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The role of the Strait of Gibraltar in the evolution of Mediterranean water, properties and circulation

by

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ABSTRACT

Many dramatic and interesting physical oceanographic phenomena take place and interact in the Strait of Gibraltar, but the main scientific question is whether the exchange of Atlantic and Mediterranean waters through the strait is maximal or submaximal. Only in the former case, which corresponds to an "overmixed" Mediterranean, can the surface water properties of the Mediterranean be said to be controlled by the strait. The system appears to be very close to the transition between these two states, as if the Mediterranean is just overmixed. However some pieces of the puzzle do not fit. Various observational and modelling programs could help to resolve this issue.

RÉSUMÉ

L'océanographie physique du détroit de Gibraltar est caractérisée par d'intéressants, voire spectaculaires, processus. La question scientifique fondamentale reste de savoir si les échanges de masses d'eau entre l'Atlantique et la Méditerranée à travers le détroit conduisent à un mélange "maximal" ou "submaximal". Seule la première hypothèse – qui mènerait la Méditerranée proche d'une limite de "surmélange" – permettrait de conclure que les propriétés des eaux de surface méditerranéennes sont contrôlées par le détroit. Le système semble très proche de la transition entre ces deux états comme si la Méditerranée était presque "surmélangée". Cependant quelques pièces du puzzle ne s'ajustent pas. Des recherches supplémentaires, conjuguant théorie et observations, permettraient de clarifier ce problème.

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INTRODUCTION

The Strait of Gibraltar is a narrow and shallow connection between the Atlantic Ocean and the Mediterranean Sea, with a minimum width of about 15 km and a sill depth of less than 300 m (Figure 1). In the present era, the main flow occurs in response to net evaporation and slight cooling at the surface of the Mediterranean. As a result one finds a deep outflow of dense water from the Mediterranean and a compensating surface inflow of lighter Atlantic water.

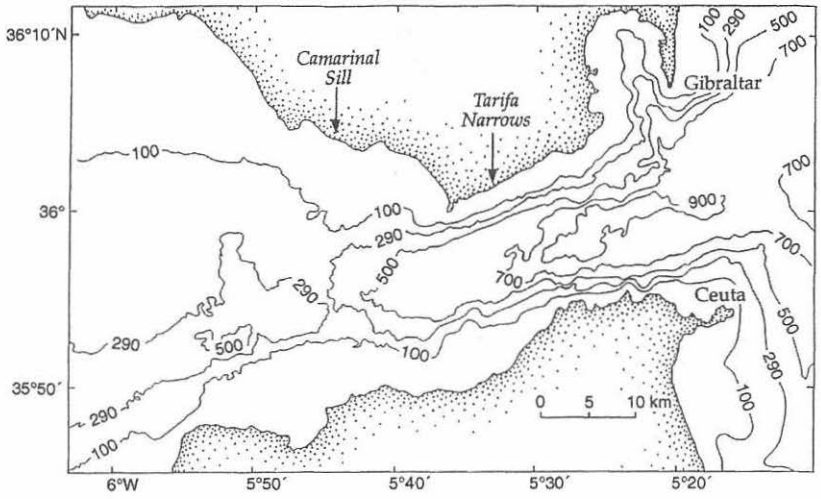


Figure 1 – Bathymetry of the Strait of Gibraltar. Contours are in meter.

A variety of other phenomena are superposed on, and interact with, this basic inverse estuarine circulation (*e.g.* ARMI and FARMER, 1988; FARMER and ARMI, 1988). Transport fluctuations at tidal and longer periods can reverse the inflow and outflow at times. At spring tides in particular, an internal bore tends to be released from the sill as the tide reverses from ebb to flood, and then breaks up into a series of large internal solitary waves (Figure 2). Successive packets of these waves can, in fact, be seen by ground-based radar (WATSON and ROBINSON, 1991) and from spacecraft or aircraft (RICHEZ and KERGOMARD, 1990; RICHEZ, 1994; ALPERS, this volume) as the associated currents interact with surface waves to cause variations in surface roughness. Intense mixing can accompany many of the large amplitude internal motions (WESSON and GREGG, 1988, 1994). There is thus a whole range of interacting phenomena, most of which have been recognized for a long time. However our understanding of the way the mean flow is determined, and of how it is affected by the tides and by the resulting internal waves and mixing is far from complete in spite of considerable clarification in recent years.

There have been indeed a number of excellent review papers. For instance, BRYDEN and KINDER (1991a) summarized much of the background material and described the conceptual, theoretical and observational

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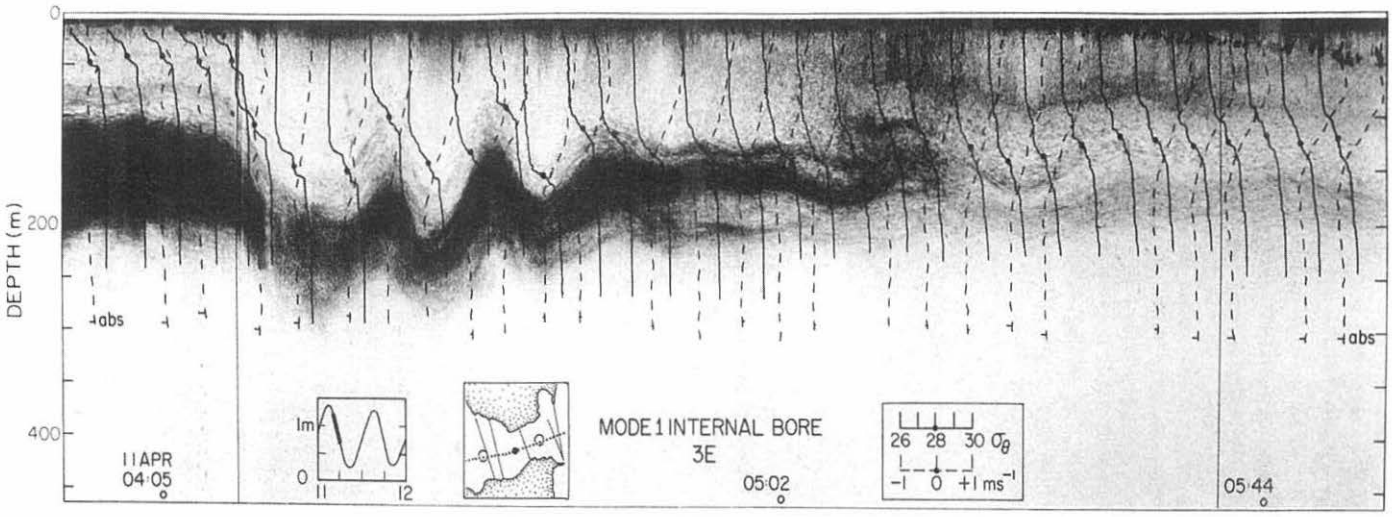


Figure 2 – Passage of an internal bore past a point in the middle of the Strait of Gibraltar, as shown by acoustic backscatter (from FARMER and ARMI, 1988).

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advances that were associated with the Gibraltar Experiment in 1985-86. CANDELA (1991) emphasized the fluctuations in the flow. Many chapters in the book edited by PRATT (1990) deal with specific issues in more detail and still more recent review material is contained in MALANOTTE-RIZZOLI and ROBINSON (1994). I shall refer to more recent advances later in this short review, but will concentrate on what I regard as the key issue, that of whether the exchange through the Strait of Gibraltar is maximal or sub-maximal.

THE CONCEPT OF MAXIMAL EXCHANGE

Let us consider the general situation of ocean water entering a marginal sea through a strait, becoming denser due to net surface evaporation and/or cooling, and eventually flowing back out through the strait. As discussed by BRYDEN and STOMMEL (1984), the outflow is likely to be hydraulically controlled in the strait if water of the same density as the outflow is only to be found at greater depth in the exterior ocean; the outflow is likely to become supercritical at the sill in the strait and perhaps then go through a hydraulic jump as it adjusts to the ocean. A strong hydraulic jump is in fact found in the Strait of Gibraltar seaward of Camarinal Sill, except when flood tide into the Mediterranean arrests the outflow (WESSON and GREGG, 1994).

BRYDEN and STOMMEL (1984) point out that this hydraulically controlled ouflow may take place in a thin layer above the bottom if the density difference between inflow and outflow is large, in which case the budgets for the sea would require only a slow exchange. This could be the case if the dense water were formed by strong evaporation on a shallow shelf, with little subsequent mixing as the dense water sank; the depths of the sea would fill with this dense water until it reached a level slightly above the crest of the sill and trickled out over it. This first scenario is illustrated very schematically in Figure 3a.

If, however, more mixing takes place in the sea, the hydraulically controlled outflow will be less dense, budgets will require greater flow rates, and the outflow will occupy a thicker bottom layer in the strait. Following STOMMEL and FARMER (1953), BRYDEN and STOMMEL (1984) argued that a limit is reached when the ouflow occupies half the depth of the strait and more mixing cannot reduce the density difference between inflow and outflow any further. This so called "overmixed" limit, with minimum density difference, then also has maximal exchange (Figure 3b). ARMI and FARMER (1985) and FARMER and ARMI (1986) corrected and extended this theory to allow for proper matching of the inflow to a semi-enclosed sea. They found that, for steady two-layer exchange through a strait of rectangular cross-section, the outflow at the sill actually occupies less than half the depth, and showed that in the overmixed limit, with maximal exchange, the inflow as well as the outflow are hydraulically controlled. ARMI and FARMER (1987) also generalised the concept of maximal exchange to allow for high frequency fluctuations such as those associated with the tides.

If further mixing in the sea reduces the vertical density difference still further, GARRETT *et al.* (1990a) have argued that there is likely to be recirculation within the sea, as shown schematically in Figure 3c. The exchange

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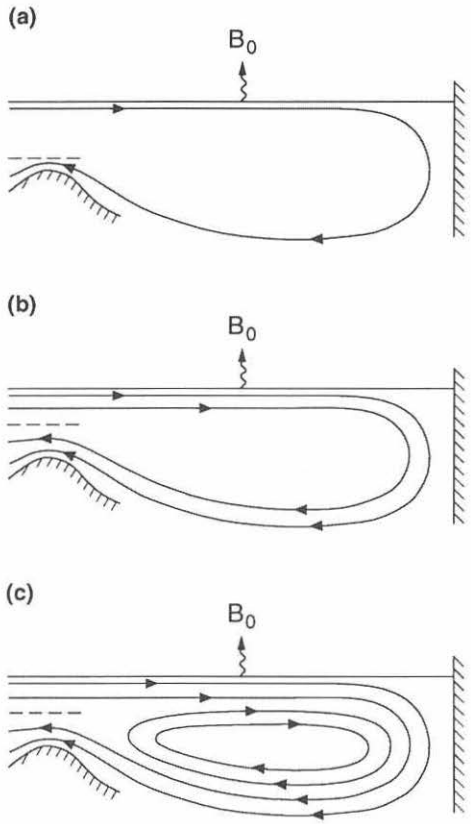


Figure 3 – Possible circulation patterns in a semi-enclosed sea subject to net surface buoyancy loss B_0 and connected to the exterior ocean by a narrow and shallow strait: (a) submaximal exchange, (b) maximal exchange corresponding to the sea being just overmixed, (c) maximal exchange for a strongly overmixed sea.

through the strait is still maximal, with the density difference between inflow and outflow still at the minimum overmixed limit, but this density difference is not achieved within the sea but rather at a front, just inside the sea, across which the inflow blends into the recirculating flow within the sea.

In all of the scenarios illustrated in Figure 3 there will be some withdrawal from below sill depth, as expected for any withdrawal from a stratified fluid and as discussed in the Mediterranean context by BRYDEN and STOMMEL (1984), KINDER and PARILLA (1987) and others. Below this depth of influence, the water properties in the sea are obviously different from what they would be in the absence of the strait. However, in the first two scenarios, submaximal or just maximal respectively, the properties of the inflow are unconstrained by the presence of the strait, apart from some possible sensitivity near the strait to an increased speed of the entering jet if the strait is narrowed. The surface layers are modified by air-sea interaction

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(which may, of course, be greatly influenced by the surrounding land masses), but, as they flow into the sea, they retain the same properties independently of the detailed geometry of the strait through which they have entered. It is only in the third scenario, when overmixing in the sea forces recirculation, that the properties of the surface waters in the sea depend on the geometry of the strait.

The observational evidence for and against an overmixing of the Mediterranean Sea, with maximal exchange through the Strait of Gibraltar, has been discussed elsewhere (*e.g.* GARRETT *et al.*, 1990a; BRYDEN and KINDER, 1991a) and will be reviewed shortly, but first the next section shall address some theoretical considerations.

Theoretical expectations

BRYDEN and STOMMEL (1984) argued that the very act of deep convection in a semi-enclosed sea subject to net buoyancy loss is associated with intense vertical mixing which should tend to drive the sea to an overmixed state. This can be examined in the simplest possible conditions of a rectangular sea subject to a steady and spatially uniform buoyancy loss at the surface. The consequences are much as illustrated in Figure 3: water becomes denser and is then driven by buoyancy forces to the head of the sea, sinking everywhere, but particularly near the head of the sea, thus feeding the return flow at depth.

PHILLIPS (1966) examined this particular simple model with reference to the Red Sea, and showed that a similarity scaling matches the longitudinal change in density along the axis of the sea rather well. GARRETT *et al.* (1990a) suggested that the buoyancy-driven flow might limit itself by turbulence when the Richardson number is reduced to $O(1)$ in the stratified return flow; the associated vertical density would then be too small to be compatible with exchange through a narrow entrance strait. Thus it seemed that such a sea, with a narrow entrance strait, would be overmixed and forced into the configuration of Figure 3c, with PHILLIPS' (1966) solution applying inside a frontal region that somehow connects the strait exchange to the recirculating flow in the sea. Basically, the expectation was that the buoyancy changes in the sea would force a rapid circulation which would effectively homogenize it compared with the larger minimal density difference required at the strait in conditions of maximal exchange.

This expectation has recently changed. MAXWORTHY (1995) pointed out that the observed vertical density gradient within the Red Sea is actually quite large and would permit exchange through the Strait of Bab el Mandeb that would be sub-critical if the interface were at mid-depth. TRAGOU and GARRETT (in press) have suggested that a more reasonable expectation is for hydraulically controlled outflow (because water of the same density as the outflow is much deeper in the external sea), but submaximal exchange. They have also fitted particular solutions of PHILLIPS' (1966) model to Red Sea data, finding that the Richardson number of the stratified return flow is, in fact, very large. The solutions require an unexpectedly large value of the eddy viscosity, up to 10^{-2} m^2 s^{-1} even at high Richardson number, for physical reasons that are not yet clear.

This would imply that, in spite of the vigorous mixing associated with deep convection, a semi-enclosed sea driven by a surface buoyancy loss is

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not necessarily overmixed with respect to a narrow entrance strait, though this depends on the strength of the internal frictional processes in the sea. Other considerations, such as the seasonality of the convection, would perhaps increase the density of the deep water even further with respect to the surface layers, making overmixing conditions even less likely. Further theoretical and modelling work will be useful in developing our intuition about these issues.

Observational evidence

There has been a tendency for the community studying the Strait of Gibraltar to accept that the exchange through it is maximal. The arguments for this presented by BRYDEN and STOMMEL (1984) seemed compelling, and the observed density difference between inflow and outflow, particularly the salinity difference of about 2 psu which dominates this difference, is very close to the predictions of models, for maximal two-layer exchange, discussed by BRYDEN and STOMMEL (1984), FARMER and ARMI (1986) and BORMANS and GARRETT (1989a,b). To be sure, these models largely ignored the role of the tides, but recently HELFRICH (1995) has shown that tides increase the average exchange much less than would be the case for lower frequency barotropic fluctuations, hence partly accounting for the success of steady models that ignore fluctuations.

Some existing models allow for friction between inflow and outflow, but most fail to incorporate the mixing of mass between the two layers (as shown by the thickness of the transition zone between inflow and outflow) despite its significance in calculations of the exchange fluxes (BRAY *et al.*, 1995) and the laboratory experiments of HELFRICH (1995) showing that mixing can reduce the exchange. While the effects of mixing will have to be examined further in the future, perhaps by adjusting the mixing coefficients and increasing the resolution of the three-dimensional numerical model of WANG (1989, 1993), it does seem clear from the density field that the Mediterranean is at least close to the overmixed limit.

On the other hand, there is no evidence of a strong density front just inside the Mediterranean Sea, as would be expected in a strongly overmixed situation. The Almeria-Oran front in the eastern Alboran Sea (TINTORE *et al.*, 1988) could perhaps be such a transition, displaced by the inertial force of the inflow, but this is far from clear and significant surface density changes occur farther to the east.

The difference between maximal and submaximal exchange through the Strait of Gibraltar is shown in Figure 4. It is based on the steady two-layer model of BORMANS and GARRETT (1989a,b), which allows for interfacial and bottom friction, but not for mixing of heat or salt between the inflow and outflow. The solutions for maximal exchange and marginally submaximal exchange have the same interface depth at Camarinal Sill and in the subcritical flow regime between the sill and Tarifa Narrows. Farther west, however, the solutions differ with the maximal exchange flow giving a shallow surface layer that separates from the north shore before reaching Gibraltar. The marginally submaximal solution, on the other hand, has a much deeper interface and does not separate; increasingly submaximal exchange would have an even deeper interface.

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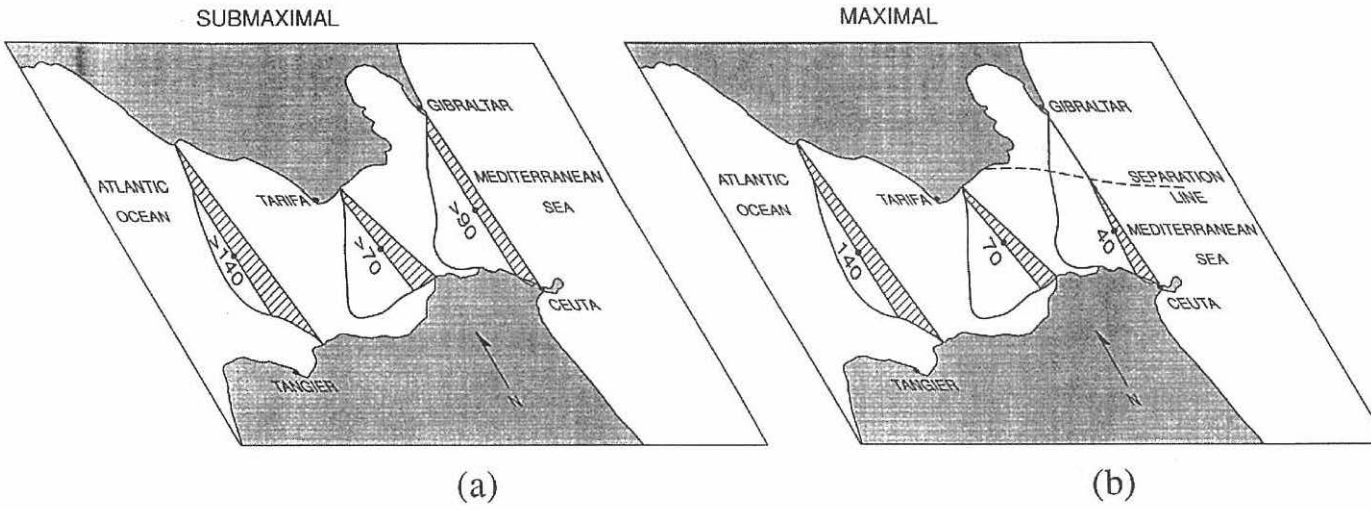


Figure 4 – Two-layer flow through the Strait of Gibraltar for (a) maximal and (b) marginally submaximal exchange, according to the model of BORMANS ar GARRETT (1989b). The hatched regions represent inflow. The depths indicated are the approximate mid-stream depth of the interface in metres.

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This model solution should not be taken too seriously, but rather as a semi-quantitative guide. In particular, ARMI and FARMER (1988) and FARMER and ARMI (1988) have argued compellingly that their observations in April 1986 of the separation of the inflow of Atlantic water from the north shore of the strait constitute evidence for supercritical flow and hence maximal exchange. On the other hand, there are occasions, such as in October 1985, when the inflowing layer seemed to be too deep to be supercritical (WESSON and GREGG, 1988), suggesting submaximal exchange.

GARRETT *et al.* (1990a) reviewed the existing evidence and concluded that the Mediterranean Sea is indeed very close to the maximal exchange state depicted in Figure 3b, but with a tendency for seasonal flips between the two states. The seasonal pattern seems to show maximal exchange during the first half of the year and submaximal exchange in the second half. They suggested that this could be a consequence of wintertime replenishment of dense Mediterranean water followed by summertime draining of this water by the outflow.

Possibly the most tantalizing evidence in support of this seasonal pattern comes from a seasonal change of about 0.1 m in the sea-level difference between the Atlantic and Mediterranean, as discussed by GARRETT *et al.* (1990a,b) and shown here in Figure 5. If the mean drop is set to 0.15 m to correspond to geodetic levelling (LEVALLOIS and MAILLARD, 1970), then the drop varies from about 0.1 to 0.2 m. These values are remarkably close to the values of 0.09 m and 0.20 m predicted by BORMANS and GARRETT (1989b) for the sea-level drop along the north shore for the marginally submaximal and maximal exchange solutions, respectively.

It must be emphasized that, quite apart from the oversimplifications of the models, the sea-level data also include the effects of changes in the Atlantic and Mediterranean away from the strait. These changes are likely

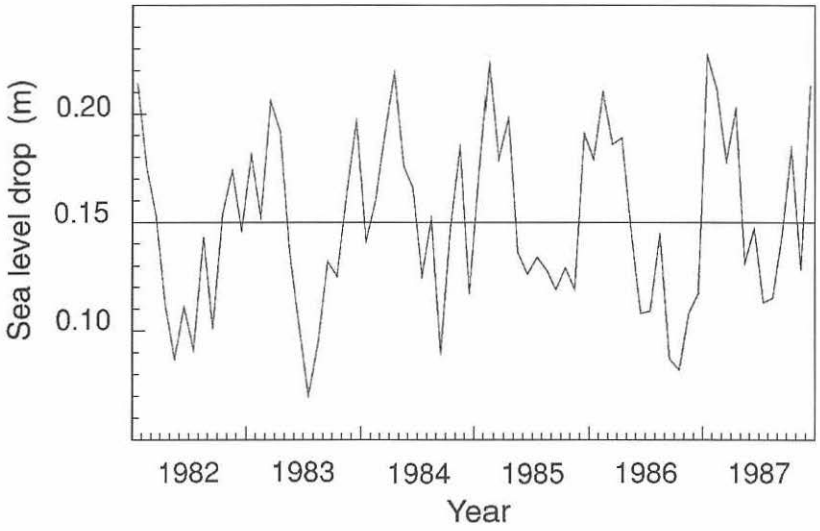


Figure 5 – Monthly mean sea-level drop from Cádiz to Málaga, based on data from 1982 through 1987 (from GARRETT *et al.*, 1990b).

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to be small compared with the signal apparent in Figure 5, but long sea-level time series closer to the strait would help in determining the nature of the exchange and would be a valuable check on models.

It must also be remarked that this simple picture of seasonal changes was not supported by an analysis of 13 months of sea-level data, from the Strait of Gibraltar, obtained between September 1981 and September 1982. The model of BORMANS and GARRETT (1989b) was used to estimate the changes in sea-level differences along-strait (Tarifa minus Gibraltar) and across-strait (Ceuta minus Gibraltar), associated with barotropic flow fluctuations through the strait (largely driven by atmospheric pressure changes over the Mediterranean). A graph of the across-strait difference against the along-strait difference should show a positive slope for maximal exchange and a negative slope for submaximal exchange, but, after adjusting the data for effects associated with an along-strait atmospheric pressure gradient, GARRETT *et al.* (1989) found only a positive value. This would actually have been expected for submaximal as well as maximal exchange if the interfacial friction coefficient were considerably greater than that used in the model, but too much extra friction would tend to eliminate the possibility of separation of the inflowing current within the strait. It was provisionally concluded that the data implied year-round maximal exchange for September 1981 to September 1982. The issue is obviously complex!

Overall, the question of maximal/submaximal exchange must be regarded as unresolved. I suspect that an eventual reconciliation of what appears now to be conflicting evidence will involve recognition of greater friction and mixing than has been incorporated into recent models, perhaps with more elaborate parameterisations than usual. There are certainly observational and modelling programs which could clarify the issue and give us more confidence about the correct assumptions to make about the exchange through the strait when considering past or future conditions in the Mediterranean Sea and when evaluating the influence of the Mediterranean outflow on the circulation of the global ocean (PRICE and O'NEIL BARINGER, 1994; REID, 1979). We turn next to some of these possibilities.

RESOLVING THE ISSUE

Observations

There are a number of possible observational programs that would clarify the nature of the exchange through the Strait of Gibraltar, as discussed on pages 530 to 535 of ALMAZÁN *et al.* (1989). Clearly, the more detail obtained on the currents, temperature and salinity structure, and mixing rates of density and momentum, the better. In particular, details of the flow over Camarinal Sill and at the eastern end of the strait, from Tarifa Narrows to the Gibraltar-Ceuta section, would allow us to determine the hydraulic nature of the flow. While the dominant flows are along the strait, recent theoretical and observational studies elsewhere (*e.g.* JOHNSON and OHLSEN, 1994; MERTZ and GRATTON, 1995) have emphasized that frictional forces in a rotating system exert their influence through secondary flows across the strait. These occur in response to the viscously-induced cross-strait fluxes in a bottom Ekman layer and in the interior, specifically at internal Ekman

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layers in the case of a sharp interface. Measurements of the strength of cross-strait secondary flows would help to establish the magnitude of frictional forces, independently of the measurement of turbulent Reynolds stresses. Improved acoustic Doppler current profiling techniques make programs of current measurement very promising.

WATSON and ROBINSON (1991) have shown how the propagation speed of different types of internal wave in the eastern part of the strait can be measured by shore-based radar, and perhaps show the hydraulic state of the inflow. Also, monitoring flow separation from the north shore of the strait – indicative of supercritical inflow and maximal exchange – would be of considerable value. Moreover, as discussed above, the seasonal variations in sea-level difference from Atlantic to Mediterranean and its shorter period fluctuations (particularly when related to cross-strait changes) can illustrate simple but revealing characteristics of the flow and provide basic checks on model validity.

Theory and Models

Models of the flow through the Strait of Gibraltar have evolved over the years with increasing recognition of the role of tidal fluctuations. Most models still assume a two-layer flow, though vertical mixing was included in the numerical model of WANG (1989, 1993). However, questions remain about the magnitude of internal mixing coefficients and about appropriate boundary conditions. Further development of models for the strait itself can clearly lead to improvements in formulas for the exchange volume flux as a function of the average net evaporation, or buoyancy loss, over the Mediterranean. The most general formula available at present is that of BRYDEN and KINDER (1991b); assuming maximal exchange and a model based on triangular cross-sections in the strait, they derived formulas for the outflow Q_2, and the salinity difference ΔS between outflow and inflow, which for small ΔS reduce to:

$$Q_2 = 1.1E^{1/3},\ \Delta S = 2.7E^{2/3},$$

where the net evaporation E is in yr^{-1}, Q_2 is in sverdrups (1 sverdrup is $10^6\ m^3\ s^{-1}$) and ΔS is in psu. The inflow Q_1 is greater than Q_2 by enough to compensate for the net evaporation.

For E = 0.52 m yr^{-1}, as estimated by BRYDEN *et al.* (1994) from Gibraltar Experiment data, we obtain Q_2 = 0.88 sverdrups and ΔS = 1.7 psu. This is somewhat different from their observed values Q_2 = 0.68 sverdrups and ΔS = 2.2 psu, illustrating the limitations of steady hydraulic models. The main point, however, is that the above scaling of Q_2 and ΔS with E is probably the best assumption to make in the light of present knowledge.

Further adjustment of the formulas is required because BRYDEN and KINDER (1991b) assumed that salinity dominates the buoyancy difference between inflow and outflow, or, equivalently, the buoyancy loss from the surface of the Mediterranean. If, however, the outflow is also ΔT colder than the inflow, it is easy to show that Q_2 in the above formula must be increased, and ΔS must be reduced, by a factor $\Gamma = (1+(\alpha\Delta T)/(\beta\Delta S))^{1/3}$, where α and β are the standard coefficients of density change. For the present state of the Mediterranean, the factor Γ is about 1.15, yielding a small,

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but significant, correction. One may estimate the correction factor Γ by using the ratio of temperature and salinity contributions to the net surface buoyancy flux, but care must be taken to allow for subleties associated with the nonlinear dependence of α on temperature (GARRETT *et al.*, 1993).

Thus the optimum formulas with respect to the present geometry of the strait would seem to be:

$$Q_2 = 0.73\Gamma E^{1/3}, \Delta S = 4.0\Gamma^{-1}E^{2/3},$$

which have appropriate dependences on Γ and E and are consistent with the observations of BRYDEN *et al.* (1994). It would be reasonable to change the numerical coefficients here if fresh data lead to new values of E, Q_2 or ΔS, but the formulas provide a tool to generate predictions for a regime with different air-sea fluxes by using the new value of Q_2 as a boundary condition. The numerical factors depend on existing mean sea-level and strait geometry but could be recalculated for different conditions.

The model and formulas do assume maximal exchange through the Strait of Gibraltar. As I have summarized above, the theoretical and observational basis for this is shaky, even though the Mediterranean Sea does seem very close to being overmixed in its present state. Numerical models of Mediterranean circulation are currently being developed (*e.g.* ROUSSENOV *et al.*, 1995). It is, of course, important that their surface forcing be adjusted to be compatible with established Mediterranean budgets of heat and water (see *e.g.* GILMAN and GARRETT, 1994). They could also serve to investigate the question of maximal versus submaximal exchange. A way to do this would be to:

1) fix T and S of the inflow to Atlantic values,

2) let the values of T and S for the outflow be determined by upstream model values in the adjacent Alboran Sea,

3) choose the inflow and outflow rates from BRYDEN and KINDER's (1991b) formula, or the modified version discussed above, using the model ΔT and ΔS to calculate Γ.

Then if the model at first gives ΔT and ΔS smaller than consistent with the exchange formula and the air-sea fluxes, less heat and salt exchange will occur than required by the surface flux, so the Mediterranean will become denser, increasing the salinity and temperature differences to approach the maximal exchange values. On the other hand, if the differences are larger than equilibrium values at first, more exchange than required for a steady state will occur, the Mediterranean will become less dense and the interface in the Alboran Sea will probably drop. If it drops far enough, this would indicate that the exchange is actually submaximal.

It could be argued that a high resolution model that extends through the strait into the Atlantic, as in the model of ROUSSENOV *et al.* (1995), is more sensible, though very high resolution is really required in the strait. Whatever the approach, an indication of strongly overmixed conditions would be the presence of a density front inside the Strait of Gibraltar, as discussed earlier, and one would then want to test the sensitivity of this to uncertain parameterisations of sub-grid scale processes in the Mediterranean Sea itself.

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OTHERS ISSUES

Apart from a mention of the dramatic internal bores (Fig. 2), tides have not been discussed here in any detail. TSIMPLIS *et al.* (1995) present a recent model for the barotropic tides, CANDELA *et al.* (1990) and GARRETT *et al.* (1989) discuss observations and WANG (1989, 1993) reproduces many features of the internal tide in a numerical model, but there is more to be learnt.

I have also only referred in passing to the barotropic transport fluctuations associated primarily with changing atmospheric pressure over the Mediterranean Sea (GARRETT and MAJAESS, 1984; CANDELA *et al.*, 1989). The interesting physics is that at low frequencies (periods longer than several days), the pressure systems are large and have time to force outflow through the strait, thus achieving an "inverted barometer" response. At higher frequencies there is not enough time for significant exchange to occur and the response within the basin is less than hydrostatic, except at very short periods where the pressure systems are small enough in scale for adjustment to occur solely within the Mediterranean Sea. Tidal and other fluctuations in the strait are interesting in their own right and important because of the effect they have on the average exchange.

There are also interesting oceanographic problems related to the role of the local meteorological forcing in the strait itself, and in understanding how the strong inflow is related to the existence and properties of the gyres in the Alboran Sea (HEBURN and LA VIOLETTE, 1990). It is even possible, as mentioned earlier, that the Almeria-Oran Front (TINTORE *et al.*, 1988) is a manifestation of the transition, postulated earlier, between the inflow and the recirculation required in conditions of maximal exchange. This might be revealed by varying the Gibraltar exchange conditions in a general circulation model of the Mediterranean.

UNDERSTANDING PAST AND FUTURE CONDITIONS

There have been many changes in the properties of the Mediterranean Sea in past eras due to different air-sea fluxes or changes at the Strait of Gibraltar. The most dramatic events were those of evaporite formation that occurred when the inflow through the Strait of Gibraltar was entirely cut off (HSÜ, 1983). It is estimated the last reopening of the strait took place some five and a half million years ago. More recently, the Mediterranean seems to have experienced changes at different stages of the last ice age, as revealed in the properties of bottom sediments (THUNELL and WILLIAMS, 1989). These will not be discussed here but it would be rash, in unravelling the oceanography associated with these changes, to assume that the Mediterranean was overmixed, though this remains of course a possiblity.

Similarly, future changes that might be associated with changing air-sea fluxes are not necessarily correctly predictable with the assumption of maximal exchange, although this might be a plausible starting point. From a monitoring perspective, in fact, GARRETT *et al.* (1990a) stressed that changes will show up more readily at the Strait of Gibraltar if the exchange is submaximal. In that case, a cessation of deep water formation, to take an extreme example, would lead to an observable drop of about 9 m a year in the interface in the strait if one uses the present outflow rate of

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Mediterranean water of 0.68 sverdrups (BRYDEN *et al.*, 1994). On the other hand, if the Mediterranean were well into the overmixed state, the implied large reservoir of dense water would need to drain for many years before changes in interface depth would be observable at the strait.

The annual draining of about 9 m mentioned above does, of course, mean that significant seasonal changes, as would occur if the drop were comparable with the height of the interface above the top of the sill, are not to be expected. It does, in fact, seem surprising that such a small drop might trigger a transition from maximal to submaximal exchange. There might be a role of seasonal changes in wind stress, as suggested by BORMANS *et al.* (1986), but a more appropriate conclusion is that we are still a long way from understanding the exchange and its variability.

The possible effects of freshwater diversion on the hydrography of the Mediterranean have been much discussed in recent years, with suspicions that increases of deep water temperature and salinity in the western Mediterranean can be traced back to reduced river discharge from the Nile and into the Black Sea (LEAMAN and SCHOTT, 1991; ROHLING and BRYDEN, 1992; SCHOTT *et al.*, 1994), though this has been disputed by BETHOUX and GENTILI (1994).

Long-term natural and human-induced changes in the hydrological cycle constitute a key problem for the Mediterranean region, especially in view of the importance of precipitation for many of the surrounding countries. To give one example, ASSAF (1989) refers to studies correlating late summer heat content of the eastern Mediterranean with winter rainfall in Israel, and goes so far as to propose offshore wave-driven mixing machines which would permit the increase of this heat content!

On a larger scale, a curiosity arising from our study (GARRETT *et al.*, 1993) of the Comprehensive Ocean Atmosphere Data Set (WOODRUFF *et al.*, 1987) based on merchant ship data, was an increase in reported cloud cover (Figure 6). Was this an artifact associated with changes in observing practice, or could it be associated with increased industrial aerosol production? Aerosols already directly affect insolation in the region (GILMAN and GARRETT, 1994) and are known to be capable of affecting cloud droplet size and persistence as well (CHARLSON *et al.*, 1992). Has the reported change in cloud cover played a role in interannual variability in sea surface temperature (Figure 7) and have either of these affected rainfall? Incidentally, Figure 7 also shows the depth-averaged temperature change computed from interannual changes in the COADS-based heat flux; the lack of correlation between the two series and the fact that changes in temperature would likely be greater in the upper layers, suggest that the COADS and bulk formulas do not accurately predict interannual changes in net heat flux.

To answer all these questions, some continued attention to the exchange through the Strait of Gibraltar seems justified, either because the Strait controls Mediterranean properties (if the exchange is maximal) or because it is a convenient choke point for monitoring purposes (if the exchange is submaximal), but we must see these studies in the context of wider problems.

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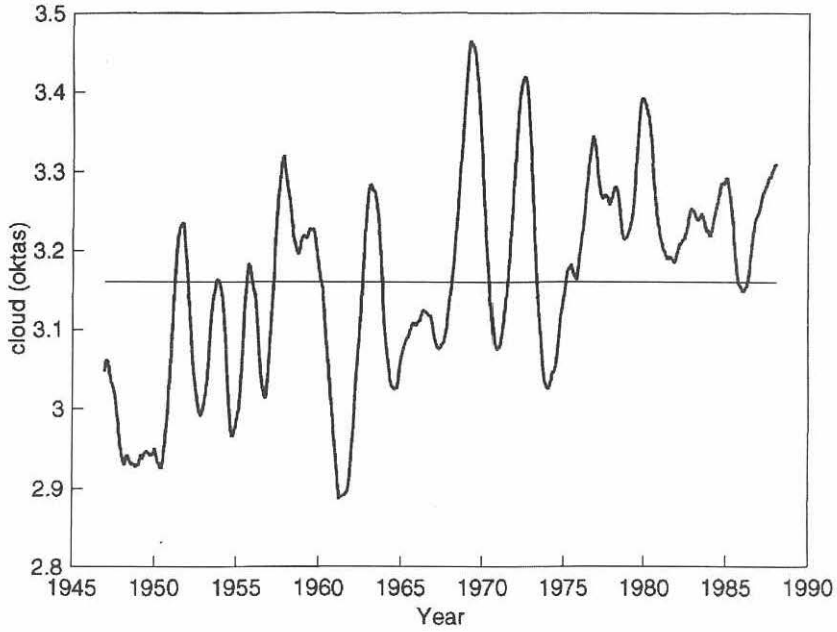


Figure 6 – Low-passed COADS cloud cover averaged over the Mediterranean (from GARRETT *et al.*, 1993).

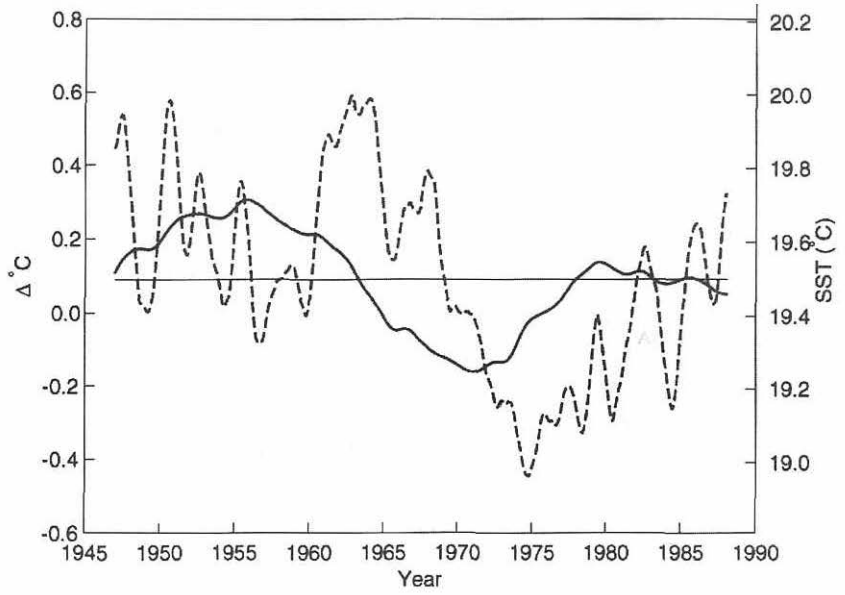


Figure 7 – Low-passed COADS sea surface temperature averaged over the Mediterranean (dashed line, right-hand scale), compared with the expected temperature change, Δ, averaged over the whole depth, computed from the COADS (from GARRETT *et al.*, 1993).

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