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Man–Induced Salinity and Temperature Increases in Western Mediterranean Deep Water

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The historical data base is used to study property changes in both the Western Mediterranean Deep Water (WMDW) and the Levantine Intermediate Water (LIW). Changes in WMDW properties during the past century have been described previously, although on a more limited data base. We are not aware of any previous study of changes in LIW properties. In the extensive data base we used, increases appear in both WMDW temperature and salinity, from 1909 to the present, which substantiate previously reported observations. In addition, we find that the density of WMDW seems to have increased as well, which disagrees with previous suggestions that it has remained constant. We observe that the WMDW temperature increase displays a distinct acceleration starting about 1955 and that a similar, although less conspicuous, acceleration occurs in the WMDW salinity increase. From our study of historical data on LIW properties, the LIW salinity also appears to have increased since 1909. We argue that the warming trend in WMDW may well be a response to the salinity increase, which seems to be imported from the eastern Mediterranean by LIW, and as such our observations endorse a recently published hypothesis. The increase in LIW salinity, in turn, is attributed to changes in the eastern Mediterranean freshwater budget, resulting from damming of major rivers that drain either directly or indirectly into the eastern Mediterranean. Finally, we demonstrate that the basin has not yet reached a new steady state after this freshwater disturbance and that the response time of the system seems to be of the order of 100 years.

INTRODUCTION

General Introduction

The Mediterranean Sea, which is separated from the Atlantic Ocean by the Strait of Gibraltar, is subdivided into western and eastern subbasins by the Strait of Sicily. Taking into account the results of 5 decades of hydrographic studies, *Wüst* [1961] presented a concise description of the Mediterranean hydrography, which we summarize in this section.

Strong dominance of evaporation over freshwater input drives an antiestuarine type of circulation in the Mediterranean, with eastward surface flow and westward subsurface flow through both the Strait of Gibraltar and the Strait of Sicily. In the northeastern Levantine Basin, near Cyprus, high-salinity surface water is cooled such that it sinks to fill the eastern Mediterranean down to about 600 m depth. The resultant Levantine Intermediate Water (LIW) constitutes a major part of the subsurface flow from the eastern into the western basin, through the Strait of Sicily, and subsequently from the western basin into the Atlantic Ocean, through the Strait of Gibraltar. Throughout the Mediterranean, the core of Levantine Intermediate Water can be recognized as a subsurface salinity maximum, as illustrated by Figure 1, which displays two typical plots for eastern and western Mediterranean salinity versus depth, based on stations by R/V *Atlantis I* (1948) and R/V *Atlantis II* (1969), respectively.

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Formation of deep water occurs in both the eastern and the western Mediterranean. Eastern Mediterranean Deep Water (EMDW) originates primarily in the Adriatic Sea [*Pollak*, 1951; *Wüst*, 1961; *Malanotte-Rizzoli and Hecht*, 1988], and Western Mediterranean Deep Water (WMDW) in the northern sector of the western Mediterranean [*Wüst*, 1961; *MEDOC Group*, 1970; *Stommel*, 1972]. The high-salinity LIW is an important component in the formation of deep water at both sites. In both basins, the higher density of deep water (relative to LIW) results from its relatively low temperature, which more than compensates for the higher LIW salinity.

Purpose of This Study

In the northern sector of the western Mediterranean, deep water formation occurs in late winter after a preconditioning phase during which the surface water density is increased by intense cooling and evaporation. As the density contrast between the surface water and the warm, high-salinity Levantine Intermediate Water of eastern Mediterranean origin is eliminated, deep convective mixing of surface water and LIW is enabled, resulting in the formation of Western Mediterranean Deep Water. This sequence of events has first been observed during the first 3 months of 1969 [*MEDOC Group*, 1970; *Stommel*, 1972].

Increases in the potential temperature of Western Mediterranean Deep Water on a time scale of decades have been described by *Béthoux et al.* [1990] and *Leaman and Schott* [1991]. From these studies, which were both based essentially on a set of average deepwater temperatures calculated by *Lacombe et al.* [1984], the increase in the potential temperature of WMDW appears to have accelerated after

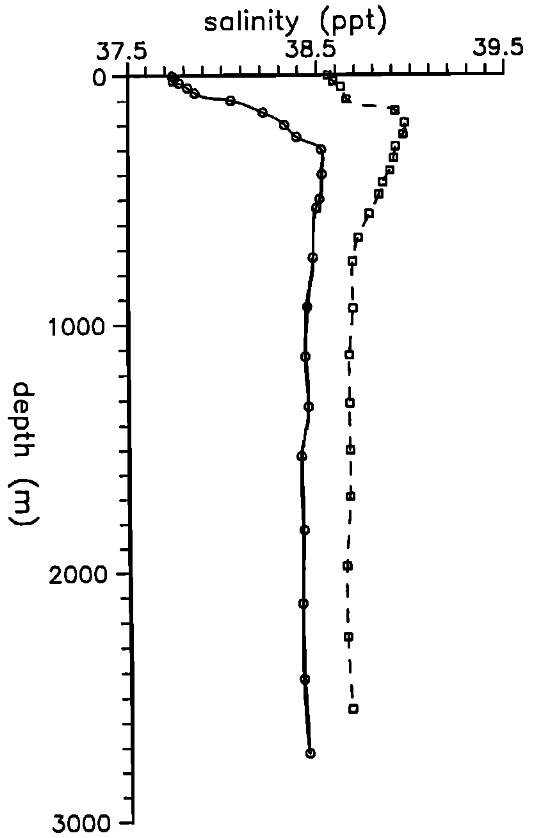

Fig. 1. Two typical profiles of eastern (squares, dashed) and western (circles, solid) Mediterranean salinity versus depth, based on a station at 32°33'N, 26°04'E, by R/V *Atlantis I* (1948) and a station at 40°40'N, 5°59'E, by R/V *Atlantis II* (1969), respectively.

1955–1960. *Béthoux et al.* [1990] ascribed this acceleration to global greenhouse warming, although his record did not extend further back in time than 1959. Alternatively, *Leaman and Schott* [1991] suggested that the acceleration might be induced by increased salinity of the Levantine Intermediate Water. They argued that if this salinity increase indeed occurred, then the upper layers would not have to be cooled as much in the "MEDOC area" in winter before they would reach the density characteristic of WMDW.

Since LIW is formed in the northeastern Levantine Basin by winter cooling of high-salinity surface water, the LIW salinity is directly linked to the surface water salinity and therefore to the eastern Mediterranean freshwater budget. Man has influenced that freshwater budget, through the damming of major rivers that feed directly (Nile River) or indirectly (via the Black Sea; Kuban, Don, Dnieper, and Dniester Rivers) into the eastern Mediterranean. The anthropogenic control of the Nile was gained by the construction of the Aswan Dam, which was completed in 1964 [*Nof*, 1979]. The control of the rivers draining into the Black Sea consists of an elaborate system of dams, of which the first unit was completed in 1947 and the last in 1980 [*Tolmazin*, 1985]. As a result of the freshwater diversion, notable anoxic events with mass mortality of marine organisms developed since 1973 on the northwestern shelf of the Black Sea [*Tolmazin*, 1985].

Nof [1979] calculated that damming of rivers that feed into the Mediterranean should result in an increase in the exchange transport through the Strait of Gibraltar, as well as in increases in the salinity and temperature of the Mediterranean outflow. *Nof* [1979], however, did not test his predictions by investigating historical data. Neither did *Leaman and Schott* [1991], who did not elaborate their suggestion of WMDW property changes being due to variation in LIW salinity, since long-term warming of WMDW was not the primary subject of their study.

Interestingly, the studies of both *Béthoux et al.* [1990] and *Leamán and Schott* [1991] suggested that the salinity of the WMDW has increased as well, as predicted by *Nof* [1979]. Thus they argued, the temperature increase was counterbalanced by the salinity increase, so that potential density of the WMDW remained constant at 1029.10 kg m^{-3} [*Béthoux et al.*, 1990] or 1029.11 kg m^{-3} [*Leaman and Schott*, 1991].

In the present paper, we apply the large data base of the National Oceanographic Data Center (NODC) on CD-ROM [*NODC*, 1991], in combination with data of *Bryden et al.* [1978], *Lacombe et al.* [1984], *Leaman and Schott* [1991] and J. P. Béthoux (personal communication, 1991), to study the property changes in both the Western Mediterranean Deep Water and the Levantine Intermediate Water in the western Mediterranean. The goal is to determine whether the changes in the properties of WMDW described by *Béthoux et al.* [1990] and *Leaman and Schott* [1991] also appear when an independent data set is used, and whether the changes in temperature and salinity have been continuous over the last 100 years or whether these changes can be related to changes in the LIW salinity resulting from damming of rivers that drain, either directly or indirectly, into the Mediterranean.

MATERIAL AND METHODS

The Western Mediterranean Deep Water Properties

In order to portray the changes in temperature, salinity, and density of WMDW between 1909 and the present, we have investigated these properties at the 2000-m depth (about 2020 dbar) level. This level is generally in, or close to, the potential temperature minimum in the western Mediterranean deep sea [*Lacombe et al.*, 1984]. Below that level, the potential temperature was found to be somewhat variable from year to year [*Lacombe et al.*, 1984], and such variability could bias our investigation of possible longer-term changes. The data are obtained from the aforementioned sources, for the area between the North African coast and 42°N, and from longitudes 0° to 10°E.

The data are averaged per vessel per year. The conversions of average in situ temperature (T), as derived from the CD-ROM [*NODC*, 1991] and from *Bryden et al.* [1978], to average potential temperature (θ) are performed using the physical properties of seawater algorithms of *Fofonoff and Millard* [1983]. The average potential temperature values reported by *Leaman and Schott* [1991] were based on the routines described by *Bryden* [1973] and are therefore identical to potential temperatures calculated using the algorithms of *Fofonoff and Millard* [1983]. Since no in situ temperature values were reported, we had to rely on the potential temperature values given in the other two studies

[*Lacombe et al.*, 1984; Béthoux, personal communication, 1991], although it is not clear what equation has been used to calculate these values. All values for the average potential density anomaly (σ_θ) reported in the present study have been obtained using the relations described by *Fofonoff and Millard* [1983].

The results are shown in Table 1 and plotted in Figures 2*a*, 2*b* and 2*c*. In each figure, the solid line represents a simple linear regression through the pre-1955 data, and the dashed line is a simple linear regression through the post-1955 data. The slopes of these lines provide a measure of the average change of a property per year in the given intervals of time. In the figure captions, the equations defining simple linear regression lines through the entire data set are given as well.

The Levantine Intermediate Water Properties in the Western Mediterranean

In order to portray the changes in temperature, salinity and density of LIW between 1909 and the present, we have isolated these properties at the subsurface level of maximum salinity. Because of the high spatial variability of the prop-

TABLE 1. Temperature (T), Salinity (S), Potential Temperature (θ), and Potential Density Anomaly (σ_θ) in Western Mediterranean Deep Water at the 2000 m (about 2020 dbar) Depth, in the Area Between Latitudes 36°50′ and 42°N, and Longitudes 0° to 10°E

Code	Year	T, °C	S, ppt	θ, °C	σ_θ, kg m^{-3}	N
ma35	1989		38.428	12.789	29.096	2
ma35	1988		38.447	12.778	29.116	2
l&s	1987		38.440	12.755	29.112	
ll35	1982	13.076	38.429	12.770	29.101	3
jc35	1981	13.069	38.432	12.763	29.104	12
b235	1977			12.727		147
jc35	1975		38.415	12.722	29.100	13
ci31	1975	13.028	38.419	12.723	29.102	2
ll35	1974		38.419	12.722	29.103	3
jc35	1973		38.410	12.714	29.096	20
jc35	1972		38.408	12.718	29.095	1
tt31	1970	13.030	38.415	12.725	29.099	1
tr31	1970	13.030	38.410	12.725	29.095	1
an31	1969	13.020	38.415	12.714	29.101	67
jc35	1969	13.032	38.407	12.727	29.092	44
b148	1965	13.070	38.410	12.764	29.087	2
mt06	1964	13.023	38.393	12.718	29.083	2
di74	1964	13.015	38.408	12.710	29.097	3
at31	1962	13.006	38.402	12.709	29.105	4
at31	1961	13.006	38.402	12.701	29.094	39
ci31	1959	12.993	38.408	12.688	29.101	8
at31	1958	13.010	38.400	12.705	29.091	3
pt35	1957	13.070	38.426	12.764	29.099	9
ld35	1957	13.056	38.423	12.751	29.100	4
ca35	1955	13.063	38.423	12.757	29.098	4
el35	1954	13.028	38.411	12.723	29.090	5
el35	1953	13.018	38.378	12.713	29.073	8
el35	1952	13.035	38.393	12.730	29.081	10
rh31	1951	13.020	38.380	12.715	29.074	1
at31	1948	13.016	38.384	12.711	29.078	5
da26	1930	13.010	38.400	12.705	29.091	1
ws64	1929	13.000	38.410	12.695	29.101	1
th26	1910	12.988	38.374	12.693	29.074	5
th26	1909	13.000	38.375	12.695	29.074	6

Codes are explained in Table 2. Results represent averages per expedition per year; N indicates the number of observations on which the averages are based. Most results are obtained from the CD-ROM of *NODC* [1991]. Additionally, b235 (1977), jc35 (1975), ll35 (1974), jc35 (1973), and jc35 (1972) are from *Lacombe et al.* [1984], ci31 (1975) is from *Bryden et al.* [1978], l&s (1987) from *Leaman and Schott* [1991], and ma35 (1989) and ma35 (1988) are based on Medatlante data from J.P. Béthoux (personal communication, 1991).

erties in LIW, resulting from mixing with the water masses above and below, we have focused on long-term changes in the properties within a small area in the northeastern part of the Balearic Basin. This area, covering latitudes 41° to 42°N and longitudes 5° to 7°50′E, lies at the southern margin of the so-called "MEDOC area" of seasonal WMDW formation. Since LIW is an important component of WMDW, long-term changes in its properties near the MEDOC area could influence those of the WMDW [*Leaman and Schott*, 1991].

After eliminating apparent anomalous salinity measurements by interpolating the measurements on each station with a spline fit (see, for instance, Figure 1), we determined per station where the "core" of LIW was located, by finding its characteristic salinity maximum. Subsequently, we averaged each set of N values of LIW salinity found per expedition per year. Two averages were determined for the 1969 data set of R/V *Atlantis II* (an31), since its 30 measurements of the LIW salinity maximum in the study area show an evident dual partition when plotted in a $\theta - S$ environment. Interestingly, no such dual partition shows up in the 26 stations from the 1969 cruise of R/V *Jean Charcot* (jc35), although that expedition took place at the same time and in the same area as the an31 expedition. (Expedition codes are given in Table 2.)

The results are shown in Table 3 and plotted in Figure 3*a*. Since there are only few pre-1955 data, it is not reasonable to determine a linear regression through only that part of the data, as has been done in Figure 2. In Figure 3*a*, therefore, the two plotted linear regression lines are that for the post-1955 data (dashed), and that for the entire data set (solid). The slopes of the regression lines allow us to consider the average rate of change of LIW salinity in the northeastern part of the Balearic Basin during the given intervals of time.

It should be emphasized that most data are based on bottle samples. As a result, it is not certain whether the maximum salinity measured during an expedition in a certain area is indeed representative of the true salinity maximum of the LIW core. In other words, most results only represent an approximation of the properties in the core of LIW. Evidently, this accounts for some of the spread in the values plotted in Figure 3. Note, furthermore, that the Y axis scales in Figure 3 are slightly compressed in comparison with the Y axis scale in Figure 2*b*.

RESULTS

The Western Mediterranean Deep Water

The slopes of the regression lines through the entire data set from 1909 to the present indicate that both the potential temperature and the salinity of WMDW have increased, the former by an average of 8.3×10^{-4} °C yr^{-1} and the latter by an average of 6.9×10^{-4} ppt yr^{-1}. The potential density of WMDW appears to have increased as well, by an average of 3.7×10^{-4} kg m^{-3} yr^{-1}.

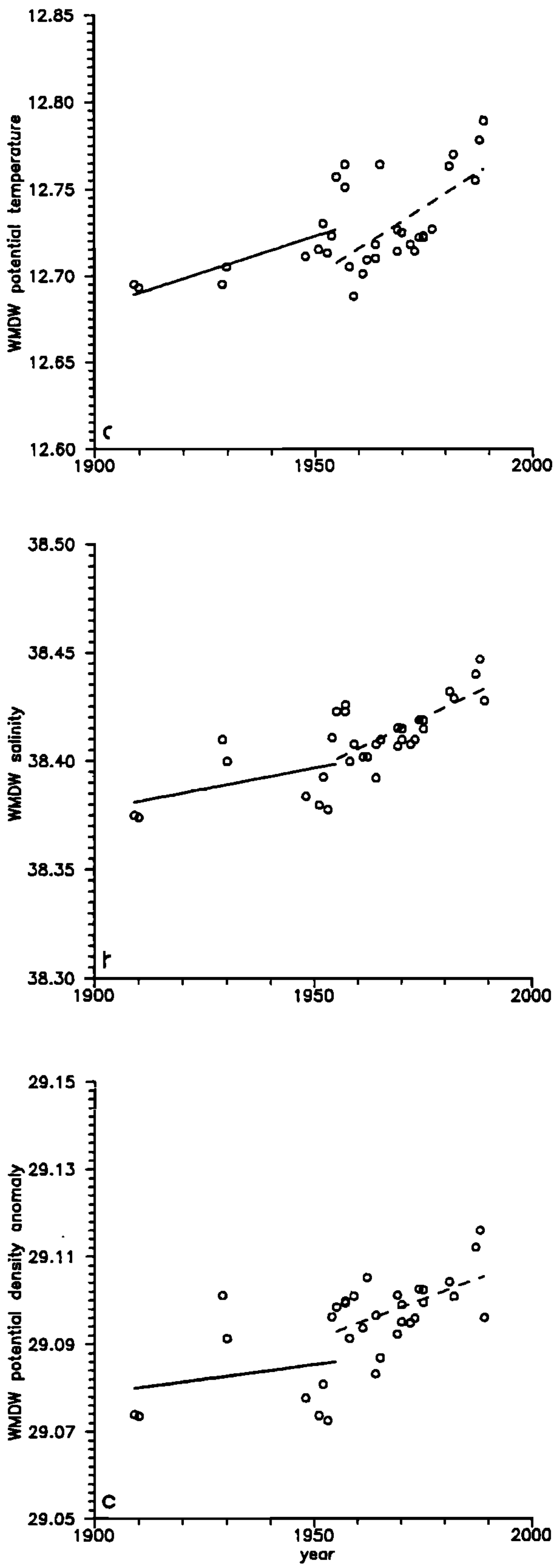

Fig. 2. (Opposite) Properties of the Western Mediterranean Deep Water at the 2000-m (about 2020 dbar) depth in the area between the North African coast and 42°N and longitudes 0° to 10°E, versus time. (*a*) Potential temperature θ (degrees Celsius). (*b*) Salinity S (parts per thousand). (*c*) Potential density anomaly σ_θ (kilograms per cubic meter). Each point represents an average per expedition per year. The plotted values are listed in Table 1. The solid lines are linear regressions for the pre-1955 data; slope and intersection are θ = (year−1900) $8.19 \times 10^{-4} + 12.682$, S = (year−1900) $3.88 \times 10^{-4} + 38.378$, and σ_θ = (year−1900) $1.34 \times 10^{-4} + 29.079$. The dashed lines are linear regressions for the post-1955 data; slope and intersection are θ = (year−1900) $16.01 \times 10^{-4} + 12.619$, S = (year−1900) $9.45 \times 10^{-4} + 38.349$, and σ_θ = (year−1900) $3.71 \times 10^{-4} + 29.073$. Linear regression through the entire data set gives θ = (year−1900) $8.3 \times 10^{-4} + 12.675$, S = (year−1900) $6.9 \times 10^{-4} + 38.373$, and σ_θ = (year−1900) $3.7 \times 10^{-4} + 29.076$.

TABLE 2. Explanation of the Expedition Codes

Code	Explanation
an	R/V *Atlantis II*
at	R/V *Atlantis I*
b1	R/V *Bannock*
b2	Buoy *Borha II*
ca	R/V *Calypso*
ci	R/V *Chain*
da	R/V *Dana*
di	R/V *Discovery*
el	R/V *Elie Monier*
jp	R/V *Pillsbury, J.E.*
jc	R/V *Jean Charcot*
ic	R/V *Ichtiolog*
ld	R/V *Le Passeur Du Printemps*
ll	R/V *Le Noroit*
l&s	*Leaman and Schott* [1991]
ma	Medatlante Project
mt	R/V *Meteor*
pt	R/V *President T. Tissier*
rh	R/V *Rehoboth*
sk	R/V *Shikmona*
th	R/V *Thor*
tr	R/V *Trident*
tt	R/V *Thompson, T.G.*
ws	R/V *Willebrod Snellius*
06	Germany
26	Denmark
27	Egypt
31	U.S.A.
35	France
47	Israel
48	Italy
64	Netherlands
74	U.K.

On the basis of Figure 2*a*, one might argue alternatively that the increase in the potential temperature of WMDW is not linear, but accelerated starting in about 1955. Figure 2*a* suggests that the increase of potential temperature between 1909 and 1955 was only about 0.02°C, while the increase between 1955 and 1989 may have been as much as 0.07°C. At the same time, a similar, although less conspicuous, acceleration seems to have occurred in the salinity increase (Figure 2*b*). Between 1909 and 1955 the salinity seems to have increased by less than 0.02 ppt, while the increase between 1955 and 1989 may be as much as 0.05 ppt. The suggested accelerations in the increase of potential temperature and salinity of WMDW, starting in about 1955, are endorsed by the slopes of the pre-1955 and post-1955 regression lines, relative to those of the regression lines for the entire data set. The pre-1955 slopes are less steep, and the post-1955 slopes are steeper, than the slopes of the regression lines for the entire data set.

Regarding a possible change in the potential density increase, little can be concluded from Figure 2*c*. The values are scattered too much to suggest more than the aforementioned average increase throughout the data set, as endorsed by the similarity between the slope of the post-1955 regression lines and that for the entire data set.

The Levantine Intermediate Water in the Western Mediterranean

In the northeastern part of the Balearic basin, near the MEDOC area, the LIW salinity appears to have increased by an average of 9.2×10^{-4} ppt yr^{-1} on the basis of the entire data set (Figure 3*a*). The slope of a linear regression line for the post-1955 data, however, suggests that the main part of the salinity increase since 1909 took place in the last 4 decades, with an average rate of as much as 24.6×10^{-4} ppt yr^{-1} (Figure 3*a*).

DISCUSSION AND CONCLUSIONS

We believe that there has been an acceleration in the potential temperature increase of Western Mediterranean Deep Water starting about 1955. The temperature difference we found in the WMDW between 1955 and the present, about 0.07°C, is very compatible with that reported by *Leaman and Schott* [1991], although it is considerably lower than the difference of about 0.11°C reported by *Béthoux et al.* [1990].

For the increase in WMDW salinity, we have noted an acceleration starting about 1955 as well, although it is less conspicuous than that in potential temperature. According to our data set, the WMDW salinity difference between 1955 and the present amounts to about 0.05 ppt, which agrees closely with that shown by *Leaman and Schott* [1991] but is somewhat higher than the difference of about 0.03 ppt reported by *Béthoux et al.* [1990].

In contrast to *Béthoux et al.* [1990] and *Leaman and Schott* [1991], who argued that the WMDW density remained relatively constant through time, we have found that this property has increased as well. Apparently, the warming trend in the WMDW has not completely counterbalanced the increase in WMDW density related to the increase in WMDW salinity. This may indicate that the salinity increase is the primary property change, enabling the warming trend to develop.

We find that the warming trend in WMDW could indeed have resulted from an increase in the average salinity of LIW, in agreement with the suggestion of *Leaman and Schott* [1991]. Alternatively, however, one might argue that the LIW salinity in the northeastern Balearic Basin has been influenced by an increase in the surface water salinity in the "MEDOC area," being transferred to the LIW layer during the convective mixing periods, and subsequently spread within that layer via lateral mixing. In that scenario, the trend of increasing LIW salinity might only reflect dilution with progressively more saline surface water. At the same time, such an increase in the surface water salinity would cause a rise in the WMDW salinity. Such a sequence of events would match with the mechanism *Béthoux et al.* [1990] proposed to explain the changes in the WMDW properties.

To distinguish whether the increase in the LIW salinity near the "MEDOC area" resulted from an overall increase in the LIW salinity, or from an increase in the surface water salinity in the MEDOC area, we have studied the LIW properties in the eastern part of the Ionian and western part of the Levantine Basin. Both these sectors are located in the eastern Mediterranean, relatively close to the formation area of LIW. The data were obtained from the sources mentioned in the introduction, and the method was identical to that followed to obtain Figure 3*a*. The results are shown in Tables 4 and 5, and are plotted in Figures 3*b* and 3*c*.

TABLE 3. Temperature (T), Salinity (S), Potential Temperature (θ), and Potential Density Anomaly (σ_θ) at the Salinity Maximum of the Levantine Intermediate Water in the Northeastern Balearic Area Enclosed by Latitudes 41° and 42°N, and Longitudes 5° and 7°50'E

Code	Year	T, °C	S, ppt	θ, °C	σ_θ, kg m^{-3}	N
th26	1909	13.110	38.440	13.074	29.054	1
th26	1910	13.270	38.460	13.226	28.039	1
ca35	1955	13.170	38.510	13.129	29.098	1
ci31	1959	13.100	38.476	13.057	29.087	1
at31	1961		38.478	13.130	29.075	6
jc35	1969		38.468	13.054	29.084	26
an31	1969		38.502	13.191	29.082	17
an31	1969		38.467	12.937	29.107	13
tt31	1970	13.280	38.509	13.207	29.087	1
jc35	1981		38.503	13.181	29.081	2
ll35	1982	13.282	38.514	13.259	29.068	1
l&s	1987	13.400	38.560	13.326	29.086	1

Results represent averages per expedition per year; N indicates the number of observations on which the averages are based. When $N > 1$, we calculated θ per station, according to its in situ temperature, depth, and salinity and subsequently averaged the values. Because of the variable depth of the LIW salinity maximum, it is not informative to average in situ temperature; therefore those cells are blank in the table. Codes are explained in Table 2.

Although steeper, the trends in Figure 3*b* are quite similar to those in the 3*a*, especially with respect to the ratio between the slopes of the two regression lines indicated in each figure. Figure 3*c* displays much more scatter, which may be due to high variability of LIW in this area close to the source region (see also *Wüst*, [1961]), but still a salinity increase appears since 1909. Thus the data in Figures 3*c* and, especially 3*b*, suggest that the LIW salinity has increased not only close to the MEDOC area, but on a basin-wide scale. This, in turn, suggests that the nature of the LIW salinity increase is related to changes in the eastern Mediterranean freshwater budget, rather than to dilution with progressively more saline surface waters in the MEDOC area.

Changes in the eastern Mediterranean freshwater budget over the past 45 years have been caused by damming of major rivers that (used to) feed into that basin. Before the construction of the Aswan Dam, the Nile discharge amounted to about 9×10^{10} m^3 yr^{-1} [*Béthoux*, 1984], whereas it decreased to a negligible amount after the completion of the Aswan Dam [*Nof*, 1979]. The discharge of the Black Sea rivers has decreased, from about 10.4×10^{10} m^3 yr^{-1} before the initiation of damming in 1947, to about 5.9×10^{10} m^3 yr^{-1} in 1981–1985 [*Tolmazin*, 1985]. Hence the total amount of diverted water is roughly 13.5×10^{10} m^3 yr^{-1}. The excess of evaporation over precipitation and runoff in the eastern Mediterranean has been estimated to be 1.8×10^{12} m^3 yr^{-1} [*Béthoux*, 1979]. The reduction of river discharge would therefore invoke an increase of roughly 7% in the amount of excess evaporation.

Rohling [1991] described a simple two-layered model for changes in the eastern Mediterranean hydrography in relation to the freshwater budget, based on statements for conservation of mass and salt, and a simple parameterization of buoyancy loss linked to excess evaporation. The model essentially uses variations in excess evaporation (buoyancy loss) and the volume of surface water inflow through the Strait of Sicily to determine variations in surface layer thickness and subsurface to surface layer salinity contrast. The applied initial values for excess evaporation and surface layer inflow were 1.8×10^{12} m^3 yr^{-1} and 40×10^{12} m^3 yr^{-1}, respectively [*Béthoux*, 1979]. As initial surface layer thickness, an average value of 150 m was used. In this model, an increase of roughly 7% in the amount of excess evaporation would lead to an increase of about 3% in the amount of surface water inflow through the Strait of Sicily and an increase of about 4% in the LIW to surface water salinity contrast at the Strait of Sicily.

According to *Wüst's* [1961] compilation profiles, the LIW to surface water salinity contrast at the Strait of Sicily was about 1.25 ppt (38.75–37.5) prior to 1960. Using the increase of 4% estimated above, the present-day salinity contrast should amount to about 1.30 ppt. If this change were exclusively due to an increase in the LIW salinity, the LIW salinity should have increased by about 0.05 ppt. This increase should, in turn, affect the western Mediterranean.

The (rough) estimate of an overall 0.05-ppt increase in the LIW salinity, resulting from the obstruction of several major rivers draining directly or indirectly into the eastern Mediterranean, seems to be in reasonable agreement with the observed increase in the LIW salinity near the MEDOC area (Figure 3*a*). Moreover, it agrees with the salinity increase in WMDW since about 1955 (Figure 2*b*). Therefore we think that the warming trend in the WMDW, which seems to have accelerated after about 1955, resulted primarily from an increase in the salinity of the LIW, in agreement with the hypothesis of *Leaman and Schott* [1991]. This increase in LIW salinity, in turn, seems likely to be a result of large-scale obstruction of major rivers which (used to) discharge, either directly or indirectly, into the eastern Mediterranean.

The above calculations are valid for a system that has reached a new steady state after a disturbance. The trends in WMDW potential temperature and salinity (Figures 2*a* and 2*b*), however, seem to indicate that the system has not yet reached steady state after the diversion of the fresh water. We can evaluate that using the study of *Bryden and Kinder* [1991]. These authors estimated that the excess

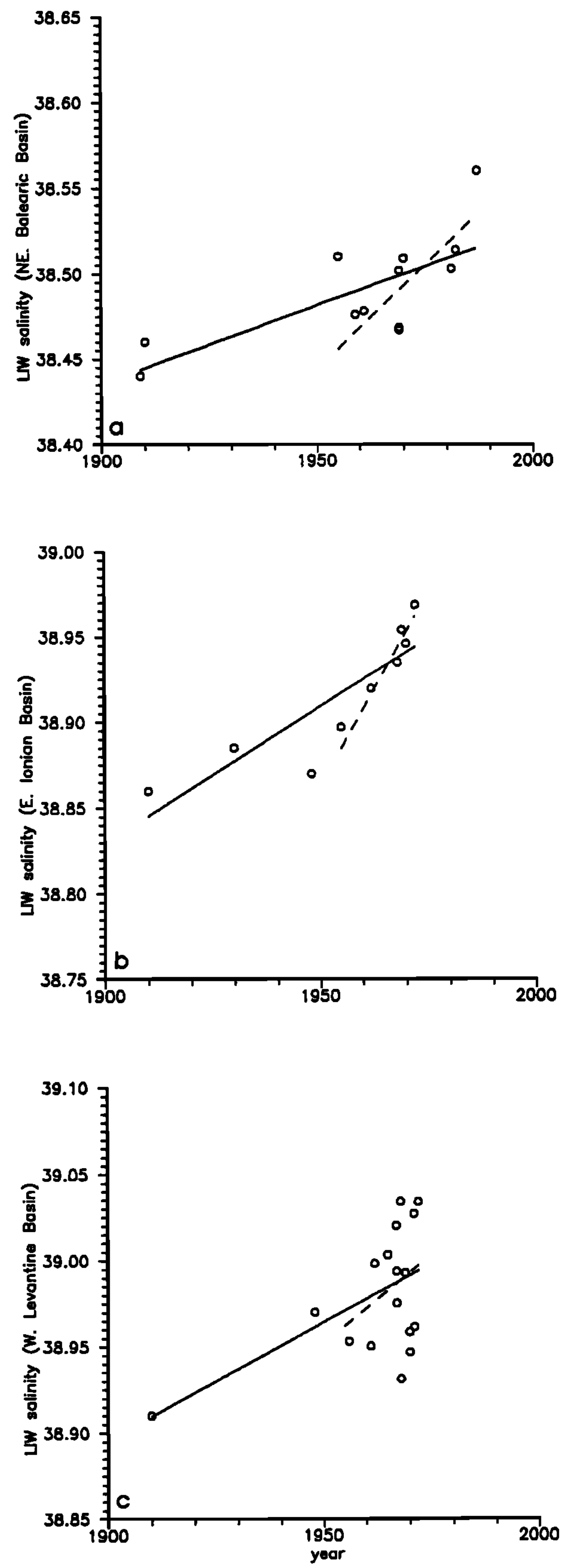

TABLE 4. Salinity at the Salinity Maximum of the Levantine Intermediate Water in the Eastern Ionian Basin, in the Area Enclosed by the North African Coast and 35°N, and Longitudes 20° and 22°50'E

Code	Year	S, ppt	N
th26	1910	38.860	1
da26	1930	38.885	2
da74	1948	38.870	1
ca35	1955	38.897	3
at31	1962	38.920	4
sk47	1968	38.935	3
sk47	1969	39.954	2
sk47	1970	38.946	2
sk47	1972	38.969	2

Results represent averages per expedition per year; N indicates the number of observations on which the averages are based. Codes are explained in Table 2.

TABLE 5. Salinity at the Salinity Maximum of the Levantine Intermediate Water in the Western Levantine Basin, in the Area Enclosed by the North African Coast and 35°N, and Longitudes 24° and 26°50'E

Code	Year	S, ppt	N
th26	1910	38.910	1
at31	1948	38.970	1
ca35	1956	38.953	8
ci31	1961	38.950	1
at31	1962	38.998	1
jp35	1965	39.003	1
jc35	1965	39.003	1
jc35	1967	38.994	4
b148	1967	38.975	4
sk47	1967	39.020	3
b148	1968	38.931	8
sk47	1968	39.034	3
sk47	1969	38.993	7
sk47	1970	38.993	3
ic27	1970	38.947	3
sk47	1971	39.027	10
ic27	1971	38.961	8
sk47	1972	39.034	4

Results represent averages per expedition per year; N indicates the number of observations on which the averages are based. Codes are explained in Table 2.

Fig. 3. (Opposite) Salinity of the Levantine Intermediate Water versus time. (*a*) The northeastern Balearic Basin, between latitudes 41° and 42°N, and longitudes 5° and 7°50'E (Table 2). (*b*) The eastern Ionian Basin, between the North African coast and 35°N, and longitudes 20° and 22°50'E (Table 3). (*c*) The western Levantine Basin, between the North African coast and 35°N, and longitudes 24° and 26°50'E (Table 4). The solid lines are linear regressions for the entire data set; slope and intersection are (for Figures 3*a*, 3*b*, and 3*c*, respectively) $S = (\text{year}-1900)\ 9.17 \times 10^{-4} + 38.436$, $S = (\text{year}-1900)\ 15.92 \times 10^{-4} + 38.826$, and $S = (\text{year}-1900)\ 13.61 \times 10^{-4} + 38.896$. The dashed lines are linear regressions for the post-1955 data; slope and intersection are $S = (\text{year}-1900)\ 24.61 \times 10^{-4} + 38.321$, $S = (\text{year}-1900)\ 45.49 \times 10^{-4} + 38.636$, and $S = (\text{year}-1900)\ 20.74 \times 10^{-4} + 38.848$.

evaporation over the entire Mediterranean amounts to 56 cm yr^{-1}, or about 1.4×10^{12} m^3 yr^{-1}. Note that this value for the entire Mediterranean is much lower than *Béthoux's* [1979] estimate of 1.8×10^{12} m^3 yr^{-1} for excess evaporation from the eastern Mediterranean alone. Using a hydraulic control model combined with mass and salt conservation statements for the Mediterranean, *Bryden and Kinder* [1991] showed that the salinity difference (ΔS), and also the density difference ($\Delta\sigma_\theta$), between the Atlantic and Mediterranean varies in accordance with the excess of evaporation over fresh water input in the entire Mediterranean (X) to the two-thirds power: ΔS (or $\Delta\sigma_\theta$) $= X^{2/3}$.

Since the diversion of 13.5×10^{10} m^3 yr^{-1} of fresh water corresponds to an increase of about 10% in X, ΔS (and $\Delta\sigma_\theta$) should increase by about 6.6%. According to *Wüst's* [1961] compilation profiles, the value of ΔS was about 2 ppt prior to 1960, and $\Delta\sigma_\theta$ was about 2.2 kg m^{-3}. Therefore the calculated increases resulting from damming of the major rivers that (used to) discharge into the eastern Mediterranean should amount to about 0.13 ppt for ΔS, and 0.14 kg m^{-3} for $\Delta\sigma_\theta$. We found that the increase in WMDW salinity since 1955 has only been about 0.05 ppt. Because of the scatter in Figure 2c, the variation of σ_θ with time is less well constrained, but the maximum difference (ma35 versus th26) is only about 0.04 kg m^{-3}, so that the increase since 1955 is definitely lower than the predicted 0.14 kg m^{-3}. The discrepancies between the observed increases and the calculated values suggest that the system has not (yet) reached a new steady state.

According to these calculations, the WMDW salinity and density will continue to rise for another 55 to 90 years, provided that the rate of change remains equal to that between 1955 and the present and that no additional disturbances are made in the Mediterranean freshwater budget. Thus it appears that the total response time for a 10% perturbation in the freshwater budget of the Mediterranean Sea is of the order of 100 years.

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