuracy in the term P (water gains) may also exist owing to misappreciation of rainfall at sea and runoff from rivers. A discrepancy of the same order of magnitude remains in the Eastern and Western basins, and we thus confirm that comparable estimates of the water loss are obtained by two different methods. This tends to substantiate the validity of the methods employed, as well as the mean annual evaporation heights suggested.

CONCLUSION

Under the action of the climate in the Mediterranean, which governs the different terms of the heat and water budgets, and owing to the boundary conditions created by Atlantic waters, the sea has reached a stationary state defined by the actual values of the characteristics of the outflowing waters and of the flows exchanged at the Strait of Gibraltar. Consideration of present heat, water, salt and potential energy budgets has enabled us to suggest a physical model of the exchanges of the entire Mediterranean with the Atlantic and of the exchanges between its two basins. Such a model would be improved by taking account of the effects of turbulent circulation on the flows in the straits. Moreover, the model may also be applied to other semi-enclosed seas.

While the present mean state of the Mediterranean is stationary, its character depends both on climatic conditions over the sea itself and on the temperature and salinity in the Atlantic. A change of one of these factors would, however, alter the present state of the sea, and the model presented permits prediction of the impact on the sea. However, it would be necessary to take into account the effect of the possible variation in the sea level on the value of the coefficient k related to the section of the strait occupied by the outflow.

It also appears possible to assume an internal modification in the Mediterranean, such as a change in the physico-chemical state of the surface layer following a natural or accidental event, and to consider the consequences. In this case, the variation in the albedo of the sea and the change in heat transfers to the atmosphere will be reflected by a change in temperature of the water, and hence in salinity and flows. This study nevertheless requires consideration of space and time variations in the different terms of the budgets. Thermal advection and water flows between different regions of this sea can become significant in this case.

Acknowledgments

The author thanks Professors A. Ivanoff and A. Morel for many discussions of the ideas contained in this paper and also Professor H. Lacombe, who made a number of helpful comments.

REFERENCES

Berliand T. G., 1960. Methodika klimatologicheskikh raschetov radiatsii, *Meteorol. Gidrol.*, **6**, 9-12.

Bethoux J. P., 1977. Contribution à l'étude thermique de la mer Méditerranée, thèse Doc. Etat, Univ. Paris 6, 192 p.

Bethoux J. P., 1978. Les actions du climat et de l'océan Atlantique sur le régime de la mer Méditerranée, notamment au cours des périodes glaciaires. Colloque International du CNES, Nice 16-20 octobre 1978, à paraître.

Boyum G., 1967. Hydrology and currents in the West of Gibraltar. Results from the "Helland-Hansen" Expedition. T.R. Nato n° 36.

Bunker A. F., 1972. Wintertime interactions of the atmospere with the Mediterranean sea, *J. Phys. Oceanogr.*, **2**, 225-238.

Defant A., 1961. Physical oceanography. Pergamon press, 729 p.

Frassetto R., 1960. A preliminary survey of the thermal microstructure in the Straits of Gibraltar, *Deep-Sea Res.*, **7**, 3, 156-162.

Garzoli S., Maillard C., 1976. Hydrologie et circulation hivernales dans les canaux de Sicile et de Sardaigne, Rapport Interne du Laboratoire d'Océanographie Physique du Muséum National d'Histoire Naturelle, Paris.

Kullenberg B., 1953. Les échanges d'eau à travers le détroit de Gibraltar, B. Inf. Com. Centr. Oceanogr. Et. Cotes, Paris, 298-302.

Lacombe H., 1971. Le détroit de Gibraltar, Océanographie physique, Notes M. Sev. Géol. Maroc, 222 bis, 111-146.

Lacombe H., Tchernia P., 1972. Caractères hydrologiques et circulation des eaux en Méditerranée, in *The Mediterranean Sea*, edited by D. J. Stanley, Dowder, Hutchinson and Ross Inc., Stroudsburg, Pensylvania, 25-36.

Laevastu T., Clarke L., Wolff P. M., 1970. Annual cycles of heat in the northern hemisphere oceans and heat distribution by ocean currents. T.N. 53, Fnwc, Monterey, California.

Mamayev O. I., 1975. Temperature-salinity analysis of world ocean waters. Elsevier oceanography series, 11.

Mission MOP-Espadon, septembre 1960. *Cah. Océanogr.* **XVI**, 4, 1964, 315-327.

Mission MOP-Calypso, septembre-octobre 1965. *Cah. Océanogr.* **XXI**, *suppl.* 1, 1969, 1-48.

Mission LOP-Calypso (Univ. Paris), mai 1965 et juillet 1966. *Cah. Océanogr.* **XXI**, *suppl.* 2, 1969, 203-243.

Morel A., 1971. Caractères hydrologiques des eaux échangées entre le bassin oriental et le bassin occidental de la Méditerranée, Cah. Océanogr., **XXIII**, 4, 329-342.

Sverdrup H.U., Johnson M. W., Fleming R. H., 1942. *The Oceans*, Prentice Hall, New-Jer, 1087 p.

Tixeront J., 1970. Le bilan hydrologique de la Mer Noire et de la mer Méditerranée, Cah. Océanogr. **XXII**, 3, 227-237.

Whitehead J. A., Leetmaa A., Knox R. A., 1974. Rotating hydraulics of strait and sill flows. Geophys. Fluid Dyn., **6**, 101-125.

Wust G., 1959. Sulle compenenti del bilancio idrico fra atmosfera, oceano e Mediterraneo, Ann. inst. univ. navale Napoli, **XXVIII**, 3-18.