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Why the Mediterranean Sea Is Becoming Saltier

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Anthropogenic changes have been made to the water budget for the Mediterranean Sea as a result of river diversion projects. The decrease in freshwater inflow to the Mediterranean represents an effective increase in the overall net evaporation over the basin. Hydraulic control models for the exchange between the Mediterranean and Atlantic through the Strait of Gibraltar predict that the salinity of the Mediterranean should increase if the net evaporation over the Mediterranean increases. Increases in the salinity of the deep waters in both the western and eastern Mediterranean basins have been observed. The causes of such higher deep water salinity are attributed to increases in intermediate water salinity which are ultimately mixed down into the deep sea during wintertime buoyancy loss events. The pattern of the Mediterranean salinity increase is instructive for understanding how the water mass properties in a basin change over time as a result of anthropogenic changes.

Key words: Mediterranean circulation, Deep water formation, Sill control, Wintertime convection, Anthropogenic chimate change, Freshwater forcing, Water mass changes

INTRODUCTION

The Mediterranean Sea (Fig. 1) is getting saltier. It is reasonably well known that the salinity of western Mediterranean deep water formed in late winter in the Gulf of Lions is increasing at a rate of 0.007‰ per decade (Lacombe *et al.*, 1985; Leaman and Schott, 1991; Rohling and Bryden, 1992). There is some evidence that Levantine Intermediate Water is also increasing in salinity (Rohling and Bryden, 1992). Most dramatically, new deep water has been observed to form in the Aegean Sea between 1987 and 1995 with a salinity 0.12‰ higher than previous deep water salinities observed in the eastern Mediterranean during this century (Roether *et al.*, 1996; Klein *et al.*, 1999). Nof (1979) argued that increasing Mediterranean salinity should be expected as result of the change in the water budget for the Mediterranean basin following the diversion of the Nile and Russian rivers for irrigation. The purpose of this work is to show how a change in the water budget for a semi-enclosed basin like the Mediterranean leads to a change in the water mass properties of the basin and to describe and understand the process by which the changes occur.

CHANGE IN WATER BUDGET FOR THE MEDITERRANEAN BASIN

The completion of the Aswan Dam on the Nile River in 1964 effectively ended the historic Nile River discharge of 90 km^3 yr^{-1} into the Mediterranean Sea (Nof, 1979). Construction of dams on Russian rivers feeding into the Black Sea and ultimately into the Mediterranean beginning in 1947 has reduced the flow of freshwater into the Mediterranean by 50 to 70 km^3 yr^{-1} (Tolmazin, 1985). Overall the reduction in freshwater input amounts to 140 km^3 yr^{-1}, which is about 10% of the overall net evaporation over the Mediterranean basin estimated from measurements of the fluxes through the Strait of Gibraltar (Bryden *et al.*, 1994). Thus the river diversion projects since the 1940's have effectively increased the net evaporation over the Mediterranean basin by about 10%.

CONSEQUENCES OF SILL CONTROL ON SALINITY WITHIN A SEMI-ENCLOSED BASIN

The Strait of Gibraltar is a bottleneck that connects the Mediterranean Sea to the Atlantic Ocean. Like the neck of a bottle, the Strait controls how much water can flow into the Mediterranean and out into

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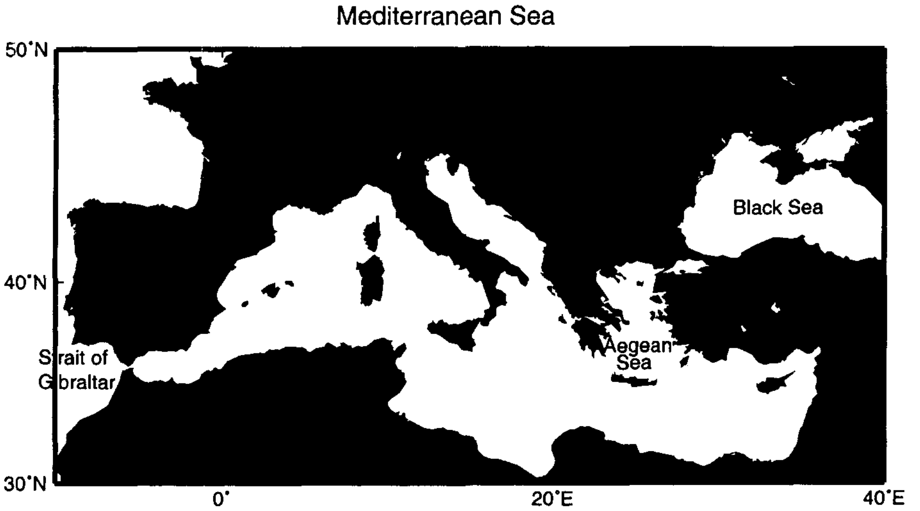


Fig. 1. Geography of the Mediterranean Sea. The Strait of Gibraltar is the only marine connection between the Mediterranean Sea and Atlantic Ocean. The Aegean Sea is the site of new deep water formation in the eastern Mediterranean Sea due to the change in river inflows to the Black Sea.

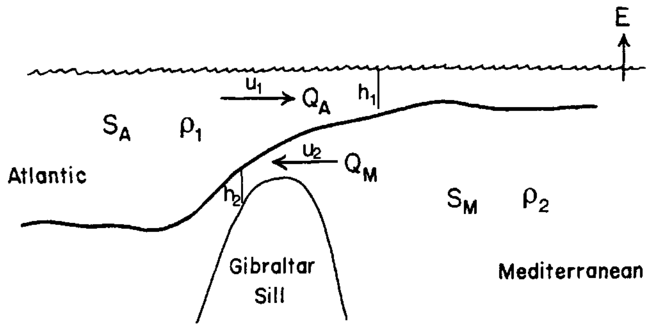


Fig. 2. Schematic of the two-layer exchange across the Gibraltar sill In the Strait, the Atlantic and Mediterranean waters are separated by a region of sharp salinity and density gradients that is shown here as a single interface between Atlantic and Mediterranean layers. At the crest of the sill, $h_1 + h_2 = H_s$, the depth of the sill, and width of the sill section is denoted by W_s.

the Atlantic. The cross-sectional areas of the strait and sill, their width and depth, determine the magnitude of the exchange.

Hydraulic control models have been developed for the two-layer exchange between the Atlantic and Mediterranean through the Strait of Gibraltar (Armi and Farmer, 1985; Farmer and Armi, 1986). These models include two locations, the sill or shallowest section and the narrowest section where the two-layer Froude number, G, equals 1:

$$G^2=u_1^2/g'h_1+u_2^2/g'h_2=1 \qquad (1)$$

where g is gravity, $g'=g\ (\rho_2-\rho_1)/\rho_2$, the subscripts 1 and 2 refer to the upper and lower layers, u is along-strait velocity, ρ is density of sea water, and h is layer depth (Fig. 2). At the sill, the lower layer flow is effectively critical so $u_2^2/g'h_2=1$; at the narrows, the upper layer flow is critical and $u_1^2/g'h_1=1$. Ultimately, the exchange, $Q=Q_A-Q_M$, is proportional to the product of a maximum velocity times the cross-sectional area of the sill, and the maximum velocity is proportional to sqrt $(g'H_s/2)$:

$$Q=C\ \mathrm{sqrt}(g'H_s/2)\ W_sH_s. \qquad (2)$$

where H_s is the depth of the sill, C is a non-dimensional proportionality constant of order 0.2 for the physical configuration of the Strait of Gibraltar (Bryden and Kinder, 1991), and W_sH_s is the cross-sectional area of the sill where W_s would be the width of a rectangular sill. With two hydraulic control points, the exchange is the maximum that can get through the bottleneck of the strait and sill region for a given density difference between the Mediterranean and Atlantic.

If the maximum exchange possible through a narrow and shallow constriction is occurring through the Strait, then the salinity difference between the Atlantic and Mediterranean is determined by the physical configuration of the Strait and by the net evaporation over the Mediterranean basin (Bryden and Stommel, 1984). Combining the hydraulic control model with the mass and salt conservation equations for the Mediterranean basin, Bryden and Kinder (1991) showed that the salinity difference between the Mediterranean and Atlantic depends only on the net evaporation over the Mediterranean, E, and the width, W_s, and depth, H_s of the strait and sill:

$$(S_M-S_A)^{3/2}=\Delta S^{3/2}=C\ E/((W_sH_s)\ \mathrm{sqrt}(H_s)) \qquad (3)$$

where C is again a proportionality constant dependent on the exact geometry of the strait and sill. The maximal exchange solution for the physical dimensions of the Strait of Gibraltar suggests that the Mediterranean should be 1.8‰ saltier than the Atlantic for the estimated net evaporation of 1300 km^3 yr^{-1}, or 52 cm yr^{-1} average over the surface area of the Mediterranean (Bryden and Kinder, 1991; Bryden *et al.* 1994). On the basis of such a maximal exchange model, Rohling and Bryden (1992) actually predicted that the Mediterranean salinity would increase by 0.13‰ as a result of the 10% change in the water budget.

EVOLUTION OF MEDITERRANEAN WATER MASSES

We argue that the change in water budget has been locally felt first in the far eastern Mediterranean where the salinity of Levantine Intermediate Water has increased as a result of the change in the Nile discharge. The Levantine Intermediate Water with its increased salinity makes its way quite rapidly through the Strait of Sicily and circulates anti-clockwise around the western Mediterranean basin (Katz, 1972). In the northernmost region in the Gulf of Lions, wintertime storms make the surface waters dense enough that they mix with the higher salinity Levantine Intermediate Water to create a slightly higher salinity (and higher density) deep water, as Rohling and Bryden (1992) documented. Thus, the mechanism for the increase in salinity of the western Mediterranean deep water can be explained.

Deep water in the eastern Mediterranean has historically been formed in the Adriatic Sea (Pollack, 1951). In 1995, a hydrographic survey of the eastern Mediterranean discovered new deep water formation in the Aegean Sea (Roether *et al.*, 1996). The new deep water is about 0.2°C colder, 0.12‰ saltier and 0.13 kg m^{-3} denser than the old deep water last observed in 1987 (Klein *et al.*, 1999). The formation of new, higher salinity eastern Mediterranean deep water in the Aegean Sea in the 1990's is puzzling. Why did it take 30 years after the initial major river diversion projects in the 1960's for new deep water to be formed?

From comparisons in Fig. 3 between hydrographic conditions in 1961 and 1962 (classic conditions), in 1987 (just prior to new deep water formation) and in 1995 (after new deep water formation), we see that the principal barrier to deep water formation in the Aegean Sea during the classic conditions in 1961–62 is a layer of a low salinity intermediate water called Transition Mediterranean Water (TMW) by Theocharis *et al.* (1999a). To enable convection and deep water formation from the pre-winter conditions in October 1961 (Fig. 3a), the waters principally above 500 m depth would need to be cooled by 3.9×10^9 J m^{-2}, and a salinity increase equivalent to a net evaporation of about 2 m would be required in the intermediate waters between 500 m and 1000 m depth to make the TMW as salty and as dense as the deep water. From the difference between the profiles in October 1961 and March 1962, we estimate that the wintertime heat loss was only 1.3×10^9 J m^{-2}, or an average of about 100 W m^{-2} over 4.5 months between the October and March surveys, and the wintertime freshwater loss was only 0.4 m. Thus, there was no evidence for deep water formation in the Aegean Sea during the winter of 1961–62 (Bruce and Charnock, 1966; Miller, 1974).

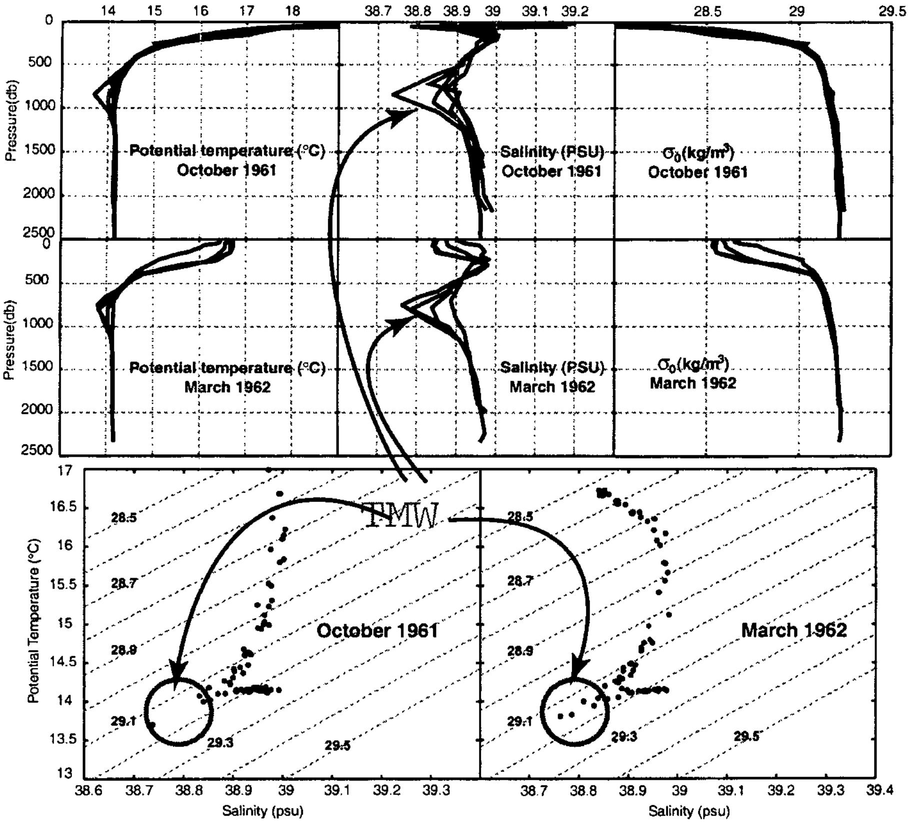
In September 1987 *Meteor* surveyed the eastern Mediterranean (Roether and Schlitzer, 1991) including full-depth profiles in the Aegean Sea (Fig. 3b). In 1987 the deep water properties in the Aegean were effectively the same as in 1961–62. Notably, the 1987 profiles show a near absence of the low salinity TMW as the minimum intermediate water salinity is about 38.9‰, much higher than the TMW salinity of 38.75‰. Comparison of September 1987 and October 1961 depth-averaged salinities shows an increase in salinity of 0.03‰, which would be equivalent to a local net evaporation of 1.6 m or an average extra net evaporation of 6 cm yr^{-1} (Table 1). Due to the absence of TMW, the September 1987 conditions appear primed for wintertime deep convection: a wintertime net evaporation of only 0.5 m and a wintertime heat loss of 2.65×10^9 J m^{-2} would allow local formation of the deep water in the winter of 1987.

In January 1995, Roether led another *Meteor* cruise to survey the modern deep water properties of the eastern Mediterranean. Remarkably, recently formed

Table 1. Deep water and depth-averaged (0-2000m) salinities in the Aegean Sea for four different surveys. Salinities in 1961-62 appear to be uncertain by ±0.02‰.

Year	Deep Salinity (‰)	Depth-Average Salinity (‰)
October 1961	38.955	38.916
March 1962	38.976	38.896
September 1987	38.960	38.948
January 1995	39.071	39.023

(a) 1961 and 1962



(b) 1987 and 1995

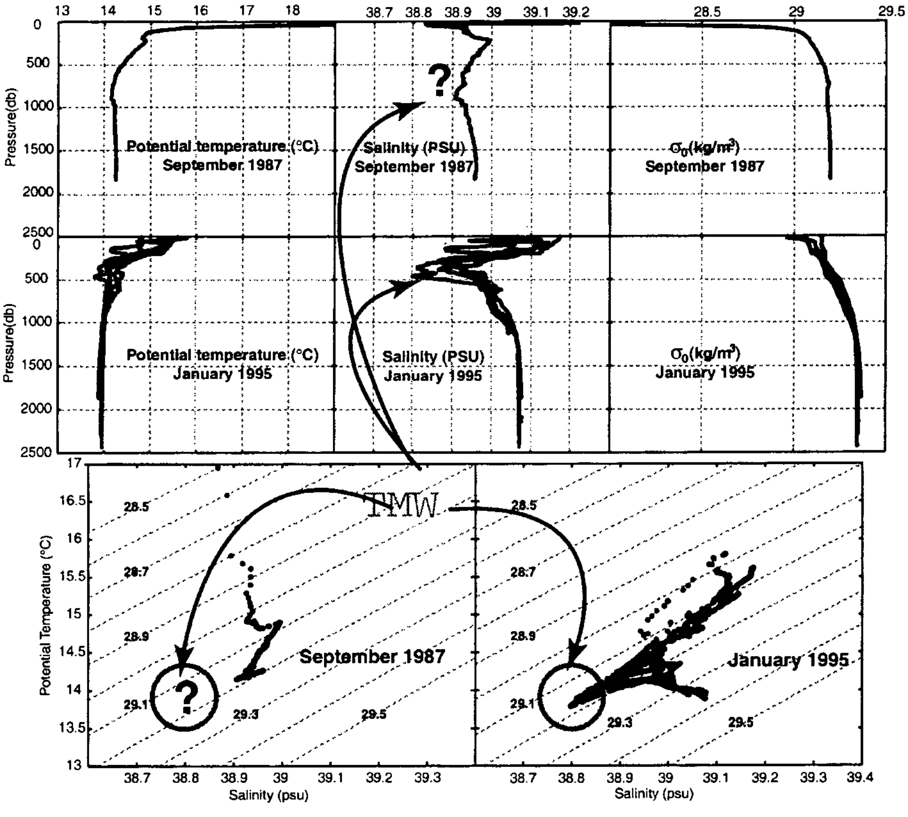


Fig. 3. (a) Potential temperature (°C), salinity (‰), density (kg m^{-3}) profiles and θ/S diagrams of deep Aegean Sea stations for the *Chain* (1961) and *Atlantis II* (1962) surveys. The arrows point out the Transitional Mediterranean Water (TMW) both in the salinity profiles and in the θ/S diagrams. (b) Potential temperature (°C), salinity (‰), density (kg m^{-3}) profiles and θ/S diagrams of deep Aegean Sea stations for the *Meteor* 1987 and 1995 surveys. The arrows point out the Transitional Mediterranean Water (TMW) both in the salinity profiles and in the θ/S diagrams. The question marks indicate that the TMW signal was very weak in 1987.

deep water was found in the Aegean Sea and it was spilling over the connecting sills and spreading out into the deep eastern Mediterranean basins (Roether *et al.*, 1996). This new deep water has a potential temperature of 13.96°C, a salinity of 39.08‰, and a potential density anomaly of 29.38 kg m^{-3} (Fig. 3b). Thus, the new deep water is about 0.2°C colder, 0.12‰ saltier and 0.13 kg m^{-3} denser than the deep water of 1961–62 or 1987. The structure of the vertical stratification, however, had returned to 1961-62 conditions with the reappearance of low salinity intermediate waters (TMW). To form the 1995 deep waters locally, a wintertime heat loss of 1.7×10^9 J m^{-2} would be required after January to mix the waters down to 600 m depth but a net evaporation of 2.1 m would be required to erode through the TMW waters so as to form the deep water. Thus, it does not seem feasible that deep water could be formed locally in a single winter from the observed 1995 conditions.

We have argued that the effective increase in net evaporation over the Aegean, has its origin in a smaller Black Sea freshwater outflow and this increased net evaporation gradually erodes the low salinity intermediate water (Boscolo and Bryden, 2001). After about 25 years of increased net evaporation, the salinity throughout the water column would become nearly uniform so that a single severe winter (or several consecutive severe winters) could lead to the production of new higher salinity deep water. Thus, while the salinity change in the deep waters of the Aegean appears to be an abrupt jump over a short period resulting from a few severe winters, the actual formation of new deep water is the result of the gradual increase in salinity due to higher net evaporation, which slowly erodes the stratification until a single severe winter can lead to the production of new deep water.

An interesting aspect of the deep water formation process in the Aegean Sea is that new deep waters are not being formed at present. The large volume of recently formed dense, deep water continues to spill over the sills connecting the Aegean Sea to the eastern Mediterranean basin and to fill the deep eastern Mediterranean. But, as the dense water flows over the sills, lower salinity intermediate waters appear to be flowing back into the Aegean to replace the dense waters so that deep water formation is turned off. Will we have to wait 25 years before deep water formation occurs again?

MODEL FOR THE FORMATION OF NEW HIGH SALINITY AEGEAN SEA DEEP WATER

To expand our ideas on the evolution of higher salinity eastern Mediterranean waters, we have developed and run a simple mixed layer model to show how persistent long-term changes in net evaporation can slowly change the stratification in the Aegean basin until suddenly deep water formation occurs during a severe winter. The initial stratification is taken to be the March 1962 observations of temperature and salinity (and hence density) versus depth linearly interpolated to 20 m intervals down to 2350 m. In time steps of one year, a net evaporation of 10 cm of freshwater is imposed on the uppermost 20 m layer, changing the salinity in this layer. If the upper layer is denser than the layer beneath, then the layers are mixed together conserving potential temperature and salinity. Mixing continues downward until the density stratification is stable.

Overall net evaporation over the eastern Mediterranean is much larger than 10 cm yr^{-1}. Bethoux (1980) estimated E to be 108 cm yr^{-1} over the eastern basin and the Southampton Oceanography Centre (SOC) flux climatology (Josey *et al.*, 1999) exhibits an e-p over the Aegean Sea of 101 cm yr^{-1}. We assume that such large, long-term average evaporation is balanced by the average circulation within the Mediterranean so that there is no local increase in salinity over time. Following the change in net evaporation due to damming of the rivers, however, the extra net evaporation would act to make the waters saltier over time. While Rohling and Bryden (1992) estimated an effective change in E of 5 cm yr^{-1} due to the river diversion, this value represented an average over the entire Mediterranean-Black Sea basin. Because the major changes occur in the eastern parts of the basin due to irrigation projects in Egypt and Russia, the local changes in E over the eastern basin would be expected to be larger than average. Comparison of the 0 to 2000 m depth averaged salinities in 1961 and 1962 with those for September 1987 indicate a salinification over time between 0.032‰ and 0.052‰, equivalent to a net evaporation between 6.3 and 10.7 cm yr^{-1} over the 25-year time period. Thus, we settled on a reasonable value for the extra annual-average net evaporation of $E = 10$ cm yr^{-1} for the model runs.

To neutralise the temperature stratification in order to concentrate on the effects of net evaporation on the deep convection, we removed an amount of heat equal to 2.6 x 10^9 J m^{-2} from the March 1962 profiles before running the mixed layer This is equivalent to one extra harsh winter as the average winter (November to February) removes 1.7×10^9 J m^{-2} of heat over the Aegean Sea according to the SOC climatology. As a result, the initial mixed layer is 600 m deep.

After 25 years of removing a net evaporation of 10 cm yr^{-1}; the model mixed layer has reached 1950 m depth and its salinity is up to 38.99‰. Temperature is of course well mixed down to 1950 m as well. Since we have not accounted for seasonal changes in heat and freshwater fluxes and the accompanying changes in seasonal stratification, these profiles are intended to represent the conditions in late-winter, nominally March 1987. For comparison, the September 1987 conditions observed by *Meteor* are stratified by temperature in the upper waters as expected for a late summer profile, but show little salinity variation below the uppermost 50 m. In September 1987, the depth-averaged salinity is 38.95‰, fully 0.05‰ saltier than the March 1962 profile. Much of the temperature stratification in the September profiles may be accounted for by the warming between March and September which amounts to 2.02×10^9 J m^{-2} according to the SOC climatology. We estimate that the September profile has a heat content of 2.65×10^9 J m^{-2} with reference to the observed bottom temperature so that 75% of the observed thermal stratification may be due to seasonal warming from March to September.

With the model conditions after 25 years of removing 10 cm yr^{-1} of net evaporation, we continue to run the mixed layer model in monthly time steps using monthly values of e-p and air-sea heat exchange

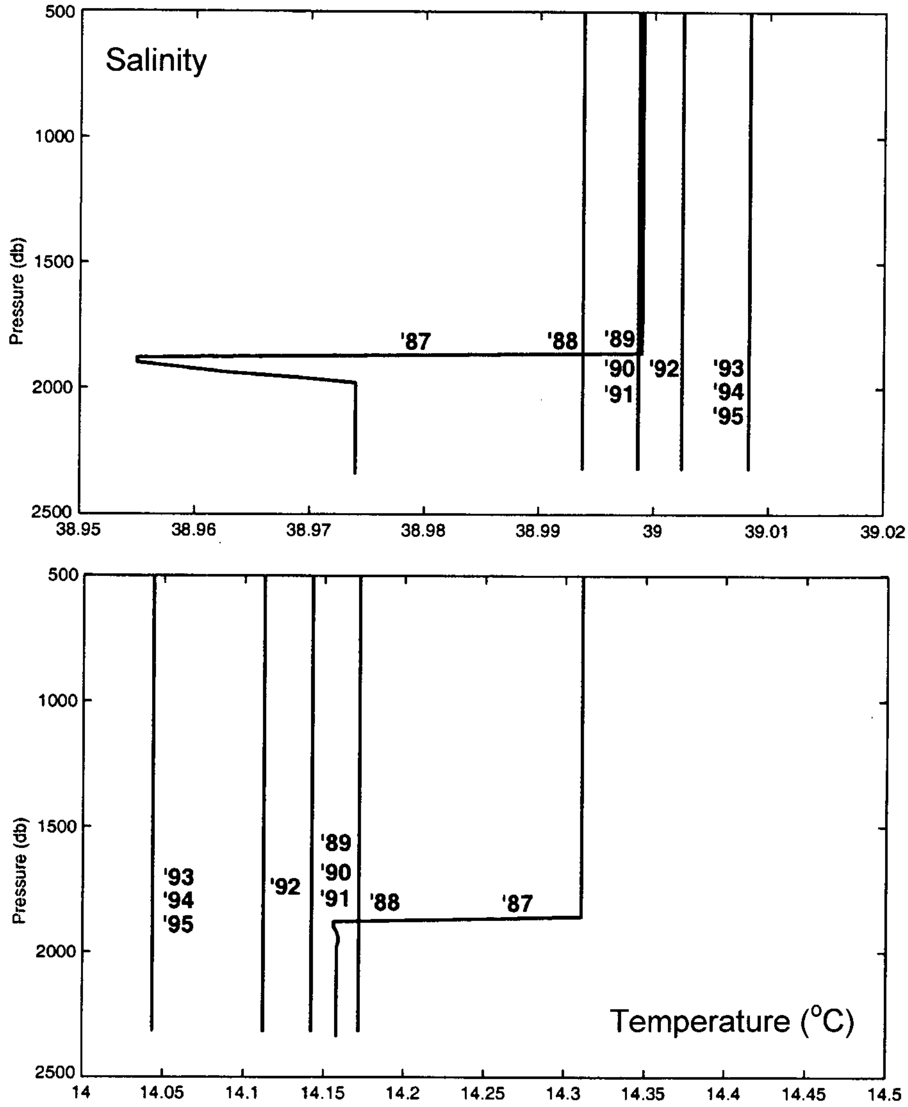


Fig. 4. Salinity and potential temperature profiles for the model late-winter deep mixed layer in March for each year from 1987 to 1995.

from the SOC climatology from March 1987 to December 1995. Because there can be local biases in the heat and water exchanges within the climatology (Josey *et al.*, 1999) and because our premise is that long-term average heat and water exchanges are accounted for by the pre-existing circulation, we removed the 16-year average (1980-1995) heat exchange of 13 W m^{-2} and e-p of 101 cm yr^{-1} from the monthly values so that the model is driven by anomalies in heat and water exchanges reflecting local climate variability over the Aegean. In addition to the monthly anomaly in e-p from the SOC climatology, we continue to remove a net evaporation at a rate of 10 cm yr^{-1} (0.83 cm $month^{-1}$) in order to simulate the effects of river diversion in the eastern basin. The effects of the heat and water exchanges are introduced into the top 20 m and potential temperature and salinity are then mixed downward until the profile is stably stratified. We examine the deep water properties each year at the end of March (Fig. 4).

Within the model, deep convection had reached 1950 m depth in March 1987. By March 1988, the entire water column is mixed with a bottom salinity of 38.99‰. New, slightly saltier deep water is again formed in March 1989, but then no new bottom water is formed through March 1991. After the winters of 1991–92 and 1992–1993 when large wintertime heat and freshwater losses occurs over the Aegean, the deep water becomes colder as well as saltier. As a result of mild conditions in 1993 and 1994, no new deep water is found in March 1994 or in March 1995 (Fig. 3). By 1995, the deep water in the model has a salinity of 39.01‰ and a potential temperature of 14.05°C. The model deep water has cooled by 0.11°C and become saltier by 0.04‰ over the 8 years from 1987 to 1995.

DISCUSSION AND CONCLUSIONS

The model shows how persistent long-term changes in net evaporation can slowly change the stratification in the Aegean basin until suddenly deep water formation occurs during a severe winter. We attribute the observed increase in depth-averaged salinity from 1961–62 to 1987 to the increase in net evaporation following river diversion for irrigation in Russia and Egypt. That salinity increase appears as the erosion of low salinity TMW, that is by an increase in the intermediate water salinity so that TMW is effectively absent by 1987. During the moderately cold winter of 1987–88, new deep water may well have been formed, as suggested by (Theocharis *et al.*, 1999b). The bulk of new deep water, however was likely formed during the severe winters of 1992 and 1993. The wintertime heat loss was so great during those winters that a deep, well-mixed water column would cool by nearly 0.1°C over the winter and the resulting new deep water in addition to being saltier would also be colder. Such cooling and salinification are both attributes of the new deep water observed in 1995 by Roether *et al.* (1996) as compared with the deep water properties in 1987. Succeeding mild winters in 1994 and 1995 cannot form new deep water because the wintertime buoyancy loss is insufficient to overcome the surface stratification built up over the summer even though the slow increase in salinity continues due to the net evaporation.

Nearly all recent analyses as reviewed by Lascaratos *et al.* (1999) have concentrated on the formation of new Aegean Sea deep waters over the time period from 1987 to 1995 using 1987 observations as the baseline from which new deep waters are formed. We are in basic agreement with these analyses that new deep waters were actually formed during cold wintertime conditions, probably during the winters of 1991–92 and 1992–93 when there were large heat and freshwater losses over the Aegean. In this work, however, we stress the change in net evaporation due to Russian river diversions as the cause for the slow erosion of the low salinity intermediate waters from 1962 to 1987, which ultimately created the conditions suitable for deep water formation during severe winters. The formation of new deep waters in the Aegean is a result of the two processes: a long, slow increase in the salinity due to changes in the water budget and then a catastrophic deep water formation event during a suitable cold, dry winter.

The presence of low salinity intermediate waters in 1995 while the newly formed deep waters are still flowing out of the Aegean over the sills into the deep eastern Mediterranean (Theocharis *et al.*, 1999b) strongly suggests that deep water will not be formed again for several years in the Aegean. Erosion of the imported low salinity TMW will be necessary before wintertime deep water formation can occur again. While it is tempting to suggest that deep water will not be formed for 25 more years until the effective extra net evaporation due to river diversion erodes the intermediate water salinity minimum, the overall circulation in the eastern Mediterranean and Aegean may have changed as a result of the Aegean deep water formation and subsequent outflow over the sills or the effects of river diversion may be increasing with time. Predictions are perilous. It is interesting, however, to note that a basin like the Mediterranean does not become uniformly saltier over time following a change in its water budget. On the basis of observations and understanding to date, it appears that salinity initially increases near to where the water balance has changed; salty deep water is then formed in a local deep basin which then spills out over the sills spreading into the greater deep basin; within the local basin the outflowing dense waters are replaced by lower salinity waters which then shut off deep water formation. The cycle may repeat: we await new observations of the next stage as the Mediterranean becomes saltier and new model simulations brave enough to predict what will happen next.

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