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Longterm increases in Western Mediterranean salinities and temperatures: anthropogenic and climatic sources

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Abstract. The deep water of the western Mediterranean Sea is known to have become warmer and saltier since about the 1950s. The causes of these changes have, however, not yet been sactisfactorily determined. Previous studies speculated on decreasing precipitation, greenhouse warming and/or anthropogenic reduction of the freshwater flux into the eastern Mediterranean. Here we report on results from a new oceanographic database of the western Mediterranean Sea together with determinations of longterm changes of the fresh water budget. We analyzed temperature and salinity data of the past 40 years to detect deviations from the longterm average. Certain areas and depth ranges are showing increases in temperature or salinity some of which have been found earlier and some which are new. From the regional and vertical distribution we conclude that the observed increases of temperature and salinity in the western Mediterranean Sea are caused both by changes in atmospheric conditions as described by the NAO-index and by the regulation of Spanish rivers.

Introduction

The Mediterranean Sea is characterized by an average loss of heat and freshwater to the atmosphere. A quasistationary freshwater and heat balance is maintained by an exchange of water through the Strait of Gibraltar with inflow in an upper and outflow in a lower layer. The outflowing watermasses are formed within the Mediterranean under local climatic conditions, some of which obviously changed since the beginning of the century. Extended use of the freshwater resources in the Mediterranean area reduced the river runoff into the Mediterranean. Furthermore the precipitation decreased significantly between the 1950s and the early 1990s. A corresponding change in Mediterranean watermass properties can thus be expected. Observations indeed revealed that the temperature and the salinity of the western Mediterranean deep water (WMDW) was continuously rising over at least the past 30 years. Studies analyzing these trends[1] speculated on connections to the changing boundary conditions [*Bethoux et al.,* 1990] [*Rohling and Bryden,* 1992] [*Leaman and Schott,* 1991]. Explanations differ in attributing the deep trends to an increase in sea surface salinity in either the eastern or the western Mediterranean. Higher salinities at the surface reach deeper levels via the formation of deep and intermediate watermasses [*Leaman and Schott,* 1991]. Since two different watermasses contribute to newly formed WMDW one or both of them may contain higher salinities. The first, the Levantine Intermediate Water (LIW), is subject to the climatic conditions in its formation area in the eastern Mediterranean while the second, the Modified Atlantic Water (MAW), is water of Atlantic origin which during its residence in the western Mediterranean is affected by the local climatic conditions.

Earlier evidence on changes in the freshwater budget suggested that the source of the trends is located in the eastern Mediterranean, where the construction of the Asswan dam in Egypt in the 1960s caused a reduction of the Nile discharge of 0.04 m yr^{-1} distributed over the eastern Mediterranean, a substantial change of the average freshwater loss of the Mediterranean Sea of about 0.8 m yr^{-1} [*Bryden et al.,* 1994]. A further known reduction of the freshwater input into the Mediterranean resulted from a 15% decrease of local precipitation over the past 30 years [*Hurrell,* 1995].

Since both these known changes affect the sea surface, longterm changes should be most distinct in the surface salinities. However, neither for the western nor for the eastern Mediterranean such longterm surface salinity changes have yet been proven. On the basis of our newly composed hydrographic dataset we are able to localize decadal changes in hydrographic properties and attempt to establish a link between them and the surface boundary conditions.

Data and Methods

For our analyses, we have compiled historical temperature and salinity data into a comprehensive climatology of the western Mediterranean [*Krahmann,* 1997]. The database (about 36000 profiles) includes profiles from the NODC CD-ROM, from the MED2 dataset

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[1]Following the nomenclature of these studies we use the term *trend* though our results indicate that it is not necessarily a progressing development.

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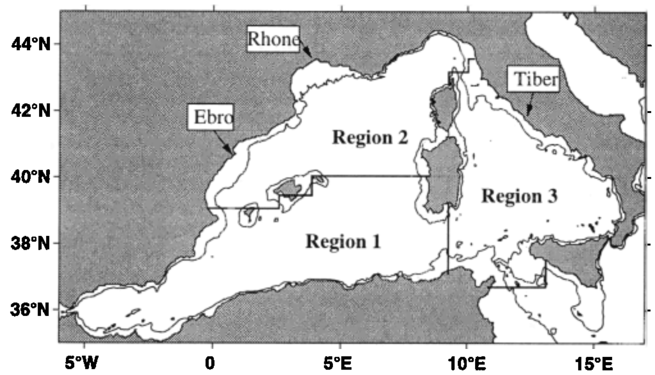

Figure 1. Division of the western Mediterranean Sea into three regions for which the longterm variations of the temperature and salinity have been analyzed separately. The locations where the three major rivers enter the western Mediterranean are also indicated.

[*Brasseur et al.*, 1996], from the French navy and from own measurements. Our climatology differs from other comparable ones [*Brasseur et al.*, 1996] [*MEDATLAS*, 1997] by its calculation method and by the underlying database. In difference to the other climatologies we have calculated monthly averages on a $\frac{1}{2}^\circ \times \frac{1}{2}^\circ$ horizontal and 31-level vertical grid for the years 1905 to 1994 thus allowing the analysis not only of the regional but also of the longterm variations. Values deviating more than 4 σ from the box average were rejected and the averages were recalculated. Climatological seasonal cycles were then derived by averaging the 90 years. A subsequent smoothing of the resulting fields consisted of two parts: first a horizontal averaging with Gaussian weights (halfwidth 53 km) was applied and then empirical orthogonal functions were used to filter in the vertical dimension. For the reconstruction of the fields only the first 10 of the 31 EOFs were used, containing more than 99.9% of the total variance. Subtraction of the climatological seasonal cycles from the monthly fields gave temperature and salinity anomalies for the period from 1955 to 1994 (before 1955 the data was too sparse to allow satisfactory analyses). For a further averaging of the anomalies the western Mediterranean was subdivided into three regions (Fig. 1). The region-averaged anomalies were then analyzed with linear regressions for each depth level (Fig. 2). The usage of anomalies rather than absolute values is better suited for the calculation of averages in regions with spatial variations and distinguishes our approach from previous ones.

Results and Discussion

The analysis revealed two water masses with significant trends. From their strengths and regional distribution we are now able to localize the sources. The first trend is the already known development of the WMDW to higher temperatures and salinities. The trends for the Gulf of Lions (a fraction of region 2) of $16 \pm 5 * 10^{-4}$ C yr^{-1} and $8 \pm 1 * 10^{-4}$ yr^{-1}, respectively, are in agreement with those found in previous studies. Below 1800 m significant trends of comparable size are present in all three regions, while in region 2, the WMDW formation area, they extend from the seafloor up to 1000 m depth. This distribution indicates that the

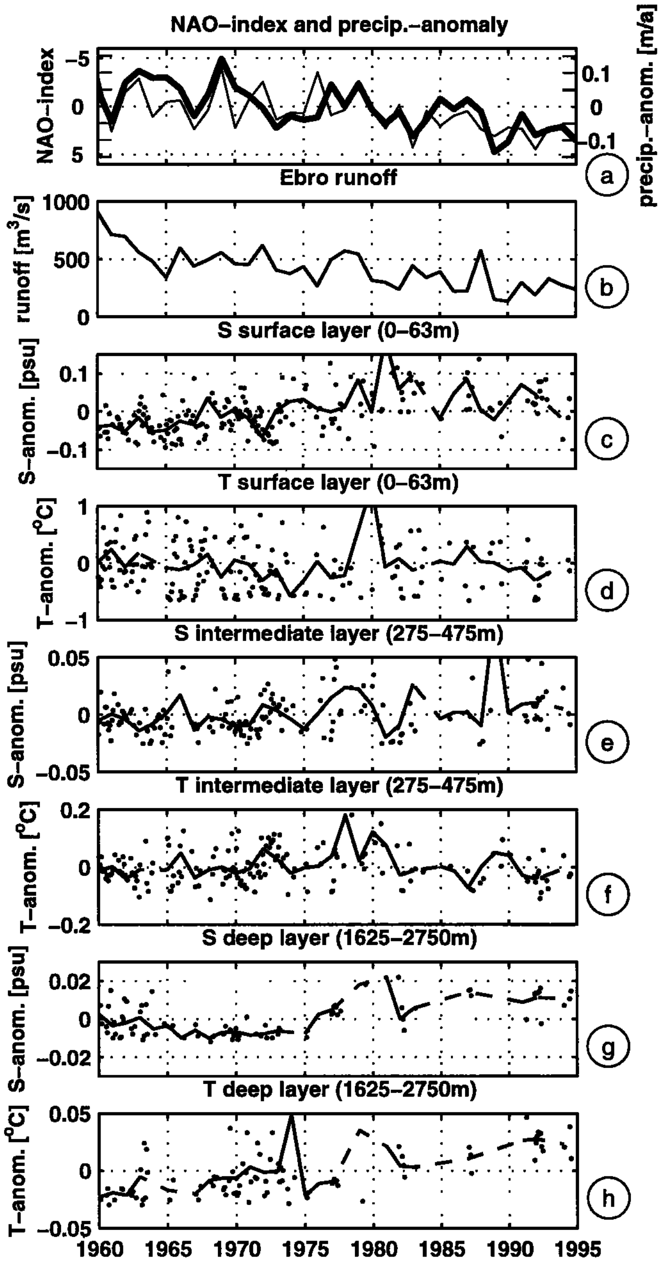

Figure 2. Longterm variations of atmospheric and oceanic properties in the Mediterranean region. Part (a) displays rain-gauge derived precipitation-anomaly time series for the western Mediterranean region (thin) and the NAO-Index (bold), part (b) the yearly averaged Ebro river runoff, and panels (c) to (h) salinity and temperature anomalies in the northwestern Mediterranean (region 2) for layers resembling the three main water masses of the western Mediterranean. Dots in (c) to (h) denote monthly averaged anomalies while the lines connect the yearly averages (dashed where yearly averages are missing). Note that the scales in (c) to (h) vary.

trends are created during the local deep water formation and not by widespread vertical diffusion. The second and up to now unknown trend is located in the uppermost levels of the northwestern Mediterranean (region 2). Between 1960 and 1990 the salinity increased by 0.13±0.03 over the upper 70 m of the watercolumn. Below 70 m the trend weakens until it finally vanishes at 150 m depth. This depth range agrees with the vertical extension of the MAW. No significant trends are present in the upper levels of regions 1 and 3. Another important result of the regression analyses is the nonexistence of significant trends at the levels of the LIW (250–500 m) in all three regions of the western Mediterranean. The slight increase in LIW salinities in figure 2e is not significant and too small to be solely responsible for the trends in the deep water. Because of the LIW being the only watermass spreading from the eastern into the western Mediterranean this excludes eastern Mediterranean sources for the deep water trends as speculated by [*Rohling and Bryden,* 1992] and [*Leaman and Schott,* 1991]. Changes of eastern Mediterranean LIW properties have, however, been documented for past 10 years [*Roether et al.,* 1996] and may well be responsible for changes in the western Mediterranean after our period of analysis.

The comparison of upper with deep layer trends in the deep water formation area shows that vertical mixing, as occurs during deep convection, is sufficient to explain the deep trends as a redistribution of the upper trends onto the newly formed deep water, the spreading of which is a point of ongoing research. The simultaneously observed warming of the WMDW can be explained by the higher temperatures at which the density of the already existing deep water is reached during the deep convection process. This is supported by our estimation of no significant variations in deep water density. Hence we attribute the deep water trends to a local increase in surface water salinities in the WMDW formation area in the northwestern Mediterranean. The search for the sources of the surface salinity increase is thus concentrated on the boundary conditions in the western Mediterranean Sea.

Three main components contribute to the freshwater budget of the Mediterranean Sea: precipitation, river runoff and evaporation. Sufficiently long time series for trend evaluation exist for all three components.

The longterm development of the precipitation has been evaluated with the National Oceanic and Atmospheric Administration baseline climatological dataset [*GCPS,* 1997]. Between 1960 and 1990 the decrease of the average annual rainfall of 0.58 m amounts to 0.093±0.051 m. From measurements in the northwestern Mediterranean it was determined that the rainfall at sea is about half that at neighbouring coastal stations [*Bethoux,* 1979]. Climatological rainfall data [*Da Silva et al.,* 1994] indicates that the maritime rainfall might be higher than found in the older study. For our calculations we use the more conservative estimate of the decrease in annual marine rainfall of 0.046±0.025 m over the three decades. The decreasing precipitation in the Mediterranean region is related to a large-scale variation in the northern hemisphere atmospheric circulation, the North Atlantic Oscillation (NAO) [*Hurrell,* 1995]. During one extreme of its oscillation (indicated by a positive NAO-index, the winterly sea level pressure difference between Lissbon, Portugal and Stykkisholmur, Iceland [*Hurrell,* 1995]) the atmospheric moisture transport is shifted northward from southern to northern Europe causing reduced rainfall in the Mediterranean region. The longterm increase of the NAO-index lasting from the end of the 1960s until 1994 thus was accompanied by a reduction of the rainfall in the Mediterranean area.

The river runoff has also changed significantly by the regulation of Spanish Ebro river [*Ibanez et al.,* 1996]. Its runoff decreased from an average of 618 m^3 s^{-1} during 1960–1965 to 245 m^3 s^{-1} during 1990–1995 with lowest transports of less than 130 m^3 s^{-1} in 1989 and 1990 [*Ibanez et al.,* 1996]. At the same time the discharges of the two other major rivers entering the western Mediterranean, the Rhone (France) and the Tiber (Italy), remained unchanged at about 1600 m^3 s^{-1} and 200 m^3 s^{-1}, respectively [*UNESCO,* 1969]. The Ebro-runoff enters the cyclonic circulation of the northwestern Mediterranean, formed by water which has been present in the western Mediterranean for some years. Distributed over this northwestern part the reduction of the annual freshwater input by the Ebro, which is at least partially anthropogenic, amounts to 0.040±0.011 m over the period of 30 years.

The longterm variation of the evaporation is difficult to determine. Two datasets, based on the same meteorological observations from merchant ships, are evaluated here. The first is the comprehensive ocean-atmosphere data set (COADS) evaluated with the methods outlined by [*Garrett et al.,* 1993] and the second is the dataset of [*Da Silva et al.,* 1994]. Both sets indicate a decrease in evaporation over the period of interest but with substantially different trend values. The drop in annual evaporation between the sixties and the nineties amounts to 0.078±0.064 m and 0.021±0.018 m, respectively, for the two datasets. These values are subject to a large uncertainty, since they depend strongly on the correction of changes in wind speed determination. Without such corrections the evaporation is about constant over the 30 year period, so that the calculated decrease is largely a product of the differing correction schemes. For the following calculation we use the value 0.021±0.018 m of [*Da Silva et al.,* 1994] because they applied the nonlinear correction to each single observation before performing any averaging, whereas [*Garrett et al.,* 1993] used a time dependent correction upon already averaged wind speed estimates. However, we feel uncomfortable with the large discrepancy of both results, which require further study.

In total the change of the yearly freshwater budget between 1960 and 1990 amounts to an extra loss of 0.065±0.054 m. Application of this additional annual freshwater deficit onto the surface layer of 70 m under consideration of a residence time of three years results in a salinity increase of 0.106±0.088, which corresponds to the observed salinity variation in the northwestern Mediterranean (region 2). The residence time of three years was derived by two estimations giving a consistent time-scale. The first value of 2.8 years is calculated by dividing the volume of the surface layer ($6.1*10^{13}$ m^3 for a thickness of 70 m) by the inflow of Atlantic Water through the Strait of Gibraltar ($0.7*10^6$ m^3 s^{-1}, [*Bryden et al.,* 1994]). The second estimate is derived from the net freshwater-loss at the surface and the horizontal salinity variation in the surface layer. For a net freshwater loss of 0.5 to 1.0 m yr^{-1} [*Bryden et al.,* 1994] and salinities of 36.4 at the inflow and 38.1 in the northwestern Mediterranean a time scale of 3.1 to 6.2 years results. Since this approach does not include effects of vertical mixing with the underlying high salinity layers it should be seen as an upper estimate of the time scale. The two calculations let us estimate a residence time in the western Mediterranean area of about 3 years for the surface waters in the northwestern Mediterranean. The second approach also reveals why the trends in regions 1 and 3 must be smaller than in region 2: firstly the residence time of surface waters in these areas is too short to create a significant trend and secondly the influence of the Ebro discharge is largely restricted to region 2.

Our evaluation does not finally prove that the decreasing precipiation and river runoff are responsible for the observed salinity changes. Nevertheless we conclude from the spatial distribution of the changes, i.e. that no significant changes are observed in the salinities of the intermediate layer and of the surface layer in regions other than the northwestern Mediterranean, that the deep water trends are caused by local variations of the boundary conditions of the northwestern Mediterranean and not by changes in the source region of the LIW, the eastern Mediterranean.

What can be said about future developments of the watermass properties in the western Mediterranean? While it is unlikely that the anthropogenic reduced freshwater input by rivers will return to higher values in the near future, the precipitation in the Mediterranean area reached again higher values during 1995-97. This increase in precipitation was, as was its longterm decrease, caused by variations of the atmospheric circulation as described by the NAO. Continuing wet conditions for some more years could again lower the sea surface salinities and a subsequent change of the properties of the newly formed deep water back to lower temperatures and salinities or at least an end of the present trends could be expected. As reported by [*Roether et al.,* 1996] the LIW in the eastern Mediterranean was getting cooler while not much changing its salinity. Therefore one may expect future anomalies in the western basin by remote effects.

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References

Bethoux, J. P., Budgets of the Mediterranean Sea. Their dependence on the local climate and on the characteristics of the Atlantic waters, Oc. Acta, *2,* 157-163, 1979.

Bethoux, J. P., Gentili, B., Raunet, J. and D. Taillez, Warming Trend in the Western Mediterranean Deep Water, Nature, *347,* 660-662, 1990.

Brasseur, P., Beckers, J. M., Brankart, J. M. and R. Shoenauen, Seasonal temperature and salinity fields in the Mediterranean Sea: Climatological analyses of a historical data set, Deep Sea Res., *43,* 159-192, 1996.

Bryden, H. L., Candela, J. and T. H. Kinder, Exchange through the Strait of Gibraltar, Prog. Oceanogr, *33,* 201-248, 1994.

Da Silva, A. M., Young, C. C. and S. Levitus *Atlas of Surface Marine Data,* (1994).

Garrett, C., Outerbridge, R. and K. Thompson, Interannual Variability in Mediterranean Heat and Buoyancy Fluxes, J. Clim., *6,* 900-910, 1993.

Global Climate Perspectives System (GCPS), http://www.ncdc.noaa.gov/gcps/gcps.html.

Hurrell, J. W., Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation, Science, *269,* 676-679, 1995.

Ibanez, C., Prat, N. and A. Canicio, Changes in the Hydrology and Sediment transport produced by large dams on the lower Ebro river and its estuary, Reg. Riv.: Res. & Man., *12,* 51-62, 1996.

Krahmann, G., Saisonale und zwischenjährliche Variabilität im westlichen Mittelmeer - Analyse historischer Daten, Ph.D. thesis, 168 pp., Christian-Albrechts-Universität zu Kiel, 1997.

Leaman, K. D. and F. A. Schott, Hydrographic Structure of the Convection Regime in the Gulf of Lions: Winter 1987, J. Phys. Oceanogr., *21,* 575-598, 1991.

MEDATLAS Mediterranean Hydrographic Atlas, http://www.ifremer.fr:582 /sismer/program/medatlas/gb/gb_medat.htm .

Roether, W., Manca, B. B., Klein, B., Bregant, D., Georgopoulos, D., Peitzel, V., Kovacevic, V. and A. Luchetta, Recent Changes in Eastern Mediterranean Deep Waters, Science *271,* 333-335, 1996.

Rohling, E. J. and H. L. Bryden, Man-Induced Salinity and Temperature Increase in Western Mediterranean Deep Water, J. Geophys. Res., *97,* 11191-11198, 1992.

UNESCO, Discharge of selected rivers of the world (studies and reports in hydrology 5), Vols. 1, 2, 3.

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