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The effect of thermohaline variability on the exchange through Mediterranean straits

T.S. Hopkins

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The effect of thermohaline variability on the exchange through Mediterranean straits

T.S. Hopkins

Executive Summary: Oceanographic research at SACLANTCEN attempts to increase the understanding of oceanographic processes to enhance the predictive capability of how they might affect antisubmarine operations.

This memorandum presents a new method for the determination of the exchange of water through a strait. It is based on certain dynamical approximations that render it valid for the low-frequency (greater than days) exchanges caused by the differences in density from one basin, or ocean, to another which are connected by a relatively narrow strait. The primary method used in the past is valid only for annual or greater time scales. Recent observations in the Mediterranean have disclosed large variability on the seasonal and on the weekly time scales, which has created a need for better physical explanations of the responsible forcings.

The method is based on the fact that the two-way exchange is controlled by the difference in the water-column weights on either side of the strait down to the depth of the sill, which are easily determined from hydrographic data. The data analysed in this memorandum have brought to light several new concepts: the importance of seasonal sequencing of the density structure between basins on the exchanges in the straits; the existence of a self-regulating action in the exchange itself; and the effect of long-term climatic warming trend on the Mediterranean circulation through a reduction in the production of denser water within the Mediterranean.

Using this method, real-time estimates of the velocity structure through straits could be made to provide improved operational information to vessels navigating straits. An equally important aspect is the improved understanding of the variability in the sound-speed structure created by the strong water-mass boundaries characteristic of straits. It is anticipated that application of this information either through improved physical models or on an operational basis will constitute a significant contribution to ASW research.

Further work is in progress to focus these concepts towards the specific exchanges occurring through the Strait of Gibraltar, the Færœ–Shetland Channel, the Iceland–Færœ Ridge, and the Denmark Strait.

The effect of thermohaline variability on the exchange through Mediterranean straits

T.S. Hopkins

Abstract: A simple method is presented for estimating the thermohaline driven exchanges through straits. The primary assumption is that the exchange is determined by the pressure force created by the differing weights of the water columns on either side of the sill and by the continuity of mass required by the internal basin. This renders the exchanges insensitive to the particular bathymetry or dynamical complications within the strait and computable from density profiles on either side of the strait. The method is applicable at time scales greater than days, and thus facilitates the resolution of seasonal variability in thermohaline circulations and the monitoring of interannual trends. Application to the Strait of Gibraltar gave summer and winter outflows of 1.7 and 2.3 Sv, respectively. The seasonal balance of exchanges for the Tyrrhenian Sea was computed to provide an example of the interdependence of exchanges in basins with multiple openings. The flow through the Strait of Sicily is driven by the steric-height differences between the Ionian and both the Tyrrhenian and Balearic Seas. Eastward upper layer flow was calculated to be 0.6 and 2.0 Sv for summer and winter, respectively. A cursory example is also given of the consequences of atmospheric warming on the Mediterranean circulation. It is shown that the vigor of the thermohaline circulation would decline in proportion to a decline in deep-water production.

Keywords: atmospheric warming ○ steric height ○ thermohaline circulations ○ water exchange

Contents

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1

Introduction

Although the mean circulation in the Mediterranean Sea still has many unsolved questions, researchers are now beginning to focus on finer space and time scales than those related to basin-wide or annual-mean phenomena. Such a focus is overdue with the impending need for more research on problems concerning pollution and coastal zone management. These problems require an understanding of the smaller-scale coastal boundary processes, in addition to an understanding of the larger basin-wide circulations that provide much of the coastal forcing. Also, comment is needed on other than annual time scales: both on the shorter time scales related with these coastal processes as well as the longer interannual time scales needed to evaluate long-term trends.

Semi-enclosed seas by definition have a restriction in the bathymetric passage connecting them to a larger parent water body. In the extreme case, that of a land-locked sea or lake, it is obvious that the circulation of the smaller water body is independent of the circulation of the larger. In the opposite extreme, for example continental shelves, it is generally true that the shelf circulations become more and more dependent on the adjacent ocean circulation with less and less bathymetric restriction between the two regimes.

However, concerning thermohaline circulations, the degree of independence of the circulation within a basin from that without is not a simple matter of the degree of bathymetric restriction. The further factor is the degree of atmospheric exchange, which in concert with the bathymetric restriction, modifies the local waters more rapidly than they can be exchanged with the external waters.

The Mediterranean Sea is a classic example in this regard, since not only is the bathymetric restriction great, but also the internal water modification is large. Therefore, Mediterranean waters are modified much faster than they can be flushed with Atlantic waters. As a consequence, a persistent two-way exchange is sustained at Gibraltar. It was early recognised that knowledge of the exchange through Gibraltar would lead to an understanding of the internal thermohaline circulation and its forcing. In fact, much of the research effort from the inception of Mediterranean oceanography until the present has been focused on this problem. Until recently, little of this effort has gone towards describing the seasonality of the exchange through Mediterranean straits, excepting e.g. the works of Ovchinnikov (1974), Bormans, Garrett and Thompson (1986), and Manzella, Gasperini and Astraldi (1988). One reason for this is that the three predominating methods used to determine the exchange through straits do not lend themselves well to describing seasonal variations.

The most common method follows that of Knudsen (1900) which relies on the conservation of mass for a two-way flow through a restricted cross-section in the form of continuity of volume

$$F_i = F_o + D, \tag{1}$$

and of salt

$$\rho_i S_i = \rho_o S_o, \tag{2}$$

where F is the volume transport, ρ the density, S the salinity and D the dilution (evaporation minus precipitation), and the subscripts 'i' and 'o' refer to in and out. These equations have been applied to the Mediterranean by a number of researchers (cf. Hopkins, 1978; Bethoux, 1980) in order to solve for F_i and F_o by approximating the values of ρ_i, ρ_o, S_i, S_o and D. The most serious limitation is the assumption of a time-invariant salt content (Eq. (2)) within the basin which restricts the application of the method to annual or greater time scales for which the variation in salt content is much less than in estimating a representative annual mean salinity values or in estimating a value for D (cf. Bethoux, 1980; Cruzado, 1980).

A more direct method involves measurement of the flow within a strait. However, the hazards of observing over long periods of time or near the surface and the uncertainties of integrating the observations at a few points over a cross-section are serious limitations. Consequently, direct observations are often used to confirm or improve the estimates based on the Knudsen relations. For example, Lacombe and Richez (1982) estimated an outflow of 0.9 Sv in September 1960 and 1.2 Sv in May–June 1961 on the basis of the flow recorded in the lower layer.

The condition of hydraulic control has been used recently to obtain another independent physical relationship for the two-layered exchange through a strait (cf. Bryden and Stommel, 1984; Armi and Farmer, 1985; Farmer and Armi, 1986; Bormans, Garrett and Thompson, 1986). Hydraulic control occurs when the flow is between being subcritical and supercritical; and exactly at this point of hydraulic control, the composite Froude number is equal to unity:

$$\frac{u_1^2}{g'h_1} + \frac{u_2^2}{g'h_2} = 1, \tag{3}$$

where u_1, u_2, h_1 and h_2 are the upper and lower layer depth-mean flows and thicknesses, respectively, and $g' = g(\rho_1 - \rho_2)/\rho$. This may be considered as the point when the ratios of the potential and kinetic energies are such that the interface is not distorted in passing a bathymetric constriction. At some point along Gibraltar Strait this occurs because the lower layer flow is subcritical on the Mediterranean side and supercritical on the Atlantic side. While providing another useful relationship, imposing this condition introduces another unknown: the depth of the interface in the strait.

Bryden and Stommel (1984) used the condition of hydraulic control together with the Knudsen relations to determine the minimum salinity difference possible for a given evaporative flux. Their solution was a limit for the special case in which the surface and intermediate Mediterranean waters are completely mixed (over an annual cycle), and in which the density is proportional to the salinity. Their problem corresponds to the 'barrier' problem stated below in which a maximum exchange occurs when the Mediterranean waters are mixed vertically.

Bormans et al. (1986) also used the condition of hydraulic control in conjunction with sea level and density observations to estimate the seasonal variation in the interface depth over the sill. They used the submaximal-exchange solution of Farmer and Armi (1986) to generate an approximately linear relation between the ratio of the inflow to the interfacial density difference and the interface depth. They were then able to obtain absolute values for the annual cycle of the interface height by assuming that in March the exchange is maximal at the same time that the sea level difference (geostrophically proportional to the inflow) is a maximum.

In this memorandum we present a simple, complementary method that has useful application to resolving thermohaline exchanges on time scales greater than days. The seasonal exchanges of Gibraltar and the more complicated situation of the Tyrrhenian are given. Finally, the method is used to discuss possible implications of atmospheric warming on the Mediterranean circulation.

2

Exchange using the steric-height difference method

Since our objective is to look at the non-frictional exchange through a strait at subinertial frequencies, we can make use of the approximation of Garrett and Toulany (1982) that gives the flow through a strait as proportional to the pressure gradient along the strait. This is derived from the continuity equation and the assumption that the cross-strait pressure gradient cannot exceed that through the strait.

The geostrophic relationship is given by

$$v = \frac{\Delta P}{\rho f L}, \tag{4}$$

where v is the flow across the strait, f the Coriolis parameter, r the density, L the length of the strait, and ΔP the pressure difference through the strait. With the subinertial assumption, we can approximate the continuity equation as

$$v = -Wu/L, \tag{5}$$

where W is the width of the strait, and u the flow along the strait. Combining Eqs. (4) and (5) we obtain

$$u = -\frac{\Delta P}{\rho f W}. \tag{6}$$

This equation says that the flow through the strait is $\Delta P/W$ proportional to the pressure gradient force between the two basins and inversely proportional to the width of the strait. We note that the transport, which is an intergration over the depth and width, is not specifically proportional to the width and therefore is less sensitive to the specific bathymetry of the strait. Garrett (1983) used Eq. (6) for computing the flow response to pressure gradients caused by sea-level differences. We now make an application to include also the differential pressure effect caused by different densities in and out of the basin.

The pressure at depth z relative to the surface ($z = 0$) can be expressed as the weight of a reference water column plus or minus any deviations, i.e. either due to variations in sea level (barotropic) or due to variations in the density of the overlying water column (baroclinic). By way of explanation we express the pressure as the sum

$$P(z) = P_{\mathrm{bt}} + P_{\mathrm{d}} + P_{\mathrm{bc}}, \tag{7}$$

where the subscript 'bt' refers to barotroptic, 'd' to dilution, and 'bc' to baroclinic. With the definition of a reference pressure, $P = \rho_r g z$, Eq. (7) can be written as

$$P(z) = Pr + g\rho_o[\zeta_{bt} + \zeta_d - \zeta_s], \tag{8}$$

where g is the gravitational constant, ρ_o a surface density, ζ_{bt} the sea level (except for that part effected by water removed, or addded, from the basin interior ζ_d), and ζ_s the steric-height parameter, defined as

$$\zeta_s(z) = \frac{[\rho_r - \bar{\rho}(z)]}{\rho_o} z, \tag{9}$$

where $\bar{\rho}$ is the vertically averaged density. As we have written Eq. (8), the variable ζ_{bt} would include the effect of all other forces distorting the sea level, for example those due to tides, winds, or atmospheric pressure variations, etc. We have not included them explicitly because over longer time periods (> 10 days) they tend to average out leaving only the sea-level distortions occurring as a result of adjustments to the thermohaline circulation. Equation (6) now can be written in corresponding components:

$$u = u_{bt} + u_{bc} + u_d,$$

or

$$u = g/fW[\zeta_o - \zeta_i]_{bt} + g/fW[\zeta_i - \zeta_o]_s + u_d. \tag{10}$$

To express a transport balance through the strait, we must integrate over the depth and width of the strait cross-section to obtain

$$\begin{aligned} F_{bt} &= WHu_{bt}, \\ F_{bc} &= W \int^{z} u_{bc}\, dz, \\ F_d &= DA, \end{aligned} \tag{11}$$

where A is the surface area of the basin and H is the depth of the sill. The flows and transports are indicated in the schematic (Fig. 1) with u_{bc} increasing with depth in the direction out of the basin, and u_{bt} and u_d remaining constant with depth. In Fig. 1a the flows are illustrated as they would occur independently, and in Fig. 1b as they would appear superimposed such that there is a zero net transport as required by the conservation of water volume. The in and out transports are found from

$$\begin{aligned} F_i &= W[u_{bt} + u_d]h - F_{bc}(h) \\ F_o &= F_i - F_d \end{aligned} \tag{12}$$

where

$$u_{bt} = F_{bc}(H)/WH$$

and h is the depth of zero flow.

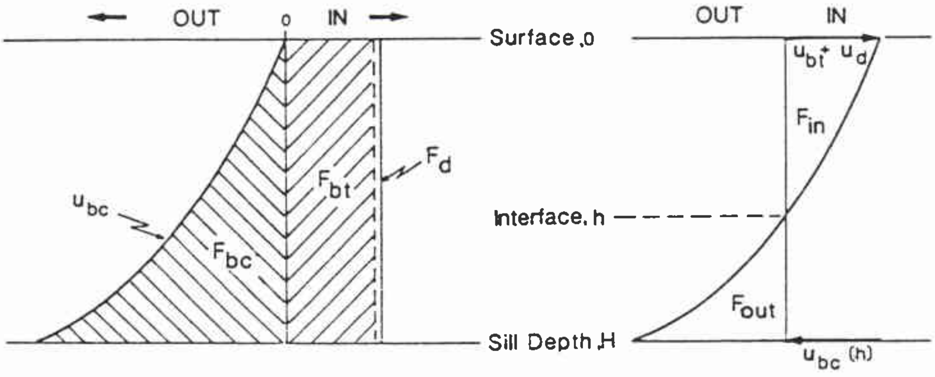

Fig. 1. Schematic of transports and velocity profile adjustments in the steric-height method.

3

Dynamical implications

Let us first consider a simple example: the circulation of the Mediterranean occurring as a result of a barrier placed at Gibraltar for a year's time and then removed. While the barrier is in place, the Mediterranean waters under the influence of the dilution deficit decrease in volume and increase in salinity. Both of these effects reduce the sea level relative to that of the Atlantic Ocean: the former because water is removed and the latter because of the corresponding decrease in specific volume (increase in density).

Upon removal of the barrier, a barotropic pressure gradient force exists which is directed inward. The immediate reaction to this force would be a barotropic flow of Atlantic water rushing inward to compensate for the sea-level difference (corresponding to the 'strong' barotropic forcing of Farmer and Armi, 1986). We note that the barotropic signal or wave travels very fast, taking for example about 6 h to travel the length of the Mediterranean. Also, the length of time to eliminate the sea-level difference would be relatively short compared to the time needed to create it; in this case, for example, it would require about 6 days with a flux of 4.4 Sv (100 cm/s) to compensate for a 1 m sea-level difference.

As the barotropic force diminished, a baroclinic pressure gradient force would begin to dominate as a result of the heavier water columns inside than outside of the strait. This force would be directed out and, as a consequence, the Mediterranean water would begin to flow out over the sill. Obviously, this outflow would again create a sea level drop and a compensating barotropic inward flow would result. We might add here that any mixing of the two waters that occurs across the shear interface makes the system less efficient in the sense that some Atlantic water would be now entrained into the lower layer export; and the result of the mixing would be to reduce the steric-height difference and thereby the magnitude of the two-way exchange.

This situation would continue until sufficient Mediterranean water had drained off and been replaced by Atlantic water such that the pressure gradient was nullified at the depth of the sill. We note that, in contrast to the barotropic signal, the baroclinic signal travels much slower, about a hundreth as fast. Further, the time for the annihilation of the initial baroclinic pressure gradient would be a matter of years, instead of days as for the barotropic pressure gradient, because of the much greater volume of water needed to be transported and because of a nonlinear decay of the outflow with the deepening of the interface. During a normal year the interface deepens at about 20 m/yr.

4

Several examples from the western Mediterranean

In order to demonstrate the seasonality of steric heights in various basins of the Mediterranean and their effects on the exchanges through the straits connecting them, we have chosen data available from literature. In most cases, they are not well suited to our purposes, being not spatially representative nor concurrent in time. In this regard we urge the reader to consider the results of this work as illustrative rather than indicative.

Gibraltar Strait For the seasonal steric heights in the Sea of Cadiz, which is the body of Atlantic water immediately outside the Mediterranean, we have used the composite data of Dietrich (1969). The data from the Alboran Sea during winter are from a station taken in March '71 and in February '74 and during summer from August '58. The station locations are shown in Fig. 2 and further information is given in Table 1. The seasonal dilution deficit was taken from Fig. 5 of Bormans et al. (1986).

During winter the steric-height difference between the Atlantic and the Mediterranean was 51 cm and the shear-interface depth about 156 m. This would not be exactly equivalent to the mean interface depth in the strait since frictional and bathymetrical effects would alter the mean velocity profile and hence the mean depth of zero velocity. The winter baroclinic shear is quite constant reflecting the mixed nature of the water columns. In Fig. 3 the two winter values are shown and demonstrate the much lesser intra-basin than inter-basin spatial variability. The two winter values varied by 3%.

In contrast, the summer steric height difference was less at 37 cm. The baroclinic shear in the upper layer is very small down to $\sim$ 100 m, due to very slight density differences between the Atlantic and Mediterranean surface waters. Below this depth, which roughly defined the surface isopycnal layer during the preceding winter, the shear remained seasonally unchanged. The inflow was reduced by $\sim$ 24% over that of winter and the shear-interface was lowered to 175 m. The magnitude of the seasonal variation of the interface ($\sim$ 20 m) is similar to that estimated by Bormans et al. (1986), although their mean interface depth was deeper at $\sim$ 200 m.

Because the elevation of the interface, due to winter deep-water production, lasts about two months and the lowering of the interface, due to outflow, transpires during

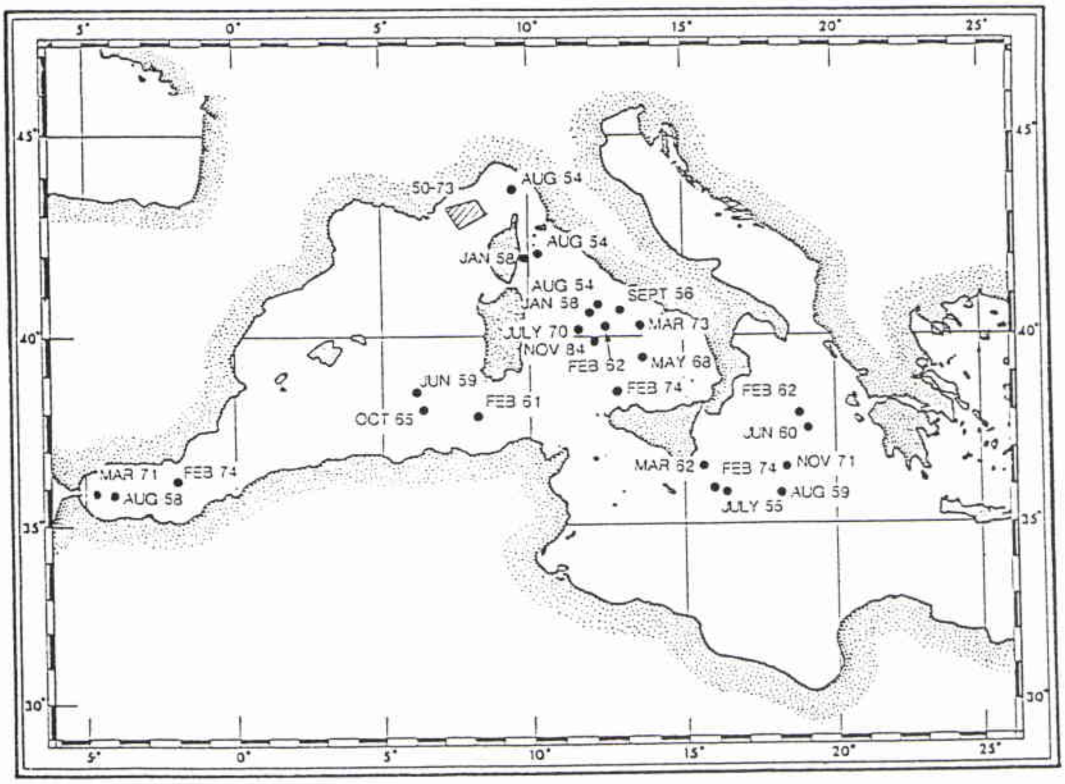

Fig. 2. Location of stations referred to in the text.

the rest of the year, we expect that the annual cycle of the interface depth (at Gibraltar) is correspondingly asymmetrical (cf. Bormans et al., 1986). An unweighted average of our summer and winter values might, therefore, return an overestimate of the annual mean transport. An average, weighted 2:1 in favour of summer, gives $\sim$ 1.9 Sv; whereas the frequently cited value of Bethoux (1980) is 1.7 Sv and range of published values is from 1 to 2 Sv.

Tyrrhenian Straits We present another more complicated example: the estimation of the exchanges between the Tyrrhenian Sea and the Ligurian Balearic and Ionian Seas through the Corsican, Sardinian, and Sicilian Channels, respectively. At this level of discussion we ignore both the Straits of Messina and of Bonifacio on the basis that their cross-sectional areas are less than 1% of the Corsica Channel, the smallest of the above.

First, we demonstrate in Fig. 4 the seasonal amplitudes in the steric heights affecting the Tyrrhenian thermohaline circulation. We make use of data readily available (Fig. 2 and Table 1), which again we emphasise were not contemporary in time

Table 1

The input and results of the various exchanges discussed in the text. The colums marked internal and external refer to the source data inside and outside the strait. For Gibraltar Strait the internal location is given in Pedenovi, Akal and Carrara (1988) and the external location (36° N, 7° W) is given in Dietrich (1969). For the straits of the Tyrrhenian Sea the location is either referenced at the end of the table or indicated by station number.

Gibraltar Strait

Season	Internal	External	h (m)	F_i (Sv)	F_o (Sv)	F_{LIW} (Sv)	F_{total} (Sv)
summer	1 Aug. '58	summer '58	175	1.78	1.66	–	0.121
winter	25 Feb. '74	winter '58	156	2.31	2.27	–	0.037
	24 Mar. '71		156	2.38	2.34	–	0.037
summer[a]	1 Aug. '58	summer '58	175	1.66	1.54	–	0.121
winter[b]	25 Feb. '74	winter '58	155	2.21	2.18	–	0.037
summer[c]	1 Aug. '58	summer '58	235	0.45	0.33	–	0.121
winter	24 Mar. '71	winter '58	174	1.58	1.54	–	0.037
summer	1 Aug. '58	summer '58	145	1.50	1.38	–	0.121
winter	24 Mar. '71	winter '58	149	2.23	2.19	–	0.037

[a] Alboran warmed 1 K–200 m and Gulf of Cadiz 1 K–75 m.
[b] Alboran pynocline lowered from 75–100 m.
[c] Maximal exchange with Alboran waters mixed to 300 m.

nor optimally located in space. Some of the stations used for this analysis were located in the middle of the Tyrrhenian, where the circulation in the stratified season is bifurcated at about 40°N (cf. Krivosheya, 1983; Moen, 1984; Hopkins 1988). Similarly, the large eddy structure in the eastern Balearic discussed by Millot (1988) or south of Sardinia by Garzoli and Maillard (1979) would introduce intra-basin error in the stations of January '59 and October '65. Little is known of the Ionian circulation, but clearly the February '62, June '60, August '59, and November '71 stations are far enough from the Straits of Sicily to introduce some uncertainty. The data from the Ligurian Sea were zonally averaged for seven periods of the year from stations taken from 1950 to 1973 (Nyffeler et al., 1980) and hence are better suited for our purposes. As an example of the variability in the southern Tyrrhenian the standard deviation of the 500 m steric height was ±3 cm among 42 stations (Hopkins 1988).

The Balearic curve, albeit with only three points, illustrates the consistently higher steric height found in the southern Western Mediterranean. Its annual mean is about 25 cm higher and its annual variation about 3 times greater than that of the Ligurian Sea. The Ionian curve has a greater seasonal range and leads that of the Tyrrhenian by more than a month, having a higher steric height in summer–fall and

Table 1 (cont'd)

Tyrrhenian Sea

Season	Internal[d]	External[d]	h (m)	F_i (Sv)	F_o (Sv)	F_{LIW}[e] (Sv)	F_{total} (Sv)
Corsica							
summer	8 Aug. '54 413,423 [2]	4 Aug. '54 403,405 [2]	–	–	0.20	−0.08 (250–400)	0.20
winter	31 Jan. '58 30–32,35 [3]	Feb. '50–73 43°N, 8°E [4]	–	–	1.30	−0.24	1.30
Sardinia							
summer	5 Aug. '54 430 [2]	27 Jun. '59 [1]	217	0.39	0.57	−0.21 (250–500)	−0.18
winter	13 Feb. '62 [1]	18 Feb. '61 [1]	299	3.19	1.92	−0.17 (250–500)	−1.27
Sicily							
summer	15 Aug. '54 445,446 [2]	19 Jul. '55 [1]	16	0.00	0.38	0.29	0.38
winter	14 Feb. '74 1,2 [5]	17 Feb. '74 13 [5]	149	0.41	0.44	0.41 (250–500)	0.03
Tunisia							
summer	19 Jul. '55 [1]	27 Jun. '59 [1]	236	0.62	0.15	0.15 (236–400)	0.47
winter	17 Feb. '74 13 [4]	18 Feb. '61 [1]	169	1.58	1.52	1.52 (169–400)	0.06

[d] [1] Pedenovi, Akal and Carrara (1988); [2] Le Floch and Romanovsky (1966); [3] Trotti (1967); [4] Nyffeler, Raillard, Prieur (1980); [5] Ozturgut (1976).

[e] Depth range is given in parentheses.

lower in the winter–spring. We would not judge these curves as conclusive in the light of the inaccurate spatial sampling mentioned above and the lack of data in the southern Balearic and southwestern Ionian Seas.

In determining the exchange through any one of the Tyrrhenian Straits, we can not necessarily impose continuity of transport, since internal volume adjustment might be compensated by a transport imbalance through one of the other openings. To resolve this, we take guidance from the observed values of flow through the Corsica Channel and compute a balance accordingly between the Balearic, Ionian, and Ligurian Seas. The currentmeter records of Astraldi, Gasparini, Hopkins and Manzella (1989) indicated a very strong seasonality to the Corsica Channel flow

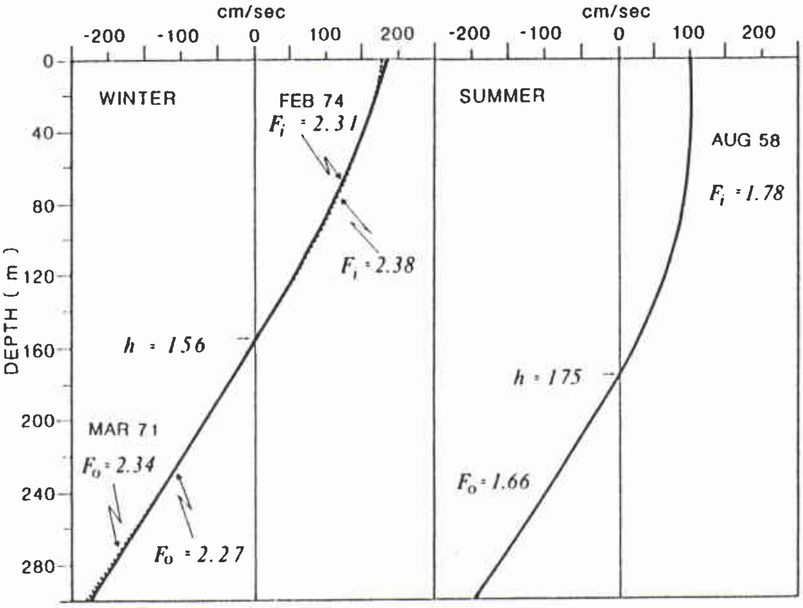

Fig. 3. Gibraltar Strait velocity profiles.

such that nearly the entire annual flux from the Tyrrhenian to the Ligurian occurs during the winter–spring period. We have taken the winter flux to be 1.3 Sv and the summer flux to be 0.2 Sv.

The dilution deficit of the Eastern Mediterranean determines the net inflow through the Strait of Sicily, and as in the case of Gibraltar, it represents only a small portion of the two-way exchange. It could be provided by a net inflow from either the Tyrrhenian or the Balearic. We have assumed that it comes from the southern Balearic as a part of the eastward surface flow. For the seasonal extremes of the this value, we have reduced the values used above for the total Mediterranean by the relative contribution of the Eastern Mediterranean, yielding 0.03 Sv for winter and 0.09 Sv for summer. We neglect any differences in the dilution deficit between the Ligurian, Balearic and Tyrrhenian Seas as being unknown and/or small relative to the error of the method.

We treated the problem in the following way:

(1) a barotropic flow through the Corsica Channel was allowed such that observed transports were equalled,

(2) the barotropic flows through the Sardinian Channel and the Tyrrhenian-Ionian portion of the Sicilian Channel were adjusted such that the total vol-

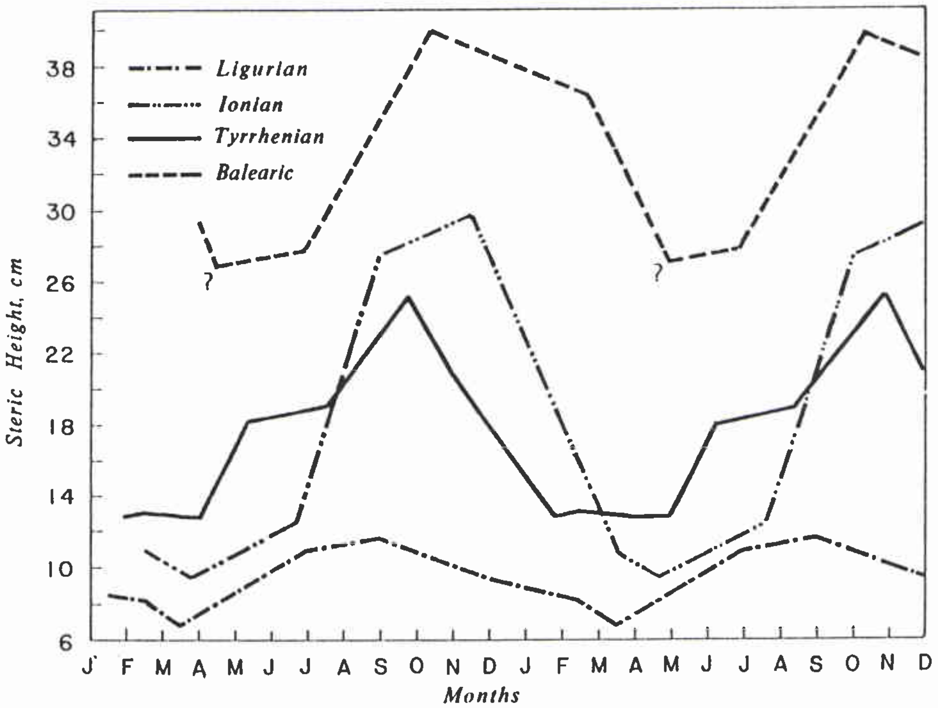

Fig. 4. Seasonal cycle of steric heights (to 400 m). Note that values are repeated more than one year.

ume flux and that of the Levantine Intermediate Water (LIW) were balanced,

(3) a barotropic flow on the Balearic-Ionian exchange was imposed such that the net flow through the Strait of Sicily equalled the dilution deficit.

The resulting exchanges are giving in Table 1 and the vertical profiles for winter and summer are compared in Fig. 5. Obviously, the solution depends on the depth ranges used to define the LIW volume. In this example, the amount of LIW entering the Tyrrhenian is fairly consistent seasonally while that entering the Balearic is much enhanced during the winter. The only direct route of LIW into the Balearic is over the Skerki Bank which has a sill of slightly under 300 m. An indirect route takes it around Skerki Bank and thereby introduces it into the southern Tyrrhenian and exposes it to the pressure forces within the Sardinian Channel where the flow, in this example, was into the Balearic. For a further discussion of the route and seasonality of the LIW the reader is referred, for example, to Morel (1972), Ozturgut (1975), Manzella, Gasparini and Astraldi (1988), and Manzella and La Violette (1989).

To solve the transport balance of the Tyrrhenian we have equated the Corsican flux

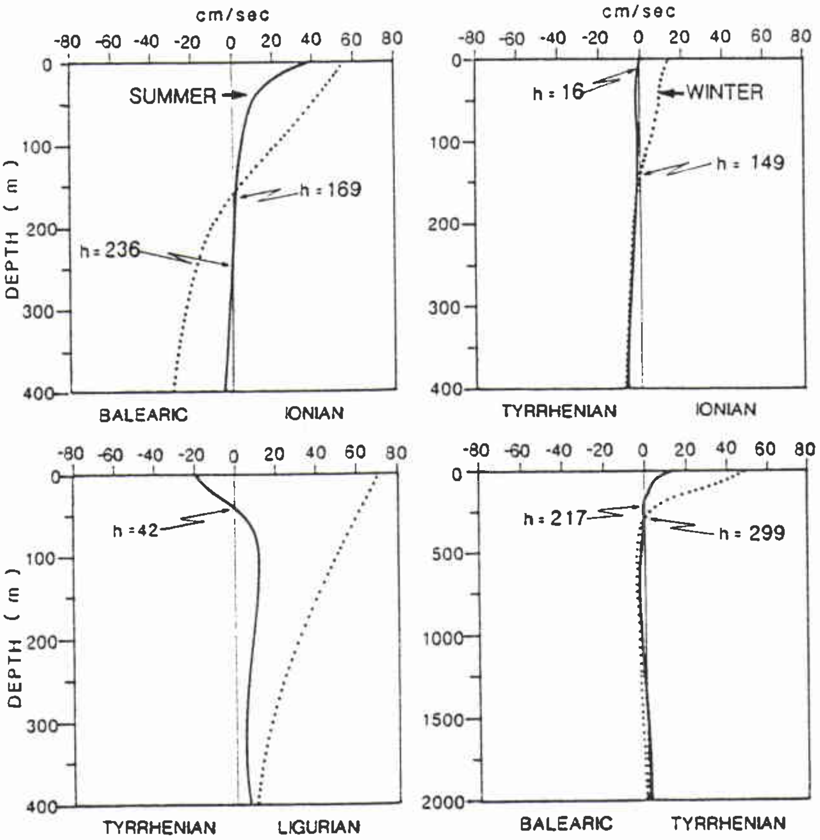

Fig. 5. Velocity profiles as computed by the steric-height method for Tyrrhenian Sea openings. The summer profile is given by the solid line and the winter profile by the dashed line.

to an observed value. In the natural setting the solution to the transport balance of the Tyrrhenian is determined differently. That is, it is determined by the net flux through the Sardinian Channel below the depth of the other sills (~ 400 m) and the vertical flux at that level. The former we might calculate (as in Table 1), but the latter would not be easily estimated and must be treated as an unknown. For this winter example, the LIW downwelling was about three times greater than in the summer. This is in accordance with Hopkins (1988), who concluded that a net annual LIW downwelling is required in order to maintain a Tyrrhenian deep water of differing characteristics than its only source, the Western Mediterranean deep water via a net inflow over the Sardinian Channel sill.

The important point demonstrated is that the thermohaline exchange is determined by the pressure gradient at the deepest point of communication, at about 2000 m through the Sardinian Channel, and, consequently, that the exchanges through the upper layers, including through the Strait of Sicily, are thereby determined. That is, the vertical circulation forced by the net transport between 400 and 2000 m in the Sardinian Channel specifies the net mass flux (together with the internal dilution deficit) required through the other straits. This does not exclude important higher frequency contributions to the sea level within the Tyrrhenian due to inter-basin variations in wind or barometric pressure.

By way of discussion we may ask ourselves why does the Tyrrhenian even need to be a part of these circulations; that is, why do the Ligurian and Balearic Seas not exchange directly and rapidly, given their large steric-height differences, leaving the Tyrrhenian Sea stagnant in a thermohaline sense? We answer this only in a general way with the following comments:

(1) The deep exchange through the Sardinian channel is dependent only on the pressure gradient at 2000 m between the Balearic and Tyrrhenian Seas, i.e. independent of the pressure gradient between the Ligurian and Balearic Seas. This pressure gradient is formed by differences in density of the Tyrrhenian water masses, which themselves are different, than waters to the west of Sardinia, less because of a different dilution deficit than because of a different history of water mass mixture.

(2) Above the level of the Sicilian sill the Tyrrhenian Sea will independently have an exchange with the Ionian Sea which, together with the Tyrrhenian dilution deficit, would lead to surface waters with densities different from those of the Balearic. In order for the Tyrrhenian to be stagnant in a thermohaline sense, its surface waters would have to have the same density structure as those in both the Ionian and Balearic Seas and its deep waters would have to be the same as those of the Balearic.

(3) A direct exchange, of course, does exist between the Balearic and Ligurian Seas. Application of the method results in a southward lower layer transport of 2.1 Sv (> 890 m) for summer and 4.6 Sv (> 450 m) for winter, respectively. The calculation did not allow for the transport through the Tyrrhenian, the Balearic sills, nor for a north–south dilution deficit difference. Presumably the estimated Western Mediterranean deep-water production (0.16 Sv) is included in this southward transport.

5

Some consequences of atmospheric warming

Predictions of atmospheric warming have estimated air temperature increases of up to 2 K over the Mediterranean and up to 1 K over the adjoining Atlantic Ocean, e.g. Manastersky (1988). Would there be an associated change in the basic thermohaline circulation of the Mediterranean Sea? The answer appears to be yes; however, a serious description would await a concomitant prediction of the atmospheric heat and water vapour exchanges.

To avoid a discussion of the non-linear interaction between the ocean and the atmosphere implicit in the coupling of their heat budgets, which surely is beyond the scope of this study, we might simply pose the question of the effects that a warmed atmosphere might have on the Mediterranean. We expect the sensible heat loss to decrease and to result in warmer surface waters and a warmer winter dense-water product. Much less obvious would be the net result on the evaporative exchange, which has a more complicated dependence on temperature due to the nonlinear dependence of water vapor on temperature. According to R.S. Stewart (personal communication) the hydrological cycle would speed up; that is, both evaporation and precipitation would increase. However, the Mediterranean atmospheric water balance is not closed in the sense that, although evaporative loss is restricted to the Mediterranean surface, the precipitation resulting from it may not return to the Mediterranean and significant portions would come from Atlantic evaporation.

We might use the Strait of Gibraltar to demonstrate some of the consequences that atmospheric warming might have on the exchange through the strait, and hence to the thermohaline circulation of the Mediterranean. Even though the quantitative changes in the rates of heat and water exchange might be difficult to estimate, the qualitative nature of the changes wrought by this climatic trend seem fairly clear: a reduction in the density of the Mediterranean waters due at least to their warming and perhaps to their freshening, and a reduction in the quantity of winter water produced in excess of the present sill-level isopycnal ($\sim$ 29.05).

The result of increasing the surface buoyancy on either side of Gibraltar would have only little effect on the exchange through the Strait, because the relative difference in the steric height would remain nearly the same. If the Mediterranean surface waters warmed more quickly than those of the Atlantic, the resultant effect on the exchange still would be small. Examples are given in Table 1: if the surface Atlantic waters were warmed by 1 K to 75 m whereas the Mediterranean surface waters were warmed by 1 K to 200 m, the reduction in the annual outflow would be about 5%.

An equivalent increase in buoyancy due to freshening would require the addition of 2 m of fresh water, or a salinity decrease of 0.35 ppt.

A much more pronounced effect is obtained if the pycnocline is lowered in simulation of a reduction in the amount of dense water produced. As an example, it was assumed that the deep-water production decreased at a rate of 5% per annum from an initial value of 25,000 km^3/yr (WMDW 5,000; EMDW 4,000; LIW 16,000). The calculated annual outflow value of 1.88 Sv (2:1 summer to winter) is 2.35 times the deep-water production. This mixing ratio was assumed to be constant in time. A relation between the annual outflow and the depth of the pycnocline was then determined by incrementally lowering the density profile. The result (Fig. 6, Table 1) is an outflow that decreases slightly less rapidly than the deep-water production, their respective half-values being 16 and 20 years. The pycnocline stabilises at the depth at which the Atlantic and Mediterranean 300 m steric heights are equal, or zero outflow.

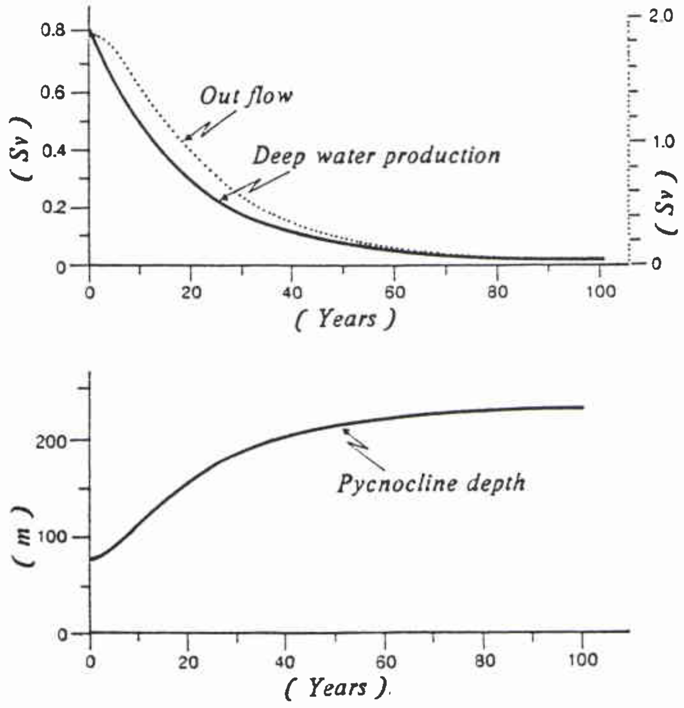

Fig. 6. Time relationship of outflow and pynocline depth given in a 5%/yr decrease in deep-water production.

6

Conclusions

The conclusion of this discussion is that the thermohaline circulation of the Mediterranean is driven from below. The driving force is baroclinic. The densities of waters behind various bathymetric restrictions are altered more rapidly than they can exchange or mix with the waters in adjoining basins, creating internal pressure gradients forces across the sills. The vertical structure of these pressure gradients determines the vertical profile of transport which would quickly eradicate the pressure force except for the condition of continuity that requires a compensating return flow, making the exchange much less efficient. The temporal stability of the inter-basin transport becomes then a question of the relative rate of production versus the rate of outflow.

At Gibraltar we found a seasonal variation in the difference of steric height across Gibraltar of 51 cm in winter to 37 cm in summer. This is a sufficiently large seasonal signal to expect that with good data, monthly to interannual variations could be monitored. The steric-height method could be applied with only one station in each basin; however, a spatial average of stations would improve the accuracy. An inherent assumption is that steric-height variability within each basin is smaller than the steric-height difference from one basin to another. Other forcings that affect the sea level will have an influence only to the extent that the internal field of mass does not adjust to them at the depth of the sill.

Within the Mediterranean, inter-basin exchanges are determined by the pressure force at the deepest point in common. The Tyrrhenian served as an example of the interaction between the mass fluxes at the various openings. The fact that the Tyrrhenian is much more of a flow-through system (through the Corsica Channel) in the winter than in the summer adds to the complexity of the internal density evolution by importing, and therefore mixing, larger quantities of LIW. With the present data available it can not be shown conclusively the significance of the different phasing of the steric heights in adjoining basins; however, it is suggested that this may cause important seasonal signals to the basin circulations.

With this interpretation, the inflow is a result of the sea level drop caused by the outflow. Attempts to measure the sea level directly to compute the inflow will be subject to relatively large observational errors and contamination with sea level transients. Instead it is suggested that attempts be made to monitor the steric heights. To render the steric-height method more accurate for the monitoring of the exchange through a strait, two preliminary studies for each strait would be required: a determination of the best way to spatially sample, and a calibration with properly averaged observed flow over the sill. Finally, this work also suggests that by monitoring the internal average of the basin's sill-depth steric height, one could monitor the deep water volume in the basin and thereby have an independent, although indirect, means for assessing the very difficult to observe air–sea exchange processes.

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