# A modelling study of the thermohaline circulation of the Mediterranean Sea: water formation and dispersal

PRIMO-0
Thermohaline circulation
Levantine Intermediate Water
Water formation
Modelling

PRIMO-0
Circulation thermohaline
Eau levantine intermédiaire
Formation
Modélisation

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Received 06/06/94, in revised form 25/10/94, accepted 27/10/94.

ABSTRACT

A model of the whole Mediterranean sea at 0.25° × 0.25° resolution has been run for ten years with a mean seasonal cycle of forcing using NMC winds and a relaxation to NODC surface temperature and salinity. The winter season water formation and dispersal in the model thermocline has been studied using isopycnal diagnostics and potential vorticity as a water mass tracer.
In the eastern basin Levantine Intermediate Water (LIW) is formed in the cyclonic Rhodes gyre and moves west in a continuous mass, accumulating and mixing in the centre of the Northern Ionian. The LIW spreading path is identified both from the high salinity and low potential vorticity values on the 28.8 isopycnal surface. Some LIW then spreads west and south towards Sicily, and some flows NW through the Otranto straits into the Adriatic. This water is further cooled and Adriatic deep water emerges from Otranto below the LIW inflow and spreads slowly south along the Italian coast and east into the southern Ionian on the 29.0 isopycnal surface. This path is completely consistent with observed tracer data. Contrary to observations, the LIW does not reach the far eastern Levantine in this model either due to deficiencies in the forcing or the lack of mesoscale eddies which are not resolved.
In the west, water is formed in the Gulf of Lions but it is fresher and lighter than observed and it becomes an intermediate water mass on the 28.8 isopycnal surface where it disperses SW towards Gibraltar. The dispersal of all the model water masses is slower than in reality because of the absence of mesoscale eddies. A 1-D vertical diffusion model is used to interpret the changes in the core LIW properties during the dispersal with some limited success.

RÉSUMÉ

Modélisation de la circulation thermohaline en Méditerranée : formation et dispersion.

Un modèle de circulation générale de la mer Méditerranée a été intégré sur une période de dix ans avec une résolution de 0,25° × 0,25° et un forçage saisonnier moyen utilisant les vents du NMC et un rappel de la température superficielle et la salinité vers les données NODC. Dans le modèle, la formation d'eau hivernale et sa dispersion dans la thermocline du modèle ont été étudiées en utilisant les isopycnes et la vorticité potentielle comme traceurs de la masse d'eau.
Dans le bassin oriental, l'eau Levantine intermédiaire (LIW) se forme dans le tourbillon cyclonique de Rhodes et se déplace vers l'ouest en une masse continue qui s'accumule et se mélange au centre de la partie nord de la mer Ionienne. L'écoulement de LIW est déduit à la fois des fortes salinités et des vorticités potentielles faibles sur l'isopycne 28,8.

Une partie de l'eau Levantine s'écoule à l'ouest et au sud vers la Sicile et une autre partie se dirige au nord-ouest vers le détroit d'Otrante et l'Adriatique. Cette eau se refroidit ensuite et l'eau profonde Adriatique sort du canal d'Otrante sous l'eau Levantine entrante et s'écoule lentement au sud le long de la côte italienne, et à l'est dans le sud de la mer Ionienne sur l'isopycne 29,0. Cette circulation est en bon accord avec les observations des traceurs. Dans le modèle, contrairement aux observations, l'eau Levantine n'atteint pas l'extrême est du bassin Levantin, à cause de défauts dans le forçage ou du manque de tourbillons de moyenne échelle qui ne sont pas résolus.
Dans le bassin occidental, l'eau est formée dans le golfe du Lion, mais dans le modèle elle est moins salée et plus légère que dans les observations et elle devient une masse d'eau intermédiaire qui s'écoule au sud-ouest en direction de Gibraltar en suivant l'isopycne 28,8. La circulation de toutes les masses d'eau est plus lente dans le modèle que dans la réalité, en l'absence des tourbillons à moyenne échelle. La confrontation entre un modèle unidimensionnel de diffusion verticale et les variations des caractéristiques de l'eau Levantine au cours de sa dispersion n'est pas entièrement satisfaisante.

*Oceanologica Acta*, 1995, **18**, 4, 401-417.

## INTRODUCTION

The Mediterranean sea is proving to be an exciting area for oceanographic research both because of its compact size and also the range of important physical processes that operate within its various sub-basins. The Mediterranean is a concentration basin with a nett E-P of about 0.6 m/year (Bryden and Kinder, 1991). The water deficit is made up by an excess inflow of fresh Atlantic water near the surface at Gibraltar with a slightly reduced outflow of saltier water below. The water turnover time in the basin, *i.e.* the time the inflow would take to fill the basin, is on the order of 100 years which is short compared with the thermohaline timescale in the global ocean (about 1000 years). This 100 year timescale is, however, still long enough to allow observational data on water properties to be accumulated within the semi-enclosed sub-basins which should allow modelling and theoretical studies of the circulation and water transformation processes to be put to the test. The heat budget of the Mediterranean may also provide a sensitive test of our understanding of the physics of air-sea interaction processes for the same reasons. The net heat loss of $7 \pm 3$ W m$^{-2}$, (Béthoux, 1979), is the result of cancellation between several terms such as longwave radiation and latent heat loss, which must be modelled independently. The small deep sub-basins connected by narrow straits, and particularly the narrow boundary with the global ocean at Gibraltar, therefore make the Mediterranean an attractive proposition for numerical modelling of the entire basin or of the individual sub-basins.

An early view of the general circulation of the Mediterranean was provided by Lacombe and Tchernia (1960) and Ovchinnikov (1966). The picture given by these early studies was of basin scale gyres exhibiting fairly strong seasonal variability. However recent observational efforts, for example Physical Oceanography of the Eastern Mediterranean (POEM, 1992; Robinson *et al.,* 1991), have provided a new and more complex picture. Many sub-basin scale gyres, often with seasonal variation or intermittency in intensity and position, are connected by meandering surface currents and jets threading their way across the basins from west to east. A strong mesoscale eddy field is also seen in many areas of the basins.

The thermohaline circulation of the Mediterranean is even more interesting and is currently the subject of much controversy. The transformation of surface waters to intermediate and deep waters is known to occur in several locations in the eastern Mediterranean, in particular in the Rhodes gyre and Cretan arc where Levantine Intermediate Water (LIW) is believed to form, and in the southern Adriatic where much of the eastern deep water is produced. In the western Mediterranean the Gulf of Lions has been studied in several observational surveys, it being a site of open ocean deep convection where western Mediterranean deep water (WMDW) is formed, see for example the Medoc group (1970), Gascard (1978) or more recently, Schott and Leaman (1991), Leaman and Schott (1991). The dispersal of these newly transformed water masses still provides many puzzles. In the western basin the dispersal of the deep water is thought to occur rapidly throughout the Algero-Provencal basin (Béthoux and Tailliez, 1993). Further south some of the WMDW appears to be drawn upwards to pass over the Gibraltar sill out into the Atlantic (Kinder and Parrilla, 1987) along with LIW which forms the bulk of the outflow Bryden and Stommel (1982).

In the east the LIW is found throughout the Ionian and Levantine basins. It has been suggested that this implies extended areas of formation; however it could also imply a wide dispersal from a few local formation sites. Deep water tracer studies by Roether and Schlitzer (1991) suggest that LIW penetrates the Adriatic to provide an important contribution and pre-conditioning for the deep water formation there. The Mediterranean outflow may play a similar pre-conditioning role in the North Atlantic where its high salinity is thought to encourage deep convection in the Norwegian and Greenland seas (Reid, 1979), (such convection does not occur in the north Pacific perhaps because the water is too fresh). A earlier viewpoint was that Adriatic deep water formation probably occurred in the shallow North Adriatic where the water is coldest in winter, however the incorporation of higher salinity LIW into the Adriatic water suggests a more southerly formation site and recent observations in the southern Adriatic by Buljan and Zore-Armanda (1976), Ovchinnikov *et al.* (1987) seem to confirm this. Levantine intermediate water also emerges into the western Mediterranean through the Sicily straits but its path through the western basin to Gibraltar is also controversial. Wüst (1961) suggested a direct westward route in the form of an Algerian undercurrent along the coast of North Africa but the physical basis of such a flow is suspect. Recent work suggests a complicated path (Katz, 1972 ; Millot, 1985), perhaps as a current around the northern coast of the basin controlled by Coriolis effects. LIW is certainly found throughout the western basin although whether this dispersal is due to mean currents or eddy mixing is presently unclear. Its most important role is again to provide pre-conditioning for deep convection in the Gulf of Lions.

Recently a number of modelling groups have begun to examine the Mediterranean in its entirety, *e.g.* Menzin and Moskalenko (1982), Stanev *et al.* (1989), Zavatarelli and Mellor (1994), or with particular emphasis on the eastern basin, Malanotte-Rizzoli and Bergamasco (1989, 1991). Of particular relevance to this study is the work of Pinardi and Navarra (1993) who have used the modular version of the PE Cox (1987) code to study the wind driven baroclinic circulation of the whole Mediterranean basin. This model was extended by Roussenov *et al.* (1995) to include a more realistic topography and higher vertical resolution and by Castellari *et al.* (1995) to include a sophisticated heat and momentum flux seasonal driving. We have used the same model for this study but with a greatly simplified surface forcing.

This study uses the above GCM of the entire Mediterranean in order to look specifically at thermohaline processes of water mass transformation and dispersal. Unlike a pure process study we have not attempted to model at extreme resolution the water formation at a single site. Nor have we attempted at this stage to simulate all of the physical processes, particularly those involving air-sea interaction, which would be needed by a fully realistic model of the circulation. This study is the first step towards obtaining a model which can correctly represent the interaction of different components of the thermohaline flow on basin and inter-basin scales. Several diagnostic tools are developed such as isopycnal property maps and potential vorticity analysis which have not, to our knowledge, been used previously in the Mediterranean. The intention is to make the modelling results more comparable with observational evidence of the general circulation which are mostly based on water property data. The water can be followed directly as it disperses within the model thermocline. We examine the relationship between water properties and hydrographic conditions at the formation sites and discuss the conditions required for the core method to be useful for tracking water.

In section Model formulation we provide a brief description of the model formulation and describe some preliminary experiments on the basis of which we have modified various model parameters and the surface forcing for improved water production. The main integration lasting for ten years is then performed. Section Water formation sites describes the water formation sites and discusses the properties of the winter mixed layer each year at the time of water formation. Section Water mass dispersal uses an isopycnal analysis and a core method to trace the LIW and WMDW masses as they disperse from the formation sites. The mixing of the water masses is discussed along with the modification of hydrography and circulation over the period of the integration. Section Core Water analysis looks at factors which affect the subduction rate and the potential vorticity of the water masses. We consider a quantitative core method in more detail to show the processes which alter the properties of the dispersing water. Section Discussion discusses and criticises the current results and infers changes which may be needed for model improvement.

## Model formulation

The ocean model used for this study is described by Cox (1987) and the equations are given below.

$$\frac{\partial \mathrm{u_h}}{\partial \mathrm{t}} + \mathbf{u}\cdot\nabla\,\mathbf{u}_\mathrm{h} + f\mathrm{k}\times\mathbf{u}_\mathrm{h} = -\frac{1}{\rho_0}\nabla\,\mathrm{p} - \mathrm{A_h}\,\nabla^4\,\mathbf{u}_\mathrm{h} + \mathrm{A_v}\,\mathbf{u}_{\mathrm{hzz}}, \tag{1}$$

$$\mathrm{p_z} = -\rho \mathrm{g}, \tag{2}$$

$$\nabla\cdot\mathbf{u} = 0, \tag{3}$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \mathbf{u}\cdot\nabla\,\mathrm{T} = -\mathrm{K_h}\,\nabla^4\,\mathrm{T} + \mathrm{K_v}\,\mathrm{T_{zz}}, \tag{4}$$

$$\frac{\partial \mathrm{S}}{\partial \mathrm{t}} + \mathbf{u}\cdot\nabla\,\mathrm{S} = -\mathrm{K_h}\,\nabla^4\,\mathrm{S} + \mathrm{K_v}\,\mathrm{S_{zz}}, \tag{5}$$

$$\rho = \rho\,(\mathrm{T},\ \mathrm{S},\ \mathrm{p}). \tag{6}$$

Spherical coordinates are used and u is the full velocity vector while $\mathrm{u_h}$ represents the horizontal velocity vector. The equation of state for sea water, (6), is based on the UNESCO formula which is simplified and adapted for use in numerical models. The model resolution is 0.25° × 0.25° in the horizontal with 19 levels in the vertical. Several authors have developed this model for use in the Mediterranean and in particular Roussenov *et al.* (1995) can be referred to for further details. A map of the model bathymetry can be found in Roussenov *et al.* (Fig. 2*a*). In this experiment the entrance to the western basin at Gibraltar is open with water masses free to enter and leave. In the "Atlantic box", a small area west of Gibraltar, the T,S properties at all levels in the model are continuously relaxed to a Levitus (1982) climatology on a timescale of five days. This provides for a specified water inflow while leaving the internal dynamics of the basin to set the model outflow which is then absorbed by the Atlantic sponge.

The model is forced by wind stress and buoyancy terms at the surface. The momentum surface boundary condition is given by:

$$\mathrm{A_v u_{hz}} = \frac{\tau}{\rho_0}$$

where the wind stress vector $\tau$ is calculated from a 9 year average of NMC analyzed data over the period 1980-88.

The monthly averages are calculated with linear interpolation for forcing the model at intervening times. The vertical diffusion parameter for momentum has the value $A_v$=1.5 cm$^2$ s$^{-1}$. The horizontal diffusion, $A_h$ = 8 × 10$^{18}$ cm$^4$ s$^{-1}$. During the integration the diffusion coefficients for heat and salt were given by $K_v$ = 0.3 cm$^2$ s$^{-1}$, $K_h$ = 2.4 × 10$^{19}$ cm$^4$ s$^{-1}$. The low $K_v$ reduces downward diffusion of the thermocline which will occur in the absence of upwelling from deep water formation. This low value is more in line with the values estimated by Garrett (1993) and Ledwell *et al.* (1993) and it also reduces the diffusive mixing of new core waters as they disperse allowing them to be followed more easily. The high $K_h$ provides smoothing of the strong property gradients produced by surface forcing in winter water formation areas, and near straits. Small scale baroclinic eddies should provide this strong mixing in reality and later studies will report model runs with lower diffusion which allow some of these eddies to grow. This experiment therefore provides a baseline in which no eddies are present.

Relaxation surface boundary conditions are used over the whole of the model domain for both temperature and salinity. The surface boundary conditions have the form;

$$K_v T_z = \alpha(T - T^*)$$

$$K_v S_z = \beta(S - S^*)$$

where T*, S* are linearly interpolated from the monthly average surface T,S, from the NODC data set. A convection scheme operates whenever the potential density profile indicates instability, which instantly mixes T and S properties between adjacent layers. While flux boundary conditions would be more realistic allowing greater surface variability, *e.g.* Castellari *et al.* (1993), the concern of this paper is to study water mass transfer from the mixed layer into the thermocline or the deep basins and subsequent dispersal, therefore we chose to specify realistic mixed layer properties each year through relaxation. It would be possible to repeat the integrations using a flux correction method, however it will be shown that the implied fluxes from the present forcing are not unrealistic and the flux correction has not been implemented. All the natural variability in water properties from the reported model run is therefore confined to the regions below the mixed layer. Currently $\alpha = \beta = 5$ m h$^{-1}$ giving a very strong surface forcing of the top layer, which is 10 m thick. The mixed layer T,S properties are effectively fixed at all seasons of the year although the depth of the mixed layer will change depending on year to year changes in the hydrography.

The initial conditions of the model were those of the Levitus annual mean climatology and the integration was begun in June to reduce the need for immediate convective adjustment which would be required by winter conditions. A run with relaxation to the original NODC surface T*, S* values was first performed for eight years, however the surface water in winter in the southern Adriatic is forced to be too fresh and only reaches a potential density of 28.7 so that no deep water is formed. The original NODC data may have excess coastal sampling where river outflow modifies the water or it may not represent conditions during convection when saltly waters are brought up from below. In any case this radically alters the thermohaline circulation of the entire eastern basin. The low density, fresh Adriatic water spreads into the Ionian where it cuts off the westward and northward flow of LIW. The circulation in the Ionian becomes blocked and shows little evolution after year 5. We decided to change S* in the South Adriatic from 38.0 psu to 38.6 psu in line with observations of the salinity of Adriatic deep water, *e.g.* El-Gindy and El-Din (1986). The effect is to greatly deepen the Adriatic mixed layer producing water of density > 29.0 which emerges into the Ionian below the LIW and does not therefore interfere with LIW dispersal. This is a temporary fix and in later runs we have instead decreased $\beta$ but the results reported here are not greatly altered. With the above modification the model was spun up for a total of eleven years from Levitus (through ten winter seasons) with a repeating cycle of seasonal winds and T*,S* surface properties. The following sections analyze the changes to the water masses over the period of the run.

## Water formation sites

Since this model is forced with prescribed surface conditions of T,S the regions of deep and intermediate water formation are fully determined as far as these water properties are concerned. Our objective is understanding the water formation process, *i.e.* the process by which water leaves

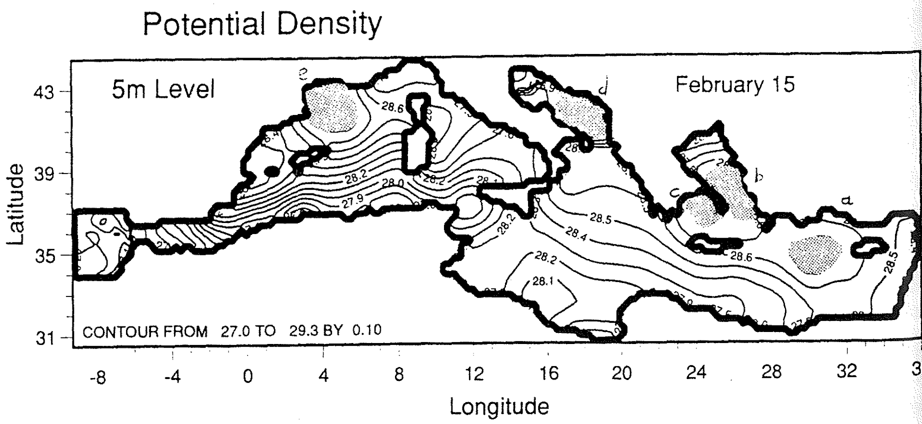



Figure 1

*Contours of surface density at the end of February. These values are controlled by the strong relaxation to the NODC data set values.*

Table 1

*Properties of Levantine intermediate water according to different authors.*

| | Temperature °C | Salinity psu | $\sigma_t$ |
|---|---|---|---|
| Wust (1961) | 15.5 | 39.10 | 29.05 |
| Lacombe and Tchernia (1972) | 15.7 | 39.10 | 28.98 |
| Ozturgut (1976) | 16.2-16.4 | 39.12-39.15 | 28.85 - 28.87 |
| Ovchinnikov (1984) | 14.7-14.9 | 39.03-39.06 | 29.12 - 29.15 |
| Plakhin and Smirnov (1984) | 14.5 | 38.85 | 29.06 |
| Hecht (1986) | 15.5 ± 0.4 | 39.02 ± 0.05 | 28.91 ± 29.01 |
| Hecht *et al.* (1988) | 15.5 ± 0.5 | 38.98 ± 0.06 | 28.86 ± 28.99 |

the winter mixed layer, and the subsequent dispersal of water masses through the basins and straits. A more sophisticated boundary condition and/or mixed layer model, would be needed to do a better job of the surface mixing and particularly for relating the mixed layer T,S properties to the hydrography, see for example Lascaratos *et al.* (1993).

Figure 1 shows contours of surface density at the end of February from the main model run. This date provides the coldest surface conditions in most regions of the Mediterranean and the five main water formation sites, where the mixed layer density is above 28.7, are shaded on the figure. A (T,S) scatter diagram which defines the core water masses from each of these regions is shown in Figure 2. Areas (a) and (b) contain what may be called the LIW water mass from the model. The Rhodes gyre area, marked (a), produces water with a temperature of 16.25-16.75 °C and salinity 38.9-39.02 psu giving a typical density around 28.7. Many points from areas (a) and (b) overlap in (T,S) space but the dominance of 28.7 water in the Rhodes gyre area is clear from Figure 1. To facilitate comparisons with previous results, Table 1 is from Lascaratos *et al.* (1993) and shows previous property definitions for LIW. While model salinity is broadly consistent with observations, the temperature of the water in the model is too warm. This probably reflects the use of monthly mean surface temperatures for forcing the model. In reality LIW is likely to form in extreme cooling events from each winter which would increase the density to 28.9 or more. However it is clear that the densest intermediate water formed in the Levantine is closely associated with the Rhodes gyre due to the requirement for colder surface temperatures which only occur in the northern Levantine. As Lascaratos *et al.* note, the T or ρ of the surface mixed layer confines the

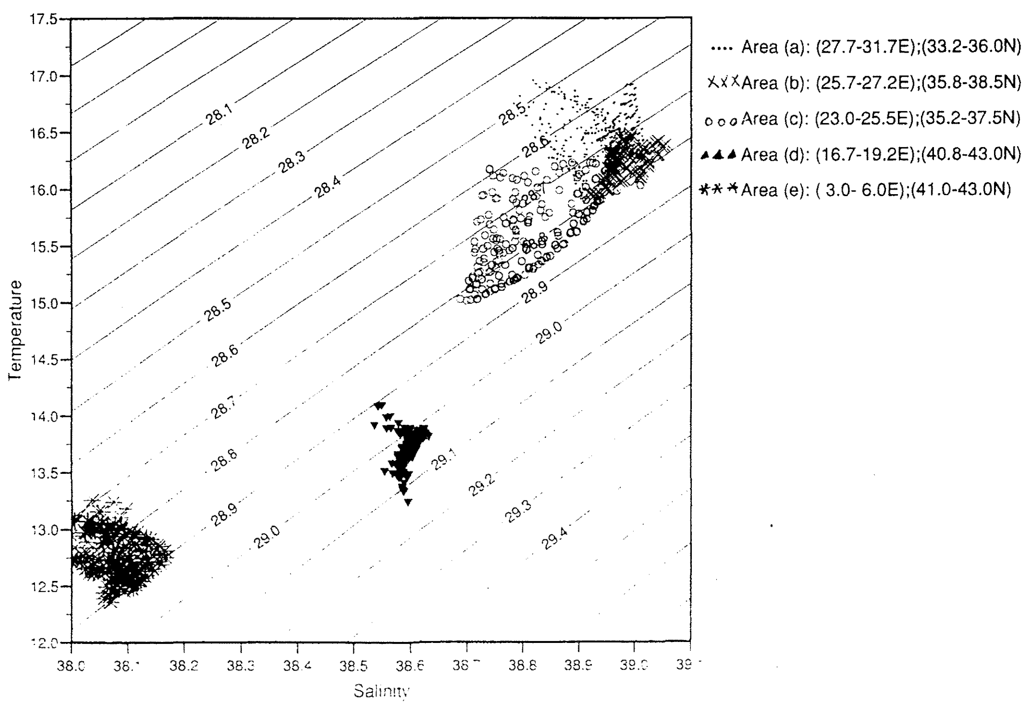


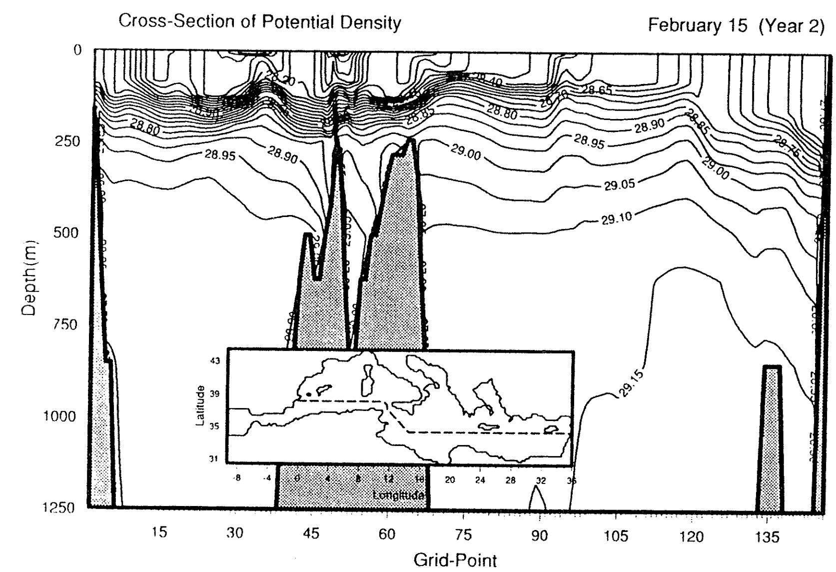

Figure 2

*Temperature-Salinity diagram of the surface waters showing the characteristic core properties at the time of formation* (i.e. *winter) from five areas, (a) Rhodes, (b) Aegean, (c) Crete, (d) Adriatic, (e) Gulf of Lions.*

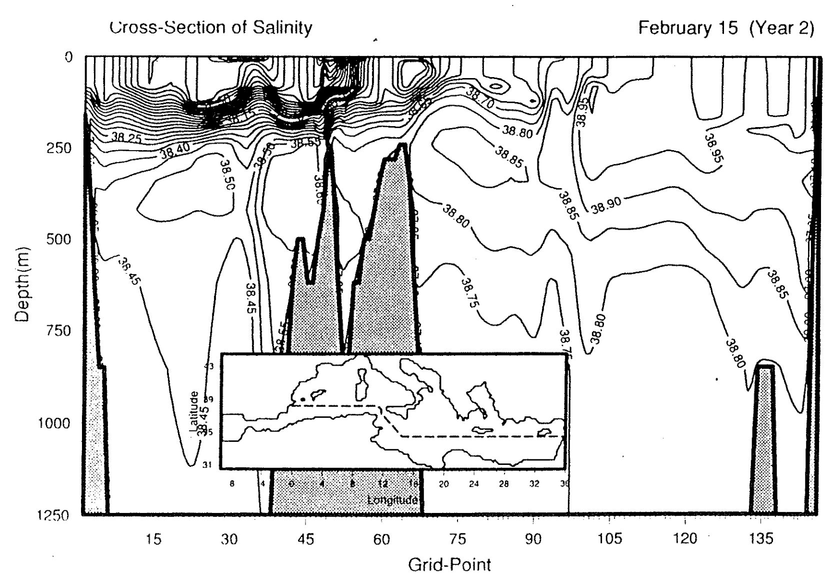
region of LIW formation whereas S becomes more useful below the surface to trace the water during dispersal. Area (b) shows water forming in the Eastern Aegean which also has high salinity and low temperature in winter. The salinity reaches up to 39.07 here, with a temperature range only slightly cooler than around Rhodes leading to a mean density of 28.75 for the core water. The high salinity values in areas (a) and (b) along with their proximity make these two water masses more or less indistinguishable and thus we refer to both of them as LIW.

Area (c) shows Cretan water formed NW of the island of Crete next to the Greek mainland. The diagram shows more spread in the core properties than the previous regions but the water is in any case clearly distinguishable from LIW by being colder, fresher and slightly denser, $\rho > 28.8$. This is consistent with observations by Schlitzer *et al.* (1991), although again the water mass in the model is warmer than in reality. Area (d) shows Adriatic core water. This is much cooler and fresher than the Cretan or LIW water with a core temperature range of 13.5-13.75 °C and a salinity of 38.6 psu (modified from NODC in February). The high salinity for the Adriatic deep water (ADW) is due to entrainment of a substantial portion-perhaps 80 %, of LIW which must enter the Adriatic over the Otranto sill and the model will be shown to reproduce this inflow well. The density of the model Adriatic water is around 29.0 and it therefore emerges below the level of the LIW at Otranto.

Finally area (e) shows western Mediterranean deep water (WMDW) in the Gulf of Lions. The water is cold, 12.4-12.75 °C, and fresh, 38.05-38.15 psu, with a mean density of 28.85. As with the original NODC data in the southern Adriatic this water is too fresh since typical WMDW sali-




*(a)*




*(b)*

Figure 3

*East-West basin cross section for potential density (a) and salinity (b) in February of the first winter near the beginning of the main model run.*

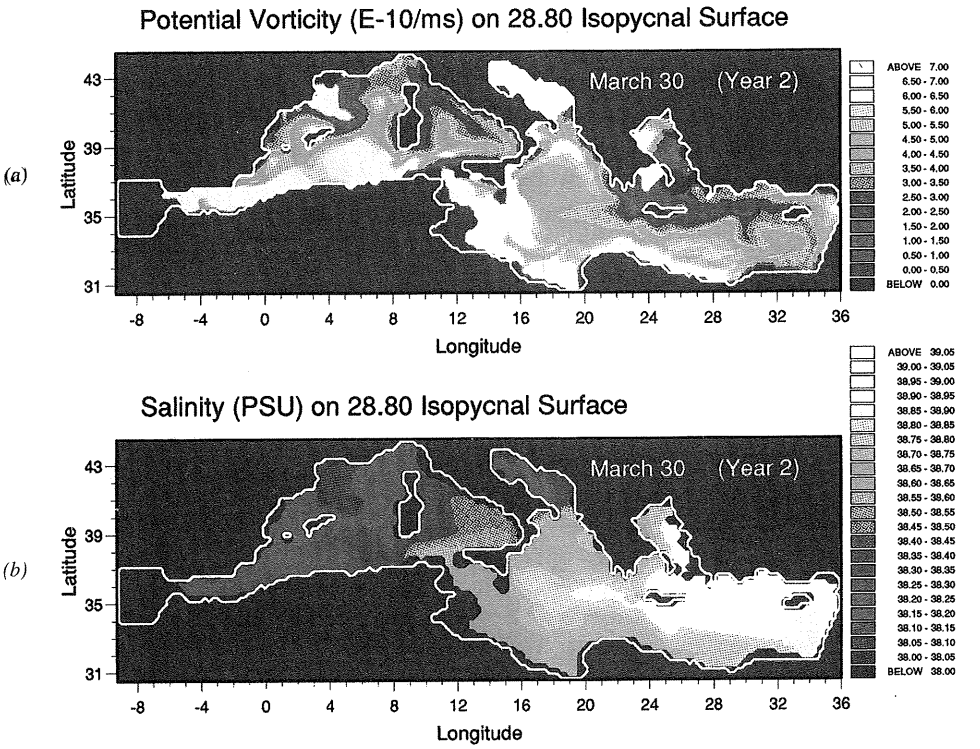



Figure 4

*Potential vorticity (a) and salinity (b) on the 28.8 isopycnal surface in March of the first winter of the model run.*

nities are up to 38.45 psu. However these properties have not been changed because the WMDW does not have such a profound influence on the other water masses.

The amount of new water formed each year depends on the local depth of the mixed layer which in turn depends on hydrography. To illustrate the hydrography near the beginning of the run an E-W cross section through both basins for density and salinity is shown in Figure 3*a*, *b* at the end of February of the second year, eight months after the beginning of the integration. The path of the cross section is shown in

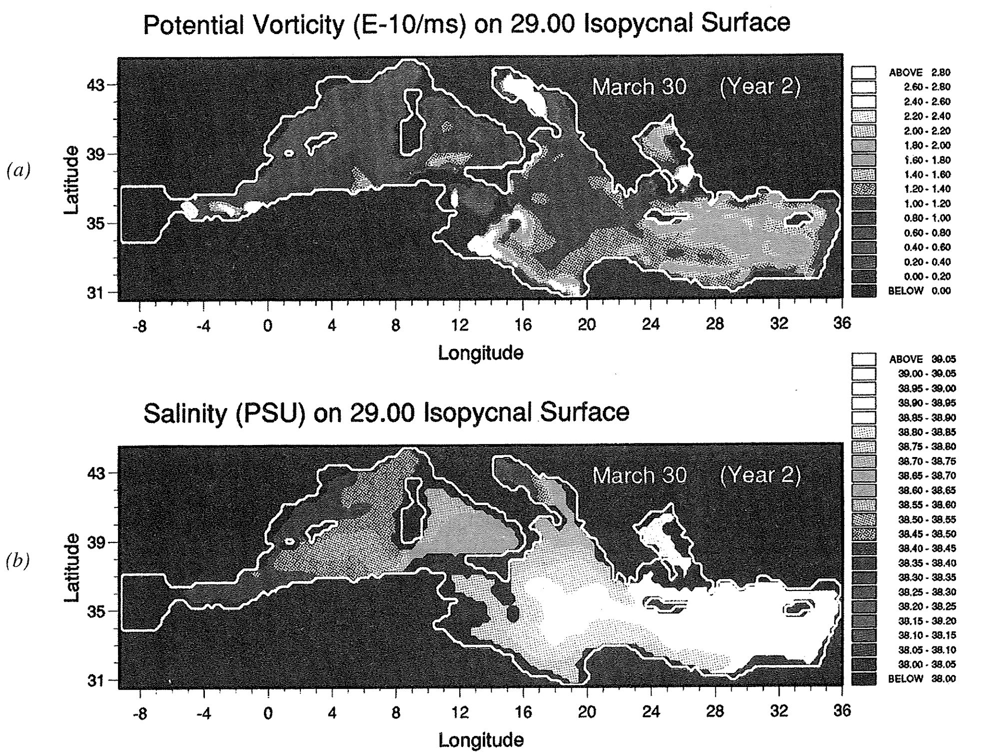



Figure 5

*As for Figure 5 for the 29.0 isopycnal surface.*

the inlay. Note the very compact pycnocline in the upper 300 m of the water column stretching across both eastern and western basins. We will study the changing structure of this pycnocline as the run proceeds and as new water intrudes along isopycnals from the formation sites. The cross section passes through the Rhodes gyre at 30° E where the isopycnals bow upwards. The region of highest mixed layer density lies on the eastern flank of this dome. Note also that the mixed layer depth is greater at the far eastern end of the Levantine basin than in the vicinity of the Rhodes gyre, although the mixed layer density, which determines the isopycnals along which water is subducted, is greatest around Rhodes. Although a subsurface salinity maximum of around 38.8 psu, characteristic of LIW, can be seen extending across the eastern basin at a depth of 250 m, near the base of the permanent pycnocline, this is a feature of the initial conditions and is not water which the model itself has produced. Up to this time no intermediate water has been actively formed by the model. These cross sections can be contrasted with those taken at the end of the run to identify the "new" water.

Finally, to provide a plan view of the formation sites while identifying the cores of new water, we have chosen to display data projected onto potential density surfaces. Such diagnostics are useful within the main pycnocline where core water masses, once subducted from the winter mixed layer, will spread by advection and horizontal diffusion along isopycnals throughout the model. The water properties on these surfaces will be only slowly changed mainly by diapycnal mixing (due to explicit vertical diffusion in the model). By tracing the core water and noting and explaining the changes in properties we hope to achieve a description similar to that obtained by observational tracer data and thereby be in a better position to modify and improve the model.

Figure 4 shows the potential vorticity (PV) and salinity on the 28.8 potential density surface in March of the second year and Figure 5 shows the same quantities on the 29.0 surface, where the potential vorticity, with relative vorticity neglected, is given by;

$$q = \pm \frac{f}{\rho} \frac{\partial \rho}{\partial z}$$

The appendix describes the method by which data from model levels is projected onto potential density surfaces and also the method used to calculate the PV. These particular potential density surfaces were chosen because they can distinguish "intermediate" and "deep" water masses formed in the eastern Mediterranean, the LIW and Cretan water on the 28.8 and the Adriatic water on the 29.0 surface. It is dispersal mainly along these surfaces which causes a permanent modification to the model thermocline and halocline, so influencing the general circulation.

We begin by considering the salinity on the two surfaces. In the Levantine both surfaces show high salinity values of 38.9-39.0 psu throughout the basin. On the deeper 29.0 surface the high salinities stretch far to the west filling much of the Ionian basin while on the shallower 28.8 surface only a thin tongue of high salinity protrudes into the Ionian and further diagnostics show that this has developed in the first nine months of the run. The salinity front between the Levantine and Ionian on the 28.8 density surface is likely to be an artificial product of smoothing on z surfaces used to obtain the Levitus data set. We can conclude that in Levitus the core of the LIW lies on the 29.0 density surface with salinity slowly decreasing westwards. In the southern Adriatic the 28.8 surface shows relatively fresh water while the water below on 29.0 is considerably more saline. In March the 28.8 surface in the Adriatic lies close to the surface in the seasonal thermocline and is thus strongly influenced by surface forcing while the deeper 29.0 surface shows the high salinity signature of the new water formed in February one month earlier.

Moving on to consider PV in the eastern basin the low PV on the 28.8 surface south of Rhodes indicates that this surface has been in recent contact with the mixed layer. Below this on the 29.0 surface the PV is actually higher in this region indicating compression of the isopycnal surfaces below the level of the dense new water. North-east of Crete in the S. Aegean there is outcropping on the 28.8 surface and NW of Crete where Cretan water is formed the high PV indicates re-capping after recent outcropping. The whole Adriatic also has very high PV value indicating re-capping of the denser winter mixed layer water. On the 29.0 surface the southern Adriatic is not outcropped and is showing moderately low values of PV associated with the new Adriatic deep water. In the northern Adriatic even the 29.0 surface has high PV indicating that it is in the seasonal thermocline.

In the western Mediterranean the 28.8 surface shows very low salinities in the Gulf of Lions indicative of the new water formation. These low salinities do not penetrate to the 29.0 density surface because the water is too fresh and light. The WMDW is known to have densities as high as 29.1 or more because of mixing with the high salinity intermediate water during convection. However water formation is dominated by relaxation to NODC in the model and thus the mixing is not deep enough. Much of the 29.0 surface in the west shows relatively low PV. This is because the water in the western basin is less dense than that in the east and consequently the 29.0 surface is at the base of the main pycnocline where there are always weak vertical gradients in potential density.

As this is the first year of water formation the new water has not had time to disperse. In the following section the same diagnostics will be used to show the changes in the thermocline and halocline structure and water properties after a further ten years of integration. A more detailed discussion of mixing and modification of water during dispersal follows in section Core Water analysis.

## Water mass dispersal

Before beginning to describe the spreading of water masses it is worth briefly looking at some methods which have been used for inferring dispersal paths from observations. The aim of the core analysis method is to trace the spreading of a water mass from its formation site or sites using changes in properties which occur as the water moves further from its place of origin. When tracing a core

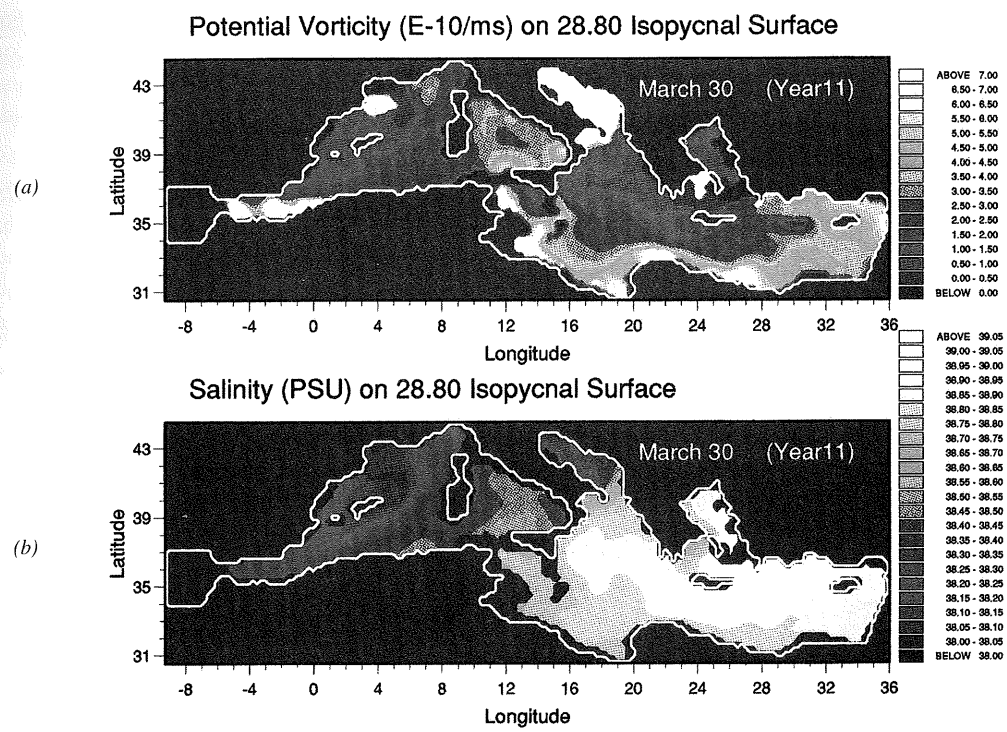



Figure 6

*As for Figure 5 on the 28.8 isopycnal surface in March on the 11th year of model integration.*

water mass it is useful to plot water properties on some 2-dimensional surface along which the water spreads. Talley and McCartney (1982) used a surface defined by the minimum value of potential vorticity in each vertical profile in order to study the spread of Labrador sea water, marked by salinity, through the North Atlantic. Since water formed by convection at local sites will have low PV values, and PV is also a Lagrangian conserved property of the water, this is a reasonable approach and it is somewhat analogous to the plotting of potential temperature on PV surfaces occasionally used in meteorology to define the tropopause, *e.g.* Hoskins and Berrisford (1988). However it is difficult to use the method if several distinct, recently formed water masses are present at different depths, *i.e.*

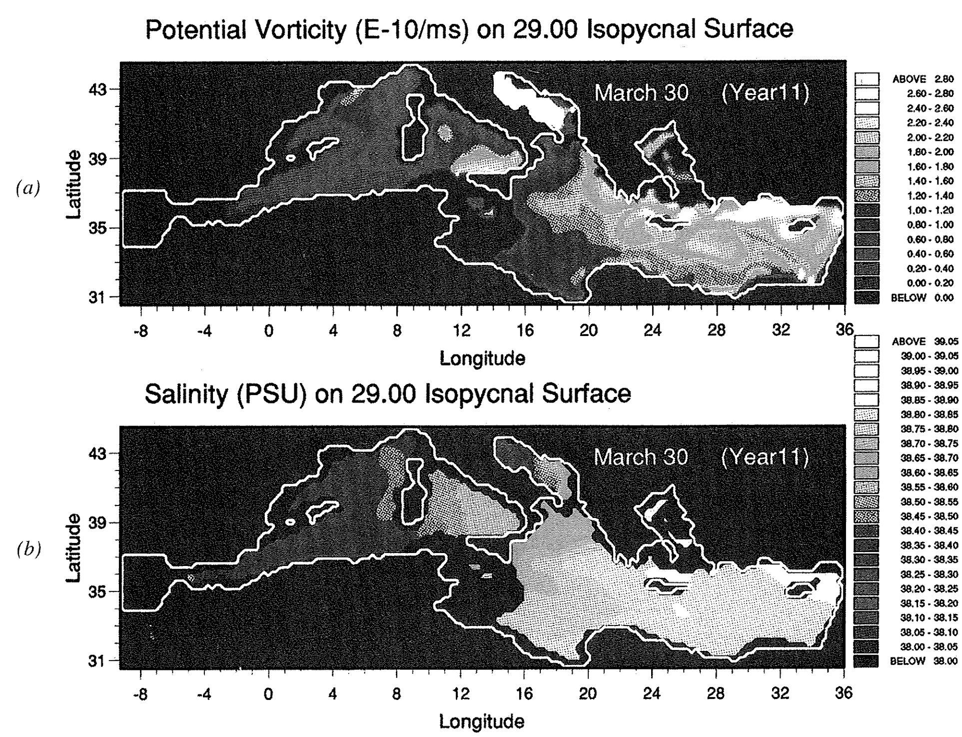



Figure 7

*As for Figure 6 on the 29.0 isopycnal surface in March on the 11th year of model integration.*

with different core densities, for then there may be more than one PV minimum in a vertical water column.

A more obvious method is to plot properties on potential density, *i.e.* isopycnal surfaces which would always provide a single valued depth to the surface at each position. There may then be problems for water passing over ridges or sills because mixing may occur and the properties, including the density, of the core water, can be considerably changed and it may therefore be best to consider straits as sources of new water with modified properties for the purposes of continued study of the dispersal. For example the LIW emerging into the western basin is considerably fresher than in the eastern basin and only in this way does it remain an intermediate water mass in the colder, fresher waters of the western Mediterranean.

In this study we track water along isopycnal surfaces mainly within the formation basins (apart from exchanges between the Adriatic and Ionian at Otranto) and therefore the isopycnal analysis method should prove adequate. Both potential vorticity and salinity are used as tracers to study

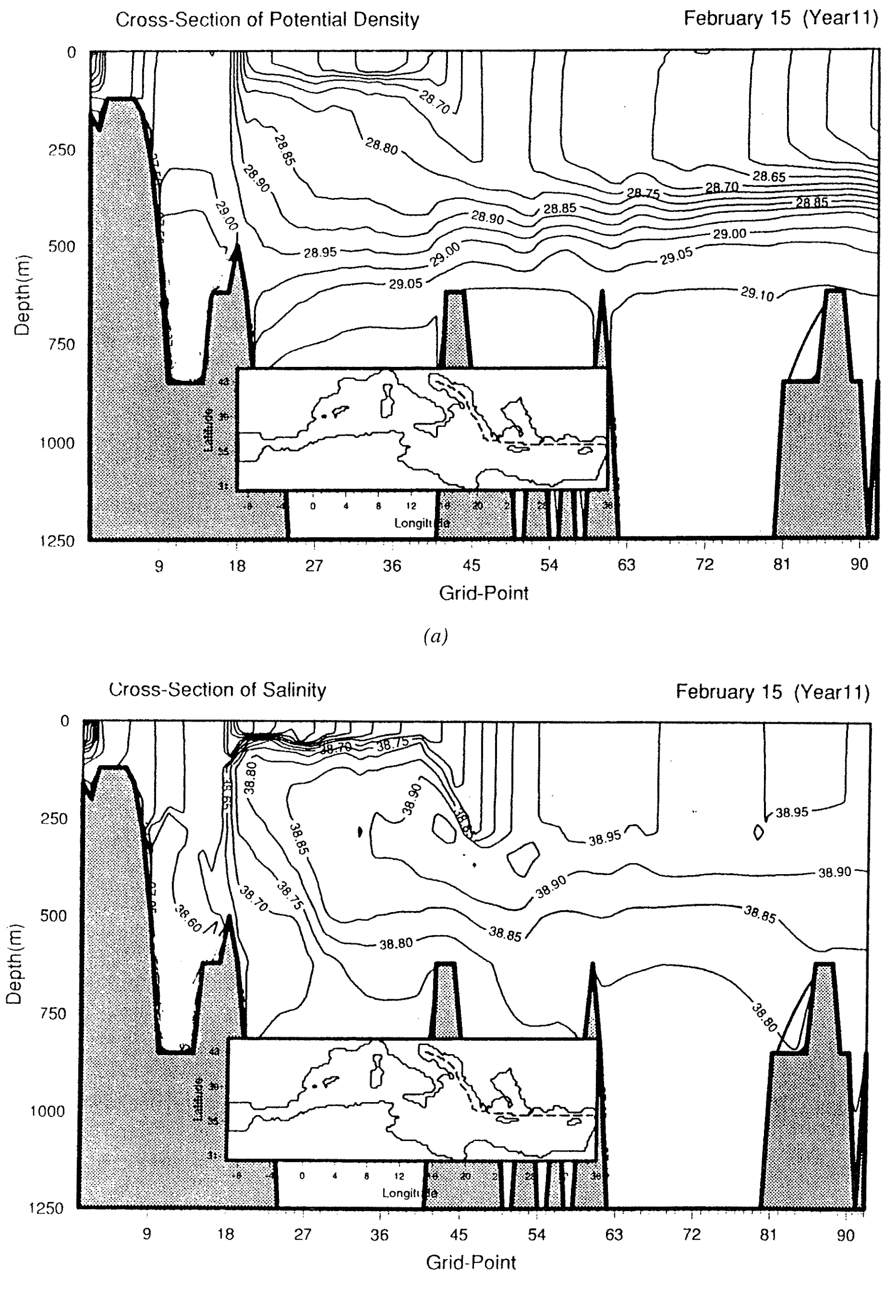


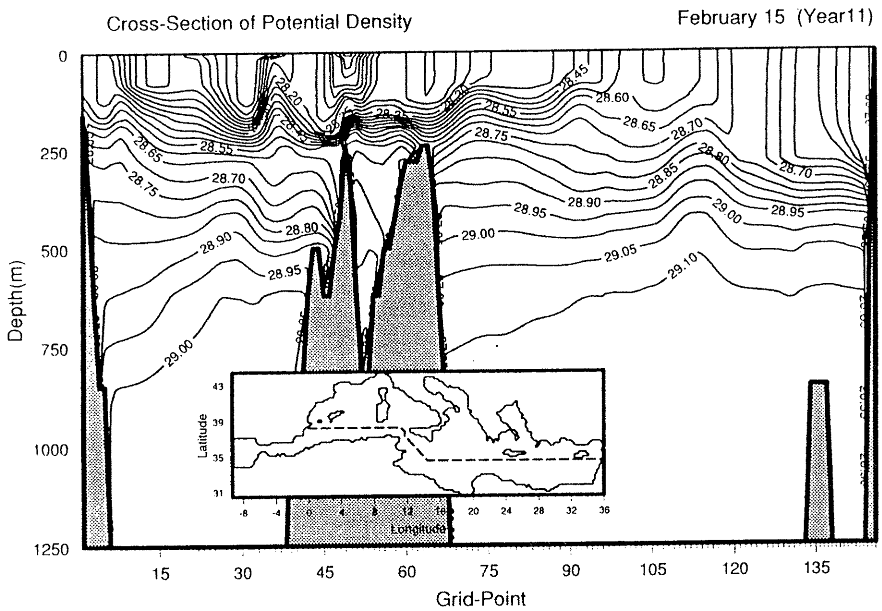

Figure 8

*Cross-section across the North Levantine and Ionian into the Adriatic through the Otranto straits. (a) Potential density, (b) Salinity, in February of the 11th year of model integration.*

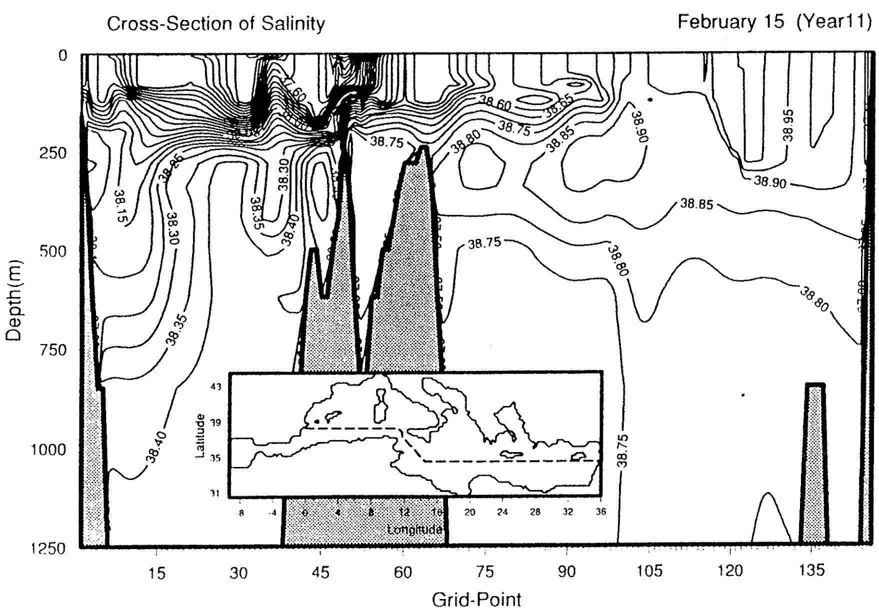
water dispersal. Figure 6 shows PV and salinity on the 28.8 isopycnal surface and Figure 7 shows the same properties on the 29.0 surface, in March of year 11, *i.e.* 10 years after Figures 4, 5. The results will be divided into three subsections covering the eastern and western basins and the exchanges of water, heat and salt at the various straits.

(i) *Eastern Basin*

From a overall perspective it is natural to begin with the eastern basin. The majority of the present results are concerned with circulation in the east because the LIW plays such a crucial role in the Mediterranean thermohaline circulation that correctly modelling its formation and dispersal is critical. Beginning with the salinity on the two isopycnal surfaces, a striking change is apparent in the eastern basin. Figure 5*b* shows that the highest salinity waters in the Levantine and Ionian initially lie on the 29.0 density surface. This has changed in Figure 6*b* which shows that the new LIW formed by the model lies on the 28.8 density surface, consistent with Figure 2. Salinity values as high as 38.9 psu extend across the northern Ionian on the 28.8 surface, while on the 29.0 surface fresher water with salinity around 38.6 psu is seen emerging from the Adriatic,




(*a*)




(*b*)

Figure 9

*As for Figure 4 in February of the 11th year of model integration.*

Figure 7*b*, and the salinity throughout the basin is lower than it was initially in Figure 5*b*. Although both the new LIW and the new Adriatic waters are less dense than observations suggest they should be, they do have the correct relative densities and the dispersal of these waters may be followed in the eastern basin on their respective core density surfaces.

Although the changes in salinity structure from the beginning to the end of the run are quite distinct, the new water masses show up best in the PV field. On the 28.8 density surface (Fig. 6*a)* shows very clearly the extent of the new LIW by the low values of PV extending from south of Crete throughout the central and northern Ionian with signs of entering the Adriatic on the east side of Otranto. Note that most of the high salinity water in the east Figure 4*b* and therefore salinity does not distinguish between the original water and the new water extending west from Crete.

All of the new intermediate water formed in the Levantine initially moves westwards. The Rhodes water moves rapidly towards Crete in the first six months after formation along the path indicated by low PV values in Figure 6*a*. Some of this water flows south of Crete but some passes into the Aegean where it can mix with intermediate water of Aegean origin and take part in further cooling during the formation of Cretan water. Much of the Rhodes water south of Crete continues westwards joining Aegean/Cretan water to the south of Greece which then flows north and west into the centre of the northern Ionian basin. The rest of the Rhodes water remains south of Crete and begins to very slowly disperse south and slightly eastwards over a number of years as indicated by the tongue of lower PV around latitude 33° N, 29° E. The lack of dispersal into the far eastern Levantine is a very noticeable feature. Since LIW is found throughout the eastern Levantine in observations, two possible explanations are suggested. The LIW in the eastern Levantine may only be formed locally either in extremely cold years or during the extreme cooling events each winter and the model forcing does not contain this variance in the boundary conditions. Alternatively, currently unresolved mesoscale eddies are required to disperse the new water into the eastern regions from the formation sites. Mesoscale eddies may disperse the water much more rapidly than the mean currents and a higher resolution modelling study is underway to test this hypothesis. Early results suggest that baroclinic eddies can transport new water from local sites to all parts of the basin.

The LIW which moves to the northern Ionian accumulates after each winter. There is probably considerable mixing occurring but water continues to disperse along two main paths. The first is westwards towards the south coast of Italy and thereafter southward towards Sicily. The extent of the new water mass is visible in Figure 6*a* after ten years with some low PV water near southern Sicily but not quite reaching the Sicily straits. The consequences of this lack of new water transfer to the west is discussed in the next subsection. The second dispersal path is up along the coast of Greece towards the Otranto straits where the LIW enters the Adriatic.

To illustrate the exchanges at Otranto, Figure 8*a*, *b* shows a cross section of potential density and salinity during February of year 11, confined to the eastern basin and passing east to west north of the island of Crete and then moving up the Greek coast into the Adriatic. The densest surface water in this section outside the Adriatic is formed north-west of Crete around grid point 48. This is the Cretan water shown in Figure 2, area (c). The most striking feature however lies further west where high salinity, low PV values are seen extending north-west towards the Otranto straits and the large volume of LIW associated with this feature is clear in Figure 8*b*. This water appears to be entering the Adriatic between 150 and 300 m depth. Below this the salinity section shows water emerging from the Adriatic with lower salinities of around 38.6 psu. This corresponds to the new Adriatic water mass which appears on the 29.0 surface in Figure 7*b*. Low PV values are also visible here on this surface from the density cross section. A very deep, dense winter mixed layer, penetrating to about 350 m, can be seen in the southern Adriatic where new water is forming. The water is still not dense enough to sink right to the bottom when it emerges into the Ionian as it should do, mainly due to excess mixing, see Roether *et al.* (1994) for further discussion of this problem.

Returning to the isopycnal property figures, on the 29.0 isopycnal surface the spreading path of the Adriatic deep water after emerging from Otranto is well illustrated by both the PV and the salinity fields in Figure 7. Low PV values extend down the south coast of Italy to reach North Africa. A tongue of low PV, low salinity water spreads from the shelf into the south Ionian at around latitude 34° N. This is consistent with the path suggested by tracer observations of Pollak (1951), or more recently, Roether *et al.* (1994), although the tracer studies show the Adriatic water to lie much deeper than in the present model. The double branch of westward and northward spreading of the LIW also shows up on the 29.0 surface in the North Ionian as tongues of high PV caused by compression of the density surfaces by the heavy LIW above.

Another perspective on the changing structure of the water masses is shown up by Figure 9 with the same cross section as Figure 3 but for mid-February of year 11. Near to the surface the outcropping locations for isopycnals are identical being determined entirely by the forcing. The depth of the winter mixed layer has changed from year 2 to year 11 especially in the eastern Levantine where it is considerably deeper to the east of the Rhodes gyre, marked by the upbowing isopycnals at around grid-point 112. This is partly the result of the thermocline diffusing downwards in the intervening period and partly the result of changing hydrography due to advection. The base of the pycnocline has deepened in both basins during the integration although not by an unacceptably large amount. The main features of interest in the east can be found on the 28.8 density surface. At around grid point 93 (the scale from Figure 3 shows this to lie just west of Crete) there is a separation of density surfaces with the 28.75 surface bowing up and the 28.8 surface bowing down. This is the signature of a newly formed water mass with low PV (*i.e.* low $\partial\rho/\partial z$). The high salinity of this water can be seen in Figure 9*b*.

The most satisfying feature of these cross sections is the continued existence of a very distinct intermediate salinity

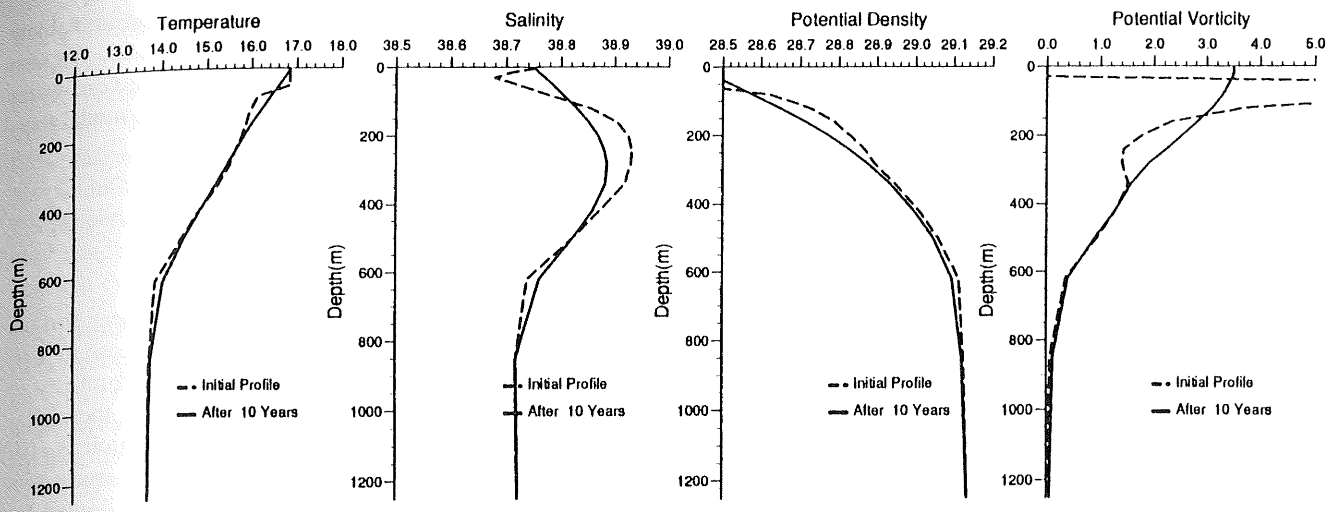



Figure 10

*Vertical property profiles through a newly formed water mass in the western Levantine at 20.5° E, 35.5° N after the first model winter, dashed lines. The solid lines show the result of ten years of vertical diffusion with $K_v = 0.3\ cm^2\ s^{-1}$ modifying the water column.*

maximum in the eastern basin indicative of LIW. Although such a maximum was present in the initial conditions of Figure 3, by year 11 it consists mainly of water which has been newly formed by the model. The new LIW lies at the same depth as the original LIW but the density is slightly lower because the whole pycnocline has diffused downwards by a small amount.

(ii) *Western basin*

We begin by considering the intermediate waters. Figure 3*b* shows an initial intermediate salinity maximum in the western basin representing the LIW present in the Levitus data. The maximum salinity is 38.5-38.6 psu and from Figure 3*a* this water lies around the 28.95 isopycnal surface. This maximum has been lost in Figure 9*b* except for a small region in the Tyrrhenian near Sicily which can also be seen on the isopycnal projections (Figs. 6, 7*b*). As noted previously, the new LIW formed in the east does not appear to reach Sicily and this allows the erosion of the western intermediate waters. Running the model for longer with the current parameters does not greatly improve the situation. The most obvious improvement would be an increase in resolution in order to better resolve the Sicily straits however the following subsection shows that water exchange at Sicily is initially quite reasonable but it decreases in time through the run. However it is possible that mesoscale eddies may improve the exchanges by increasing local current speeds and also by allowing the eastern LIW to lie nearer to the surface which would

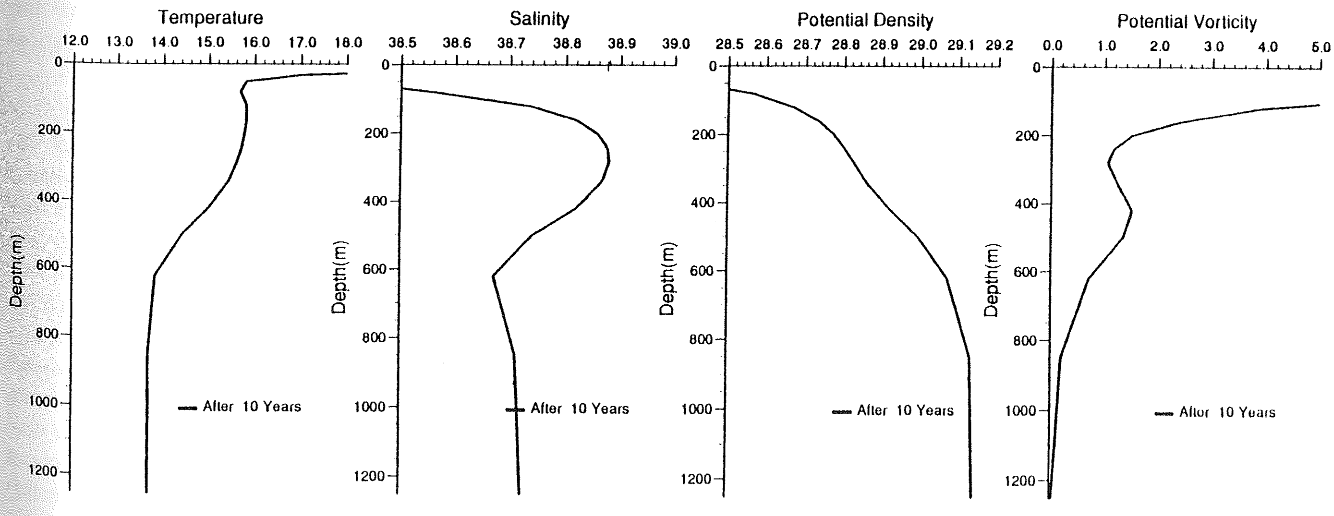



Figure 11

*Vertical property profiles at 17° E, 37° N in year 11. This point passes through the edge of the new LIW water mass in the western Ionian. Properties on isopycnals may be compared with those from the 1-D diffusion model in Figure 11.*

enable it to get over the Sicily sill. The whole eastern thermocline below the 28.8 isopycnal surface has deepened during the run because the new waters cannot break down into mesoscale eddies which would allow more rapid dispersal along isopycnals. This is a topic which will be examined in a following paper.

Winter cooling in the Gulf of Lions does produce water in this run which contributes to altering and eroding the saline intermediate water initially present in the west. The extent of this new fresh WMDW is clearly visible on the 28.8 density surface (Fig. 6*b*). It appears to move down the south coast of Spain towards Gibraltar without much dispersion into the SE Balearic or the Tyrrhenian basins. The water spreads on either side of the Balearic islands but does not appear to pass the Gibraltar straits. The spread of water is slower than in the eastern basin and the accumulation of this water along the coasts south of France and Spain greatly deepens the thermocline below the level at which the water settles as seen in Figure 9*a, b*. Associated with this are the very low PV values seen in Figure 6*a*. As in the east, the inability of the new water to diverge along isopycnals causes this deepening which then prevents the water from passing through the straits.

We conclude that mesoscale eddies are needed for any successful modelling of the western basin. These would help LIW to pass the Sicily straits and to reach the Gulf of Lions. With high subsurface salinities the WMDW can have an increased density allowing in to reach below the thermocline. The more rapid dispersal and upwelling of this new western deep water could then maintain the lower thermocline at a reasonable depth allowing more water exchange at Gibraltar.

(iii). *Strait exchanges*

Despite the simplicity of the model forcing the fluxes through the straits are not unrealistic. Over the final three years of the integration the mean heat flux through Gibraltar corresponds to a gain of 0.4 W $m^{-2}$ over the basin with fluctuations of ± 1W $m^{-2}$ through the year. This indicates insufficient water exchange although it compares reasonably well with the observed value of +7 W $m^{-2}$. The salt flux at Gibraltar is equivalent to an evaporative water loss of 46 cm/yr comparing well ith the 60 cm/yr from observations. However there is a decreasing trend reflecting the loss of salt from the western basin which is not adequately replaced through Sicily. The volume exchange at Gibraltar averages around 1.3 Sv with an annunal fluctuation of ± 0.15 Sv. The eastern basin alone gains 1.4 W $m^{-2}$ of heat on average and loses salt at a rate equivalent to 17 cm/yr of evaporation through the Sicily straits. All of the exchanges above show a trend of decrease with time reflecting the inability of the new water masses formed to pass over the shallow sills. The exception to this is at the Otranto straits where LIW inflow and ADW outflow are maintained throughout the integration, probably due to the depth of the sill which lies below the main thermocline at around 800 m depth.

In the following section we will discuss the physical processes of water formation and dispersal in more detail and make further observations on the realistic and unrealistic features of these processes in our current model. We also look at ways of assessing the changes to the core water masses due to diffusion as they age within the model thermocline.

## A core water analysis

Observations showing a gradual increase in near surface salinity moving west to east along with a decrease in salinity of the intermediate water (around 300 m) from east to west, first led Wüst (1961) to propose the basic thermohaline pattern for the upper Mediterranean which is still broadly accepted today. The Atlantic water increases its salinity due to evaporation at the surface followed by entrainment of this surface water into the Atlantic water stream just below. When this modified Atlantic water reaches the Levantine it has been preconditioned to such an extent that winter cooling can cause overturning at least to the top of the deep water layer somewhere between 300 and 500 m depth. This water then flows back westwards as LIW. As it does so it slowly mixes with the fresher Atlantic water lying above and the deep waters lying below so its salinity is reduced.

Recently Ovchinnikov *et al.* (1987) have criticized the use of core analysis in the Mediterranean for not considering along isopycnal mixing as a process modifying water properties. While eddy mixing may strongly influence water properties on isopycnals such that mean currents need not be directed up or down the gradients of water properties, nevertheless the broad picture of a "lagoonal" circulation for both the eastern basin and the Mediterranean as a whole, cannot be doubted, although the detailed water paths are difficult to determine from property values alone. The advent of numerical GCMs provides an ideal opportunity to test the validity of the inferences of core water analysis in a controlled environment. In the current GCM version the absence of mesoscale eddies due to lack of horizontal resolution suggests that a core analysis should be quite successful for tracing water paths and that this may provide a baseline for comparison with observations and with future model runs which do resolve eddies.

A simulated "CTD" vertical profile was taken at 20.5° E, 35.5° N in August of year 2 from the main model run. The PV field on the 28.8 density surface at this time, similar to that in Figure 4*a*, shows that some of the intermediate water formed in the previous winter north of Crete has been subducted into the thermocline over the intervening few months and had moved to the above location. The dashed line in Figure 10 shows the hydrographic property profiles where the presence of the low PV water is visible in the water column at a depth of around 200-300 m, coincident with the salinity peak which corresponds to the core of water with S = 38.93 psu. To calculate the effects of vertical diffusion the T,S profiles were inserted into a 1-D model given below;

$$\frac{\partial T}{\partial t} = K_v \frac{\partial^2 T}{\partial z^2}, \qquad \frac{\partial S}{\partial t} = K_v \frac{\partial^2 S}{\partial z^2},$$

where a value of $K_V = 0.3\ cm^2\ s^{-1}$ corresponding to the GCM value was used. The above equations were integrated for ten years and the new T,S, ρ and $\partial\rho/\partial z$ profiles calculated. Figure 10 shows both the initial and final vertical profiles (dashed and solid lines respectively). To reduce anomalous influences from the surface T,S the yearly average T,S properties over the Ionian were used for the top boundary conditions which were then kept fixed, *i.e.* with no seasonal cycle imposed.

The purpose of the above integration is to compare the final vertical column properties with those found for the new water mass in various parts of the basin ten years later. Again the PV field in Figure 6*a* provides a guide to finding the new water in year 11. A vertical profile at 17° E, 37° N, (Fig. 11), this time lies at the edge of the new intermediate water in the north west Ionian on the 28.8 isopycnal surface and can reasonably be expected to consist of water formed early during the model integration, perhaps in year 2. Since the original water column may have moved vertically in the intervening period as the water spreads west, a density surface is used for water mass comparisons. On the 28.8 density surface, Figure 10 shows that the initial T,S properties are T = 15.8 °C, S = 38.91 psu and after ten years of vertical diffusion within the water column the predicted properties are T = 15.7°C, S = 38.87 psu on the same density surface. Passing to Figure 11 it can be seen that on the 28.8 density surface at the edge of the body of new water the properties are T = 15.7 C, S = 38.87 psu, in excellent agreement with the predicted changes due to vertical diffusion alone. The salinity on the 28.8 surface reduces by approximately 0.007 psu every two years due to vertical diffusion. If we descend further onto the  = 29.0 surface the initial (T,S) are (14.8 °C, 38.88 psu) which vertical diffusion alone would only slightly alter to (14.8 °C, 38.86 psu) in ten years. However, Figure 11 has T = 14.4 °C, S = 38.74 psu on the 29.0 potential density surface showing that other processes must be operating. In this case water of Adriatic origin which is colder and fresher has moved in below the LIW layer as shown by Figure 7.

If it could be assumed that the initial vertical profiles of Figure 10 were representative of the new water formed every winter immediately after entering the thermocline and that vertical diffusion is the major process modifying the water then the water in the model could be "aged" according to the observed T or S properties on an isopycnal. We used salinity on the 28.8 surface to try to derive the age of the new intermediate water within the central and northern Ionian, but rather than a gradual decrease in salinity across the basin which could be identified as a spreading path, a salinity peak is found in the central Ionian. This feature, which is also suggested by Figure 6*a*, *b*, shows that even without mesoscale eddies the new water does not spread at a uniform rate through the basin. It flows rapidly into the centre of the North Ionian where it accumulates and thereafter spreads more slowly in two streams, passing northwards towards Otranto and west then south towards Sicily. The accumulation of intermediate waters in the central Ionian will result in horizontal mixing of water formed in different years. It is possible that the accumulation of LIW in the northern Ionian could explain the water storage suggested by the tracer studies of Roether and Schlitzer (1991). They showed that the LIW which is involved in Adriatic deep water formation should have been aged within the thermocline for a considerable period.

In any case the results show that it is difficult to design a quantitative core method for conservative tracers in the Mediterranean and future studies should include an explicit age tracer to follow the details of dispersal paths. Nevertheless the quantitative extent of the new waters is well depicted by the property distributions, particularly by low PV for both intermediate and deep waters on the 28.8 and 29.0 isopycnal surfaces respectively. The above analysis tests for the validity of the core method to water spreading in our low resolution GCM but cannot be seen as a refutation or justification for its use in other situations. It can provide a useful and even quantitative description in some circumstances which would be a valuable aid to the interpretation of observations and for the tuning model parameters such as $K_V$, however conclusions must be drawn carefully.

## DISCUSSION

In this paper we use a GCM of the Mediterranean to study thermohaline aspects of the general circulation. The surface boundary conditions have the simplest possible form with a repeating yearly cycle of windstress and T,S surface properties controlled by relaxation. With these constraints the water mass formation each winter is guaranteed to show reasonably realistic spatial variations and properties and the dispersal of the water and modification of the model thermocline and halocline may be studied. We concentrate on the eastern basin in this paper but future work will consider the west in more detail because the western circulation relies on obtaining realistic exchanges at Sicily. Isopycnal diagnostics are used to illustrate the water dispersal from the main formation sites in the Rhodes region of the Levantine, the Aegean and the Adriatic in the east and from the Gulf of Lions in the western basin. Low values of PV for the new water provide a good tracer, especially for the LIW which is difficult to distinguish from the old water present in the Levitus initial conditions on the basis of salinity alone.

The present integration lasts for ten years. Many features of the water dispersal are consistent with observational evidence. About 1/3 of the area of the entire eastern basin has been filled by the end of the run which is consistent with estimates of a 25 year turnover time for LIW within the eastern basin, Ovchinnikov (1983). The spreading path of the LIW is mainly westwards and northwards from the formation sites N and E of Crete. Most water gathers into the centre of the North Ionian within one to two years of formation where it mixes and continues spreading more slowly either up the Greek coast and through Otranto into the

Adriatic, or west and south towards Sicily. The storage of LIW in the central Ionian is consistent with tracer studies suggesting ageing of LIW within the thermocline prior to deep water formation in the Adriatic, Roether and Schlitzer (1991). No new LIW penetrates the far eastern Levantine during the period of the run which is inconsistent with observational evidence which shows LIW near Cyprus and Israel to be always present. One possibility is that extreme winter events and/or extremely cold years may be needed to form intermediate water locally within the far eastern Levantine. Alternatively mesoscale eddies may be necessary to disperse LIW into these regions from a formation site in the Rhodes gyre. Observational evidence also suggests that new water probably disperses through the basins more rapidly than occurs in the current model and mesoscale eddies may help to explain this discrepancy.

A considerable success of the current simulation is seen in the exchanges of water at the straits of Otranto. Salty intermediate water disperses from the Levantine and Aegean and clearly passes into the Adriatic at around 150-300 m depth on the eastern side of the straits. This water is modified by cooling in winter to form the Adriatic deep water which emerges on the western side of Otranto at around 500 m when it then sinks to 700 m in the Ionian and spreads down the south coast of Italy near the base of the main thermocline along the 29.0 isopycnal surface. This water spreads out into the centre of the southern Ionian at around 34° N showing a remarkably similar path to that indicated by oxygen tracer data of Pollak (1951), see also Malanotte-Rizzoli and Hecht (1988), (Fig. 5).

In the western basin, water is currently formed in the Gulf of Lions which then spreads down the Spanish coast towards Gibraltar with little dispersal into the rest of the Balearic basin. Mesoscale eddies may also speed up the dispersal of this water.

A core water analysis method has been developed and used to "age" the intermediate water mass within the pycnocline of the eastern basin on the basis of vertical diffusion alone. The method was shown to work in some cases with the conservative tracers, T,S, although if eddies had been resolved then along isopycnal mixing may become the dominant mechanism causing water mass properties to change. An explicit time dependent tracer for the age of a water mass would therefore be a more useful diagnostic and this is planned for future investigations.

The current integration has many unrealistic features which are being improved in later model versions. The surface relaxation for salt, $\beta$, can be reduced throughout the eastern basin without compromising water production which mainly requires rapid winter cooling. This relies on the LIW entering the Adriatic to provide convective pre-conditioning and fortunately the present model reproduces this well. It is necessary to get LIW passing from the eastern to the western basin in sufficient quantity to reach the Gulf of Lions in order to improve the properties of the water formed here. In the present run none of the new intermediate water from the eastern basin passes the Sicily straits into the west. This is partly because the length of the run is limited to ten years combined with the slow dispersal of the new waters. Mesoscale eddies, by speeding water dispersal, will improve the chances of achieving this. Baroclinic eddies have been produced by decreasing the horizontal diffusion and/or increasing the resolution and an eddy-resolving study will be presented in a follow-up paper. Eddies also permit an exchange of stretching vorticity, $\partial\rho/\partial z$, for relative vorticity so that new intermediate water can sink more rapidly and spin off into anti-cyclonic eddies where it is often found in observations, *e.g.* Özsoy *et al.* (1989). With truly deep water forming it is also possible to study the maintenance of the model thermocline so the model can be run for longer periods than the ten years of the current integration.

## APPENDIX

In order to study dynamical aspects of water mass formation and movement we have developed an isopycnal diagnostics package. Data from the Cox Mediterranean model are stored as T,S,u,v fields at various model levels. The following procedures allow useful diagnostics to be produced.

(1) Potential density is calculated at each grid point using the UNESCO equation of state and a surface reference pressure $p_0 = 0$. A higher $p_0$ may be appropriate in the deep basins but results do not vary significantly.

(2) The depth of a given potential density surface is calculated by linear interpolation between adjacent model levels in the vertical. This allows any property to be projected, again with linear interpolation, onto an isopycnal surface, eg. currents, T,S, or potential vorticity fields.

(3) Potential vorticity can be found either at levels or on isopycnals. Relative vorticity has been neglected in the maps shown here although it could be included in the package.

$$PV = -\frac{f}{\bar{\rho}}\frac{\partial \rho}{\partial z}$$

where f is the Coriolis parameter, $\rho$ is the potential density and $\bar{\rho}$ is the mean density.

Stratification is found by extrapolating to find the depths of adjacent isopycnals above and below, the vertical separation of which then permits the potential vorticity to be calculated on an isopycnal.

**Acknowledgments**

This work was funded by the EC under contracts MAST-0039-C(A) and MAST-CT93-0055. We thank N. Pinardi and V. Roussenov for their initial help in running the GCM. We also acknowledge many useful discussions with N. Pinardi, W. Roether, A. Lascaratos and other members of the MAST-MERMAIDS project during the course of this work.

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