1. INTRODUCTION

The workshop was held at the Adriatico House of the Abdus Salam International Center for Theoretical Physics, ideally nested on the wooded shore of the Gulf of Trieste, from 29 March to 1st April 2000. Seventeen scientists, originating from ten countries, did participate at the invitation of CIESM. In opening the meeting the Director General of CIESM, Prof. Frédéric Briand, warmly welcomed the participants and gratefully acknowledged the hospitality of ICTP. He further expressed his gratitude to Prof. Alex Lascaratos, Chair of the Committtee of Physical Oceanography, and to Dr Miroslav Gacic, for joining forces in the conceptual and logistic preparation of this event.

1.1. Aims and objectives

Frédéric Briand presented the genesis and specificity of the CIESM Workshop Series, where researchers are brought together not to deliver the usual sequence of bright monologues, but instead to engage during four days in a lively – at times intense – debate, based on a constructive confrontation of their latest hypotheses and perspectives. A major objective is to identify in this way some of the most promising questions for further research, with a particular interest for multidisciplinary aspects. Hence the invitation extended to several biologists with an active interest in the issue.

Alex Lascaratos, coordinator of the workshop, followed. He reminded the participants that this workshop was convened to specifically examine questions related to the abrupt climatic change in the Eastern Mediterranean known as the Eastern Mediterranean Transient (EMT). The aim was to determine what is known and understood as well as what needs further investigation and clarification. The workshop would also review examples of similar effects of climatic changes or trends on the ecosystem of other areas such as the Atlantic and consider the potential influence of the EMT on the Western Mediterranean.

1.2. Topics covered

During the course of the four days, the topics discussed by the group eventually included :

- The causes and origins of the EMT. Are these causes of local origin or are they related to larger scale atmospheric variability (*e.g.* NAO)?
- How sensitive is the Mediterranean system? Are similar transients to be expected in the future?
- The evolution and fate of the EMT; how long do we expect the EMT to affect the EMED before it fades away?
- How much will the WMED be affected by this transient?
- What are the known and expected effects of the EMT on the ecosystem ? Are there indications that these effects could influence not only primary and secondary production but fisheries as well ?

2. EVOLUTION OF EMT

An increasing amount of information now exists about the evolution of the transient and its effects on the thermohaline circulation of the Eastern Mediterranean. While important aspects of the transient have been investigated separately, for example the temporal evolution in the Aegean, changes in the local and global salt budgets, changes in the circulation and the uplifting of mid-depth waters, changes in the bottom layer of the Southern Adriatic, a comprehensive analysis of all existing data and a consistent interpretation is still missing. Additionally, some of the analyses and most of the recently collected data are still unpublished and therefore not available to the public. During the plenary discussion following the various presentations, it was therefore suggested that a first necessary step would be to build the sequence of events leading to the transient (according to the group's best interpretation and knowledge of observational evidence), along with a list of open questions. This would structure the further discussion. The list is reproduced below.

List of events

1975 — Densities in the deep water of the Cretan Sea start to rise, but only for a short period.

Q: Is this a similar event to the transient, and why did it end? Suggestion to include additional data from Israel and Turkey into analysis.

1980 — Cooling of LIW by ~ 0.5 °C is observed.

Q: Is this important for the onset of the transient?

1983 — LIW salinities in the northeast Levantine increase by 0.2.

1984 — Shikmona gyre is evidenced for the first time.

Q: Is there a dynamical link between changes in the circulation system and the transient?

1986-1987 — Change of circulation in the Ionian from cyclonic to anticyclonic (Pinardi *et al.*, 1997a). Very strong anticyclonic activity everywhere (POEM Group, 1992, Malanotte-Rizzoli *et al.,* 1997). Meteorological winter conditions very cold and dry over the whole EMED, therefore strong deep water formation in the Adriatic and Aegean. Adriatic and Aegean show good ventilation of deep layer. First appearance of σ_θ>29.2 in the bottom layer of the Cretan Sea. Russians report deep water formation in the Levantine.

1988 — Change in wind direction and strength over the Aegean in winter is initiated. Volume of dense water at the bottom of the Cretan Sea increases.

1989 — Deep water with σ_θ>29.2 reaches sill level of Cretan Strait in the East (Theocharis *et al.*, 1999a). The outflow increases but it is not dense enough to get to the bottom yet in the Eastern Mediterranean.

Q: Are there similar changes in the Levantine? Suggestion to get Turkish nutrient data or the Rhodes Gyre Area.

1990 — Marked increase of nutrients (200-800m layer) is observed in the Adriatic.

Q: Is this to early to be related to the transient?

1991 — σ_θ>29.2 level rises to 400 m in the Cretan Sea (Theocharis *et al.*, 1999a) . Outflow from the Aegean through western Strait replaces waters in the intermediate and deep layers (σ_θ= 29.0-29.18) in the Ionian (Malanotte-Rizzoli *et al.*, 1999).

In the Ionian strong chemical differences are observed in the deep layer between the western and eastern parts.

Q: Could these be signs of deep outflows from the Aegean?

Strong inflow of MAW into the Ionian. In the Levantine an increase in surface salinity is observed. Additionaly an increase in multilobe anticyclonic circulation in the Levantine is observed (Malanotte-Rizzoli *et al.*, 1999).

Q: Is this accumulation of salt due to circulation changes or E-P changes ?

Meteorological data from ECMWF show cold and dry winter in the North Aegean but not in the South Aegean.

Q: Does this agree with observations for example COADS? Is the North Aegean the more important area to trigger the transient?

1992 — Strongest winter heat loss since 1985 in the Adriatic. Deep layer density in the Adriatic the last time at 29.3, starts increasing afterwards (Klein *et al.*, 1999).

In Cretan Sea highest winter heat loss since 1979, very low air temperature. Maximum of deep water production in the Aegean, σ_θ>29.2 reaches 300 m level (Theocharis *et al.*, 1999a). Density jumps in the bottom layer of the Aegean to 29.25.

Q: Where is the deep water in the Aegean actually produced and where does it get stored before outflow?

Mid-depth salinity minimum layer appears in the Cretan Sea for the first time.

Reported deep water production in the Levantine.

1993	Sediment temperature profiles prove presence of Aegean deep water at the bottom of the Eastern Ionian (Della Vedova *et al.*, 1997). Temperature and salinities anomaly, as high as in the CTD profiles from 1995, are noted in proximity of the Western Cretan Arc Straits. Signal must have been propagating since 1991. Biological observations in the Ierapetra show large increase in abundance and species composition of benthic species. Uplift of water column dilutes the LIW. Uplift of mid-deep water dilutes the LIW layer that intrudes the Adriatic Sea. Salt content in the intermediate layer in the Adriatic jumps to its minimum.
1994	Extremely warm year, warm winter. Winter temperature in Adriatic as high as 16 °C. Outflow of ADW at Otranto has density greater than 29. 20 (Gacic *et al.*, 1996), but starts to register decrease in both temperature and salinity (Klein *et al.* 1999). Volume of dense water in the Aegean begins to decrease but density is increasing. Densest outflow both through Kassos and Antikythera Strait
1995	At the bottom of the Ionian and Levantine Basin the dense Aegean Water has propagated halfway through both basins already (Klein *et al.* 1999). No deep convection inside the Southern Adriatic. A well mixed water column down to 600 m is surface ventilated to 400 m. Density in the bottom layer 29.25. Estimated outflow rate at Otranto 1.67±0.26 Sv in February 1995 (Poulain *et al.*, 1996). ADW (0.27±0.1 Sv) decreases in temperature and salinity. It may indicate stronger dense water from northern shelf in the absence of deep convection in the southern basin. Signal of diluted LIW reaches Sicily Strait. Aegean same as 1994
1996	No data in Aegean. Convection in Adriatic only to 600 m (Manca and Bregant, 1998). Intermediate layer salinity core as high as 38.94 observed to intrude the Adriatic in the Otranto Strait interior in February, but at shallower depth than that of traditional LIW. *Q: Is this already a salty intermediate water supplied from the Aegean?*
1997	No deep convection in the Adriatic. Density in the bottom layer decreases to 29.24. ADW outflow rate at Otranto reaches a minimum (0.1 Sv) and in the Ionian (zonal section at 38.5 N) the ADW water is centred to 1000m depth (Manca *et al.*, 1998). Little new production of dense water in the Aegean; Aegean outflow less than 0.3 Sv. Aegean water in the Ionian still denser than Adriatic, but warmer and less dense than previously. It does reach bottom any longer in Ionian. Ionian anticyclone still present.
1998	No new deep water production in Aegean. CFC data in Aegean show increase but oxygen decreases. *Q: Is the oxygen decrease an intercalibration problem or does it indicate increased consumption because of increase in sinking material?* *Q: Where does the CFC increase come from if no deep water was produced in Aegean, are there areas on the shelf which have not been sampled?* Ionian anticyclone weakens, and it seems that the MAW does not spread into the Northern Ionian anymore.. Decreasing trend of temperature and salinity in the LIW at Sicily Strait likely reaches an end. In the Adriatic convection only to 400m, outflow at Otranto increases but is still low with 0.5 Sv
1999	Ionian anticyclone at surface vanishes and circulation is cyclonic again. New Cretan Intermediate water intrudes Adriatic for the first time. Aegean deep water reaches the western end of Ionian basin at the bottom (general increase of salinity in the deep layer). Bottom flows in the western (close to Maltese escarpment) and in the Northern Ionian (38.5 N zonal section) show very strong abyssal northward currents (15 cm/s). Entire Levantine Basin is filled with Aegean deep water. Bottom layer in Cretan Passage is stagnant, new outputs from Aegean settle at 1500-2000m. Convection in Adriatic reaches 600 m and outflow at Otranto increases further.

3. Causes and origins of EMT

The well documented changes in meteorological forcing over the Eastern Mediterranean, and particularly the Aegean sea, include three cold winters in the early months of 1987, 1992 and 1993. It was noted also that from 1988 onwards the winter wind fields over the Aegean and the Western Mediterranean changed and stronger northerlies prevailed for all the years 1988-1993. It is probable that there were also changes in net Evaporation-Precipitation, in particular several dry years appeared during this period. All of these changes may have been partly responsible for the formation of Aegean deep waters. Other possible contributions included long term trends in Evaporation-Precipitation and the historical damming of the Nile and Danube rivers, and perhaps changes in salt exchange with the Western Mediterranean. But the relative importance of anomalies in meteorological parameters as wind speed and direction, air temperature and precipitation in triggering the EMT was judged differently. Conflicting hypotheses either attribute the origins of the EMT to a combined effect of the observed anomalous dry years over the area (resulting in increased salinities) followed by two successive cold winters or simply to a series of cold winters.

The role of the salt increase in the eastern half of the Eastern Mediterranean in relation to the EMT remained controversial throughout the discussion. No consensus could be reached on the importance of the observed salt increase in the Cretan Sea to start the EMT. Some viewed this salt increase as an outcome of the deep water production in the Cretan Sea and the resulting increased exchange rate between the Cretan Sea and the Levantine, and not as a prerequisite. It was suggested to investigate these problems using specially designed model simulations. The value of modelling in unravelling the causes of the Eastern Mediterranean changes would be that the various possible contributions mentioned above can be tested in isolation for their effects. Some contributions may be much more important than others. The most important prerequisite for this task however are reliable models which can reproduce the properties and circulation prior to 1987.

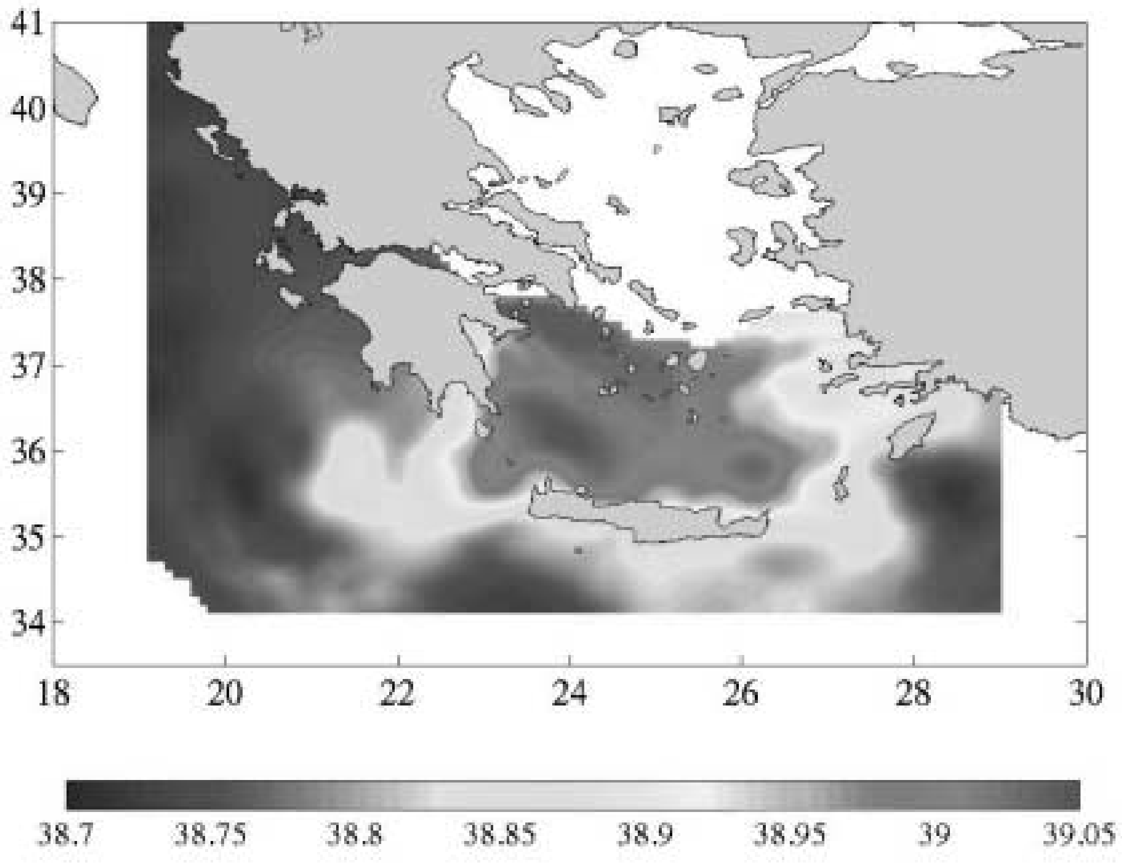

Fig. 1. Salinities at the 29.18 sigma-theta horizon in late spring 1991. **See full colour image on page 1.**

Currently two modelling efforts have attempted to reproduce the changes caused by the EMT, using different models and different forcing anomalies. There was some discussion of the relative value of comparing the salt budgets in these models with observations. Observations demonstrate clearly the importance of redistribution of salt and successful model simulations should reproduced water properties and final salt distributions very similar to those observed. However similar salt redistributions might be achieved in several different ways within a model, all leading to similar end states. It was therefore agreed that the next step should be to try to use models to reproduce the sequence of events present in the observations rather than just focussing only on the final end state (*e.g.*, as observed in 1995 by *Meteor*).

Keeping to the spirit of using models to isolate different effects, one important experiment should be to apply the known changes in winds and the known cold winters to a model but without explicitly changing E-P and without introducing any other preconditioning changes prior to 1987. If this experiment can reasonably reproduce the sequence of events from 1987 onwards it will suggest that E-P and river runoff changes might have played a less important in preconditioning the new eastern deep waters. This is a sensible approach because to date the E-P forcing is the most poorly known of the meteorological forcings. After more indepth analysis of meteorological time series including new data sets for the E-P forcing a set of forcing scenarios should be put together and should be the basis for the future modelling studies. In order to intercompare the forecasting skills of different models a common way of presenting results either on sections of through budgets should be developed.

An open issue has been the mechanism by which the Aegean increased the production rate and where the huge amounts of water produced were stored. It was suggested that for comparison with experimental data, rates of deep water formation on the northern shelf should be computed from the model runs. A question that should be adressed in model runs with realistic forcing is the stability of the thermohaline circulation of the Eastern Mediterranean as a whole. What makes the winter 91 so unique compared to a similarly cold winter in 87? This is related to the question why the transient has only been observed one time over an observation period of 100 years, while meteorological anomalies of similar magnitude have existed in the past.

Salt budgets of the Eastern Mediterranean indicate a larger salt content in the present situation compared to the past. The salt increase is in the order of 5-6 10^{13} kg and can only partly be attributed directly to changes in the freshwater flux. One hypothesis suggests that a salinity increase in the inflowing Modified Atlantic Water (MAW) through the Strait of Sicily could be responsible for the salt content increase. This would indicate a connection of the EMT with the Western Mediterranean, but the data base for the analysis is small and associated with large errors. In a differing hypothesis it was suggested that disturbancies either of the freshwater budget (E-P-R) of the basin or the water formation mechanism would cause an imbalance of the exchange of water masses and salt through the Strait of Sicily and could upset the salt budget, at least temporarily. A simple 2 layer box model of the basin indicated that either a 10% increase in E-P or a 10% decrease in the water formation rate could lead to a net influx of salt at Sicily of around 4 10^{12} kg/yr. This is reasonably consistent with the required salt inflow over 10 years to explain the observed increase in salt content. In the model case in which the salt influx is achieved without any change in E-P, it is accompanied by a 10% drop in the volume exchange at Gibraltar. Such a change would be very hard to detect in observations. Following this hypothesis the changed salt content of the Eastern Mediterranean observed in 1995 could have been easily supplied through Sicily but could simply be a response to changing water formation conditions inside the eastern basin, rather than to causes in the Western Mediteranean. Both hypotheses however would agree on a salt import from the Western Mediterranean to the Eastern Mediterranean and this should be checked in future analysis.

Relation of EMT to larger scale atmospheric anomalies

Correlation analysis has shown that the Mediterranean atmospheric anomalies display a connection with Indian monsoon in summer and with the North Atlantic oscillation (NAO) in winter. The existing analyses have been performed on detrended time series, the influence of a long scale trend therefore has not been explored yet, neither has the onset of the EMT been related to the large scale atmospheric anomalies. In the discussion the need for more meteorological analysis was expressed and the necessity to establish the relation of EMT and these large scale anomalies was stated. Focus in the meteorological analyis should be given to changes in the freshwater balance over the Mediterranean which to date are poorly known. Concern was expressed that if disturbancies in the fresh water flux play an important role in the triggering of the EMT and thus provide a destabilizing factor for the thermohaline circulation, the magnitude of these anomalies should be known in order to judge the potential for future hazards due to continued increasing use of freshwater in the countries surrounding the Mediterranean.

4. Influence of EMT on the ecosystem

It was felt that a direct assessment of changes in the ecosystem related to the EMT was difficult given the complexity of the system and the lack of data. The group regretted the scantiness of biological time series in the Mediteranean being available to monitor changes. Scarce evidence of ecosystem changes exist as the appearance of larger copepod species in the Ionian or abundance and species changes in the Ierapetra gyre. Problems in the analysis of existing data sets were seen in the necessity to distinguish between advective changes in species versus reaction to changes in the environment and the treatment of the high mesoscale activity. The role of viruses and bacteria and marine microbiology in general would need to be considered as well. Overall it was felt that a modelling approach would be more promising to assess ecosystem changes and might even help providing guidelines in the interpretation of biological data sets.

Following the discussion about biological data the following recommendations have been given :

- design a series of process oriented modelling studies to assess the importance of horizontal advection *versus* verical mixing/upwelling on nutrient supply in the euphotic zone;
- combine existing data sets to identify depth of nutricline and euphotic zone for various parts of the Eastern Mediterranean;
- try to calculate the total nutrient content of the Eastern Mediterranean and its variability (regional/temporal);
- changes in (N/P) ratio needs to be identified. The data suggest radical changes in (N/P) ratio in Thyrrhenian Sea;
- establish times series at critical locations for biochemical monitoring: Southern Adriatic, Cretan Sea, Northern Levantine, (Rhodes, Cicilian basin), Sicily Channel;
- it would be desirable to implement new technology to moorings as *in-situ* sampling of nutrients and chl-a;
- put sediment traps at several locations (use models to spot locations):
- identify role of eddies on nutrient supply:
- investigate invasive species and their role on the ecosystem;
- study seawifs chl-a data to learn about patchiness of the biological production;
- carry out simplified coupled physical biogeochemical modelling study to understand interannual nutrient evolution (PZN model);
- explore the connection (intensity, event sequence) on nutrient accumulation at near-surface levels on the biological production;
- initiate continous surface measurements (nutrient, chl-a) by ferries.

Influence of climatic changes on the ecosystem

A relationship between a climate index and changes in the ecosystem might be difficult to find and is probably of indirect nature. One of the more important indeces for the European region, the North Atlantic Oscillation (NAO), is basically a winter index and only species for which winter is an important season are likely to show a correlation. Similar analyses carried out in the North Sea and North Atlantic provide guidelines how such an influence between climate changes and ecosystem changes could be detected. A specific issue named in the discussion was the relationship between atmospheric blocking and changes in the ecosystem. Since atmospheric blocking is related to stratification changes in spring it could effect the ecosystem severly during a time when the most important changes in biology are to be expected. This relationshipp should be investigated in future analyses.

Can the Eastern Mediterranean transient be considered a factor influencing the present trophic state of the Southern Adriatic basin ?

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The Southern Adriatic basin (SA) constitutes the southernmost and the deepest part of the Adriatic Sea. Morphologically, it is an almost round-shaped pit delimited by the Palagruza Sill (about 250 m) to the north and by the Strait of Otranto (sill at about 800 m depth) to the south, that connects the basin with the Ionian Sea. Concerning the biogeochemical fluxes between the two adjacent marine regions, it is well known that the Adriatic exports mineral nutrients to the Ionian. Recently, Civitarese *et al.* (1998) showed that, at least in 1995, the total nitrogen and phosphorus exchanges were almost balanced (net transport at the strait = 0), suggesting that the SA is a region where significant mineralization processes can take place. Large part (about 75%) of the water entering through the Otranto Strait recirculates within the SA (Gacic *et al.*, 1999). Therefore, the flow from the south can be considered the most important advective contribution in the basin. From this perspective, the hydrology and biogeochemistry of the SA is influenced by the oceanographical characteristics of the rest of the Eastern Mediterranean, in particular of the Ionian Sea.

Fig. 1. Map of the area.

In the last decade, the Eastern Mediterranean basin have experienced a strong modification of its thermohaline circulation (Roether *et al.*, 1996; Klein *et al.*, 1999). The thermohaline cell, previously starting in the Southern Adriatic changed its pathway. The Eastern Mediterranean "conveyor belt" is now driven by the deep water of Aegean Sea origin (the Cretan Sea Overflow Water, CSOW), warmer and saltier than the Eastern Mediterranean Deep Water (EMDW) previously formed with the Adriatic contribution. This change was called Eastern Mediterranean Transient (EMT). The relatively fast replacement of the deep water by the CSOW, at a mean rate of at least 1 Sv for some years, caused an uplifting of the deep isopycnals by about 500 m with the consequent upward displacement of the oxygen minimum and the nutrient maximum layer (Klein *et al.*, 1999). In spite of a possible decrease of the nutrient pools in the deeper layers of the Eastern Mediterranean due to the intrusion of the new Aegean nutrient poor water, the 0-800 m layer evidenced a significant nutrient increase from late 80s to 1997 (Fig. 2), with a slighter increment during the last three years. Since the 800 m horizon corresponds to the Otranto sill depth, the analysis will be restricted to this portion of the water column, in order to study the evolution of the EMT and its advective propagation in the

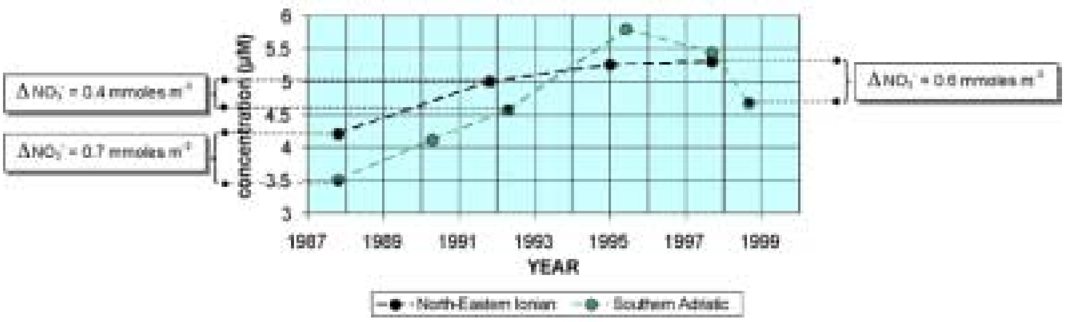

Fig. 2. Depth averaged nitrate concentration in the layer 200-800 m. For the Southern Adriatic, only the post-convective phase is considered.

adjacent SA.

Fig. 2 gives information on the EMT propagation into the South Adriatic (SA) basin. Due to the short residence time of the nitrogen in the SA (about 1 year), the nutrient pool there represents always the combined result of vertical mixing and horizontal advection. As already noted by Mc Gill (1963), winter convective mixing through the water column is an effective means of maintaining the nutrient level lower than in the adjacent North-Eastern Ionian, where this process doesn't occur. Pollak (1951) stressed the susceptibility of the Adriatic to short term weather fluctuations due to its restricted size and shallow mean depth. After mixing, the autotrophic nutrient consumption by the biota during the following productive season accounts for most of the difference between the two basins.

With a lack of vertical movements sufficiently strong to destroy the stratification, the nutrient content in the interior of the SA will be determined by the advection from south, and by possible lateral input inside the basin. Nutrient regeneration processes within the water column might be additional internal source of nutrient. The mineralization is presumably enhanced when the absence of noticeable deep water formation events reduces the exchange at the Otranto Strait with the consequent increase of the water residence time within the basin. These contributions led to a nitrate average concentration higher than in the Ionian, during the period 1995-97. In 1998 a stronger convective activity was recorded in the SA, leading again to a significant differentiation of the nutrient content in the two basins. However, one should take into account that we are depicting the interactions between two systems subject to different forcing mechanisms by means of few and geographically limited experimental realizations. This, of course, introduces some uncertainty into the analysis.

To summarize, local climatic factors interact with the larger scale transient in modulating the nutrient pool of the SA. The relative nutrient impoverishment of SA in comparison with the Ionian is related to the physical and biological dynamics of the upper layer: after an active seasonal mixing, the nutrient deep reservoir will be diluted on a larger volume of water and, more importantly, these new nutrients will be autotrophically consumed. Therefore, the difference in the nutrient pools of the two areas is a measure of the new production in the SA due to the convective mixing processes.

The difference in the nutrient content between the SA and the Ionian varies from 0.7 in 1987 to 0.4 mmoles m^{-3} in 1992. These values, integrated on the 600 m thickness of the layer, amount to 420 and 240 mmoles m^{-2} y^{-1}, that gives a correspondent range of carbon production of 35-20 g m^{-2} y^{-1} (using the C/N = 7 molar ratio). In 1998 the internal nitrate pool in the SA was 0.6 mmoles m^{-3} less than in the Ionian, leading to a new production estimate of about 30 g C m^{-2} y^{-1}. For the same year, new production estimated from the nitrate consumption in the photic layer was about 22 g C m^{-2} y^{-1}. Due to possible nutrient sources other than vertical enrichment, like atmospheric deposition, horizontal advection by mesoscale eddies or breaking of internal waves at the thermocline, the last estimate can be considered a lower limit. Thus, the two figures are in a good agreement.

New production estimates derived from convective processes in the Southern Adriatic ranged from 20 to 35 g C m^{-2} y^{-1} in the period 1987-1998. The present rough analysis of the nutrient trend during the last decade leads to the preliminary conclusion that during the considered period the EMT was not effective in changing the biological activity in the SA. The nutrient differences between the two basins, thus the amount of new carbon produced, do not seem to be related to the increasing pool. The local winter climatic conditions, determining the vertical extent of the convective mixed patch, control the short term (interannual) variability of the amount of nutrient available to autotrophs, thus the new production. The EMT, as the main factor controlling the nutrient pool in the SA, presumably acts on longer time scale, which can be masked by the short term year-to-year variations. A continuous monitoring program would allow a better understanding of the mechanisms governing the trophism of the Southern Adriatic basin.

The evolution of the Eastern Mediterranean Climatic Transient during the last decade: the tracer viewpoint

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Origins of the EMT

The Eastern Mediterranean Transient (EMT) is now underway for about a decade. EU and nationally-funded programs during this period have helped to document the changes in the thermohaline circulation. More and more evidence has been collected to its origin and causes as summarized in Lascaratos *et al.* (1999), but a consistent theory has still to be developed.

It has been commonly accepted that one of the essential ingredients in causing the EMT has been an increase of salinity in the vicinity of the Cretan Sea. A number of hypotheses have been suggested to explain this accumulation, such as internal redistribution of salt, changes in the atmospheric forcing and changes in the circulation. The observed salinity increase in the deep water would have required an extra net evaporation of 0.2 m/y over the entire surface of the Eastern Mediterranean for a period of 7 years (Roether *et al.*, 1996). A continuous decrease of rainfall over the Mediterranean area has indeed been noticed (Tselepidaki *et al.*, 1992), but the magnitude and spatial extend are unsufficient to account for all the extra salt observed. Preliminary assessment of land based stations has shown local anomalies over the Adriatic and Aegean in the order of 0.1-0.2 m/y for the period 1988-1995 (Theocharis *et al.*, 1999a) but the ship based global average over the entire Mediterranean amounted only to 0.04 m/y (Josey *et al.*, 1997).

Internal redistribution of salt within the Eastern Mediterranean contributed to the triggering of the EMT. In the early 90's a multi-lobed anticyclone had developed at the eastern end of the Cretan Passage comprising the Mersa-Matruh and Iera-Petra gyre (Malanotte Rizzoli *et al.*, 1999). This change in the circulation disrupted the flow of the Modified Atlantic Water (MAW) from the Ionian into the Levantine Basin causing salinities in the latter basin to rise. The waters of Levantine origin flowing into the Aegean had therefore higher salinities than previously (Theocharis *et al.*, 1999a). A quantification of the salinity differences between the climatological state and the transient surprisingly indicates a large net increase of salt in the global budget of the Eastern Mediterranean, ruling out internal redistribution as the single mechanism. But the predominant feature of the budget calculation is the transfer of salt from the surface and intermediate layers to the deep water (Fig. 1). This pattern is most evident in the Ionian Basin (Fig. 1a) and the Cretan Passage (Fig. 1b) where the presence of Levantine Intermediate Water (LIW) and

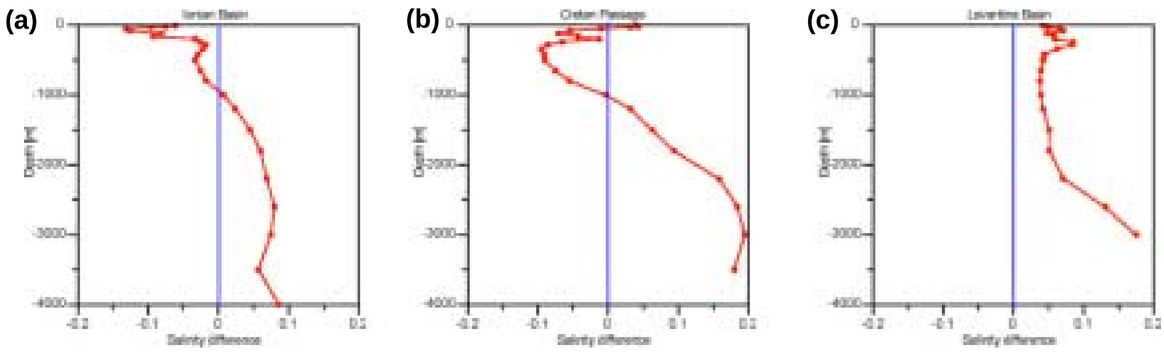

Fig. 1. Composite depth profiles of salinity changes (psu) between the climatological situation up to 1987 and 1995 for a) Ionian Basin b) Cretan Passage and c) Levantine Basin.

Cretan Intermediate Water (CIW) had been most pronounced. The Levantine Basin on average shows a continuous increase in salinity from top to bottom (Fig. 1c). In the upper 2000 m the increase is small and nearly constant, compared to the large increase at the bottom caused by the Cretan Sea Overflow Water (CSOW). The salt accumulation in the Levantine Basin thus apparently also enabled deeper convection in the previous LIW formation area. However, even considering the large error margins in the salt budget calculations the huge salt excess remains to be explained. Part of it (40%) can be attributed to the above mentioned changes in the atmospheric forcing, but for the larger part (60%) a different explanation must be found. A further possibility is a redistribution between the Western and Eastern Mediterranean invoking the transfer of water masses through the Strait of Sicily. Synoptic sections in the Strait of Sicily indicate a jump in average MAW layer salinity around 1990 synchronous with the onset of the EMT (Fig. 2). The integration of the signal in time can account for the missing part of the salt budget. The reason for the apparent jump in MAW salinities has yet to be discovered and could be related to larger climate oscillations like the North Atlantic Oscillation (Vignudelli *et al.*, 1999). A further coupling of the climatic changes between Eastern and Western Mediterranean is given in the outflowing LIW. Recent observations indicate a continuous decrease of salinity and temperature of the outflow (Astraldi *et al.*, 1999a).

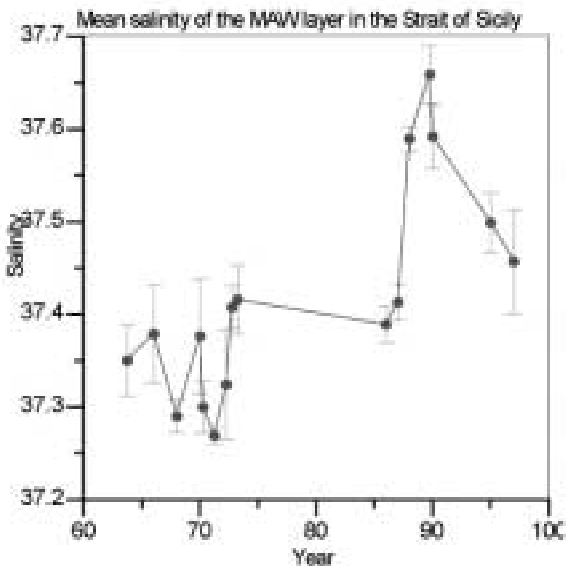

Fig. 2. Temporal evolution of the mean salinity of the Modified Atlantic Water in the Strait of Sicily. Integration of individual profiles has been carried out between the surface and a lower density boundary of 28.3 kg/m^3. Individual means have been averaged seasonally and means and standard deviation for the seasons are displayed

SPREADING OF THE EMT IN THE IONIAN AND LEVANTINE BASINS

In 1995 large amounts of Aegean-derived deep water were still deposited in the near bottom waters around the Cretan Arc, piling up to about 2000m from the bottom (Fig. 3a). Outside the Cretan Passage the influence of the Aegean water extended eastward into the Levantine Basin to ~ 31 °E and westward into the Ionian Basin to ~18 °E, covering essential parts of both basins. Four years later the spreading of the Aegean water into the surrounding waters has progressed even further (Fig. 3b). The bottom of the Levantine Basin is now entirely filled with the Aegean water. In the western Ionian Basin the CFC distributions have become ambiguous because CFC-rich Aegean waters meet with similarly ventilated dense waters of Adriatic origin. The dome of CSOW water deposited in the Cretan Strait has been partly drained to fill the Levantine and Ionian Basin as can be seen from the flattening of the 0.5 pmol/kg isoline. The fact that the near bottom CFC-concentrations in both basins do not increase between 1995-1999 furthermore indicates that the subsequent advance of CSOW at the bottom has been supplied from the earlier outflows but has not been refilled by similarly dense water output from the Aegean which should have led to increased CFC concentrations. Closer to the Cretan Arc the CFC distribution begins to show inversions (Fig. 3b). The more recently ventilated waters from the Aegean obviously did not obtain sufficiently high densities to reach the bottom but are settling about 500 m above the bottom. The vertical structure of "old" and "new" outflows from the Aegean can be seen more clearly by comparing profiles from similar locations (Fig. 4). Stations at the eastern end of the Levantine Basin show the initial advance of the CFC-rich Aegean water at the bottom with the associated uplift of the water column indicated by lowered CFC concentrations above 500m (Fig 4a). Closer to the Cretan Sea there is a clear signature of the recent outflows of dense water from the Aegean between 1200-2000m (Fig.4b). In this depth range both the CFC concentrations and salinity increase. The lower 500 m show a slight decrease in CFC concentrations and salinity. The lack of continuous ventilation of the bottom layer and the effects of diffusion are responsible for the decrease. In the western Ionian Basin both the CFC profiles and the salinity profiles are ambiguous (Fig. 4c), the observed increase in both properties between 2000-3000m could either be the advance of Aegean derived waters or a more saline output from the Adriatic. A careful mixing analysis will be necessary to identify the origin of these waters.

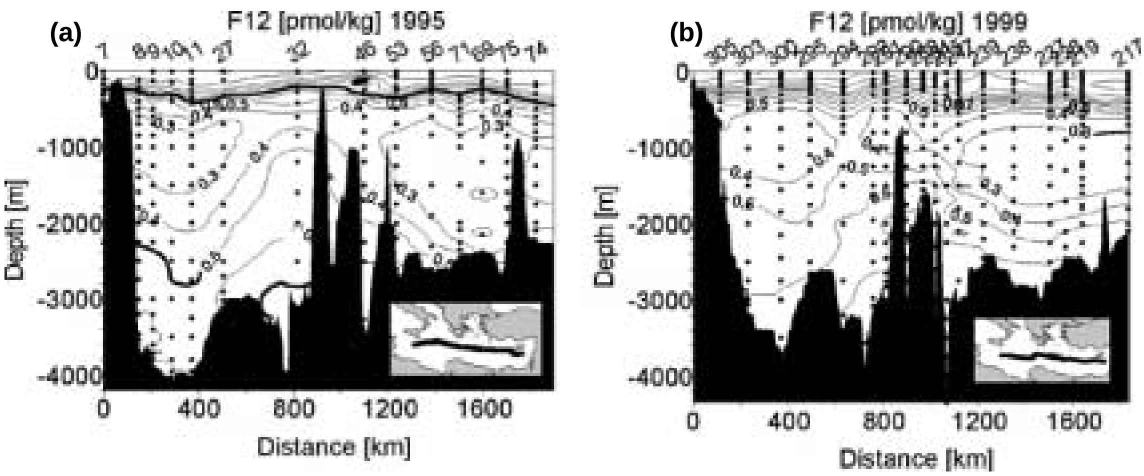

Fig. 3. Zonal sections of CFC-12 along the entire Eastern Mediterranean in 1995 (a) and 1999 (b). Section locations is indicated in the accompanying maps.

PERFORMANCE OF THE ADRIATIC AND AEGEAN AS A DEEP WATER SOURCES

A possible negative feedback between the EMT and the continued deep water production at both formation sides resulted from the fact that the salinity in the Levantine Intermediate Water layer was reduced. The vigorous discharge of deep water from the Aegean had resulted in an uplifting of the residing water column (Roether *et al.*, 1996) and "old" mid-depth water was

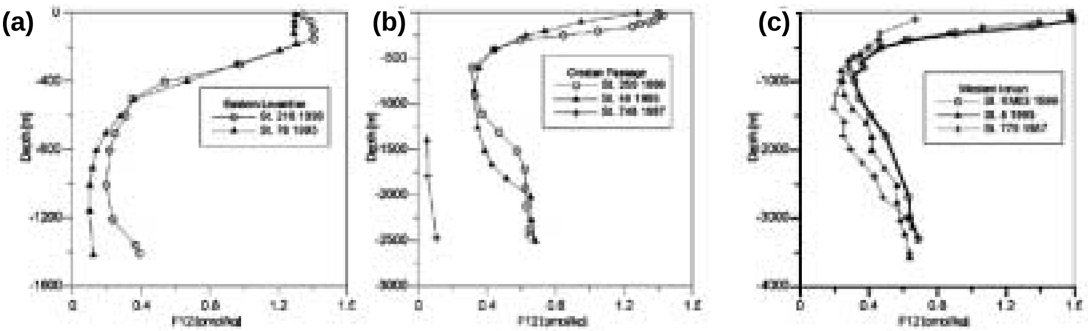

Fig. 4. Vertical profiles of CFC-12 for selected near-by station pairs at different observation times. Eastern Levantine (a), Cretan Passage (b) and Western Ionian (c).

introduced into the LIW (Roether *et al.*, 1998). The CFC distributions indicated a dilution of up to 30%. The density of the deep water produced at both formation sites crucially depends on the salinity being entrained into these waters, and the further evolution of the properties in the intermediate layer was therefore important.

The profiles in the southern Adriatic show different evolutions in the deep and intermediate layer (Fig. 5). CFC concentrations below 700 m remain constant between 1987 and 1999, demonstrating the lack of any appreciable renewal. The intermediate layer on the other hand, which in 1995 was strongly influenced by the old, CFC-poor mid-depth waters, already receives new input in 1997 and the CFC concentrations increase moderately. In 1999 the increase in CFC concentrations is extremely strong and also very pronounced down to 500m. Profiles at the Strait of Otranto indicate that the intermediate water arriving at the entrance to the Adriatic is much more ventilated than previously and also more saline. The source of this new type of intermediate water can be traced into the Aegean. While the LIW is ageing considerably during its travel through the Cretan Passage and the Ionian into the Adriatic, the intermediate water supplied from the Aegean is taking the more direct route through Antikythera Strait and thus appears more ventilated. Winter convection inside the Adriatic in 1999 is responsible for mixing the freshly ventilated and saline Aegean intermediate water deeper into the water column, but the density of the product has not been sufficiently high yet to replace the dense waters the bottom of the Adriatic. It can be speculated that given the extra salt supply now in place with an intermediate water supply from the Aegean, the Adriatic should be able to produce denser types of deep water again.

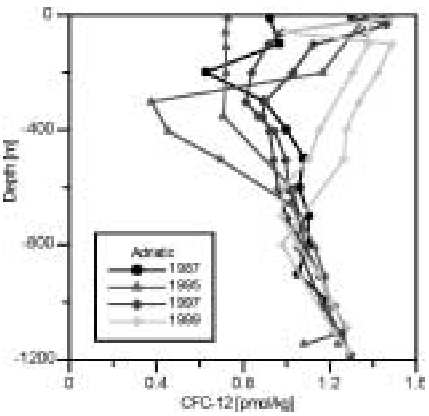

Fig. 5. Evolution of CFC-12 profiles in the Southern Adriatic between 1987 and 1999. Station locations near to 41.40 °N, 17.80 °E.

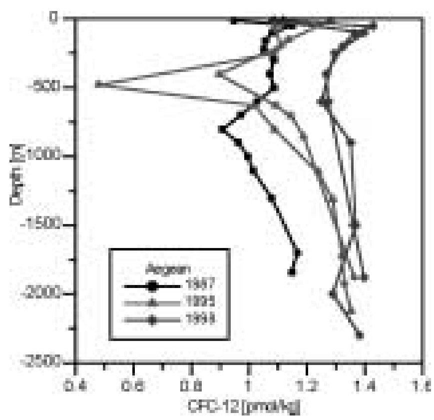

Fig. 6. Evolution of CFC-12 profiles in the Aegean between 1987 and 1998. Station locations near to 35.87 °N , 25.19 °E.

CFC concentrations in the deep layer of the Aegean start from a high level in 1987 (Fig. 6), compared with the atmospheric concentration the saturation exceeds 85% and is higher than in the Adriatic. Continued strong ventilation of the deep layer is documented in the further increase in CFC concentrations in 1995. Except for the layer around 500m where old mid-depth water from the Levantine Basin is intruding into the Aegean, the concentrations are close to the surface equilibrium values. In contrast to the Adriatic the Aegean deep water even continued to receive new input until 1998. In the later stages, the water sinking in the deep Aegean probably did not reach all the way to the bottom and the water column below 1500 m was left behind. Hydrographic surveys in the Aegean do not indicate deep convection, and the water masses ventilating the deep Aegean after 1995, therefore, can not be formed locally. Also remarkable is the strong increase in concentrations above 500m. After the dilution of this layer with old waters and a resulting drop in saturation to 30% in 1995, saturation returned to its pre-EMT value of 80% in 1998. These waters are characterized by salinities in excess of 39.0 and form the new source of intermediate waters observed in the Adriatic.

Acknowledgments

This work was supported by the European Union, grants MAS-3-CT95-0043 and MAS-3-CT96-0051. The *Meteor* cruises were funded by Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg, Germany.

Recent changes in dynamics of the Eastern Mediterranean affecting the water characteristics of the adjacent basins

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Basin-scale hydrological surveys conducted in the Eastern Mediterranean in the 80's and 90's have evidenced the role of the south Aegean Sea as an additional source of dense water, affecting the deep and intermediate thermohaline circulation. Consequently, the hydrological characteristics of the water masses and their distributions have been strongly modified (Roether *et al*., 1996; Klein *et al*., 1999). Furthermore, the upper thermocline circulation is subjected to a seasonal variability, investigated so far by modeling simulations (Roussenov *et al*., 1995) and AVHRR-SST satellite images (Marullo *et al*., 1999). Important long-term fluctuations due to meteorological anomalies, such as changes in the wind stress (Pinardi *et al*., 1997; Samuel *et al*., 1999), can overcome the seasonal cycle.

The building blocks of the circulation in the Eastern Mediterranean have not revealed a steady-state situation. The climatic shift related to the new dense water production has been largely attributed to the increase of salinity. This feature might have been conditioned by the reduced transport of the Modified Atlantic Water (MAW) into the Levantine basin, as well as by other factors mostly related to meteorological events (Theocharis *et al*., 1999a). The return pathways of the LIW from its formation site in the Levantine basin to the west is altered by the presence of permanent or recurrent cyclonic/anticyclonic structures, which were able to recirculate the LIW prevalently in the Levantine basin (Malanotte-Rizzoli *et al*., 1999).

This note presents results from hydrological surveys conducted in 1997-1999, which reveal strong changes in the dynamics, affecting the thermohaline properties in the adjacent seas and in the straits of the Eastern Mediterranean. These changes may be a prelude to a return to the previous situation, and may have an as yet unknown influence on the circulation of the Western Mediterranean basin.

SURFACE LAYER

Large scale hydrographic surveys performed in 1987 and 1991 provided evidence of the scales and dynamics of the horizontal general circulation and its variability (POEM Group, 1992; Malanotte-Rizzoli *et al*., 1999). The Modified Atlantic Water (MAW) enters through the Strait of Sicily and is advected in the Northern Ionian by the meandering Atlantic-Ionian Stream (AIS). The AIS extends into a Northern Ionian anticyclone and branching out to the south rejoins the Mid-Mediterranean Jet (MMJ) that constitutes the major transport of MAW to the Eastern Levantine basin (Malanotte-Rizzoli *et al*., 1999). These structures are in good agreement with the drifter-inferred currents obtained as part of a multi-year program (Poulain, 1998). It seems that the meandering AIS extending in the Northern Ionian anticyclone, which is in contrast with previous observational pictures of the basin general circulation (Ovchinnikov, 1966), was established in 1987 by an anomalous wind stress amplitude reversing the current directions in a major subportion of the basin (Pinardi *et al*., 1997a). The enhanced advection of MAW into the Ionian (S < 38.0), and the corresponding decrease in the Levantine basin, might have contributed to a decrease of salinity in the Ionian and an increase of salinity in the upper ocean in the Levantine basin, making then available salinity in the area where deep convection occurs (Malanotte-Rizzoli *et al*., 1999).

Recent hydrological observations conducted in the Northern Ionian and in the Eastern Levantine with the R/V *Urania* in January 1999 and the R/V *Meteor* in April-May 1999 respectively, have revealed a new picture at present. The meandering current system recomposes itself along a zonal flow pattern at about 35 N, reducing the anticyclonic sense of rotation in the central Ionian and transporting MAW directly into the Eastern Levantine. An overall cyclonic circulation has been established in the Northern Ionian reversing the flow current and transporting into the basin interior highly saline water (S > 38.60) from the eastern basin. Horizontal salinity distributions in the sub-surface layer (the 50 m is the horizon traditionally occupied by the MAW) clearly indicates the presence of more saline water traditionally advected from the Eastern Levantine and a reduced extension of MAW in the Ionian basin (Fig. 1). It seems that the cyclonic regime in the Ionian was installed since March 1998, as observed by direct Eulerian current measurements at the mooring positioned in the Northern Ionian (38.5 N, 18.0 E) within the MAST/MTP II/MATER project.

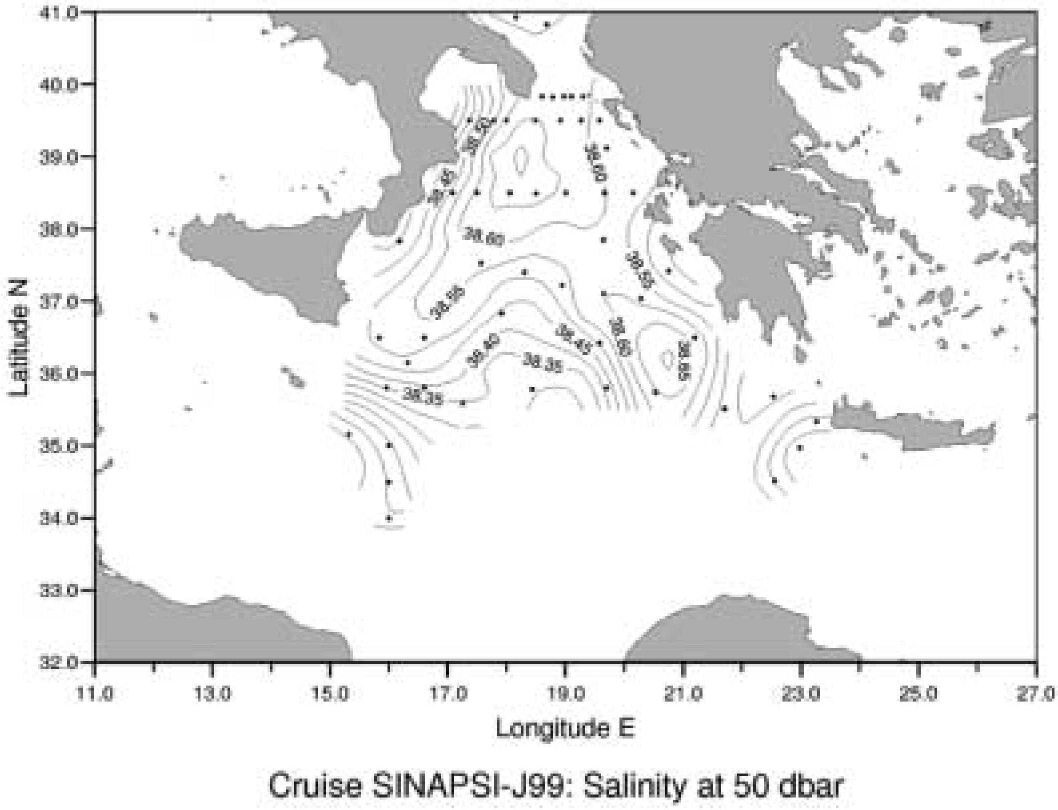

Fig. 1. Horizontal salinity distribution in the sub-surface layer (50 dbar) in January 1999. The dots denote the station positions.

Fig. 2 shows a comparison of salinity distributions along a west-east section through the Eastern Mediterranean in 1995 and in 1999. The upper 0-500 m layer is enhanced in the upper panels. The different penetration of MAW into the Levantine basin is striking. In 1995, the most noticeable feature is the well developed frontal system established in the Eastern Ionian. It makes more separate the circulation in the Ionian Sea from the Levantine basin both in the surface and

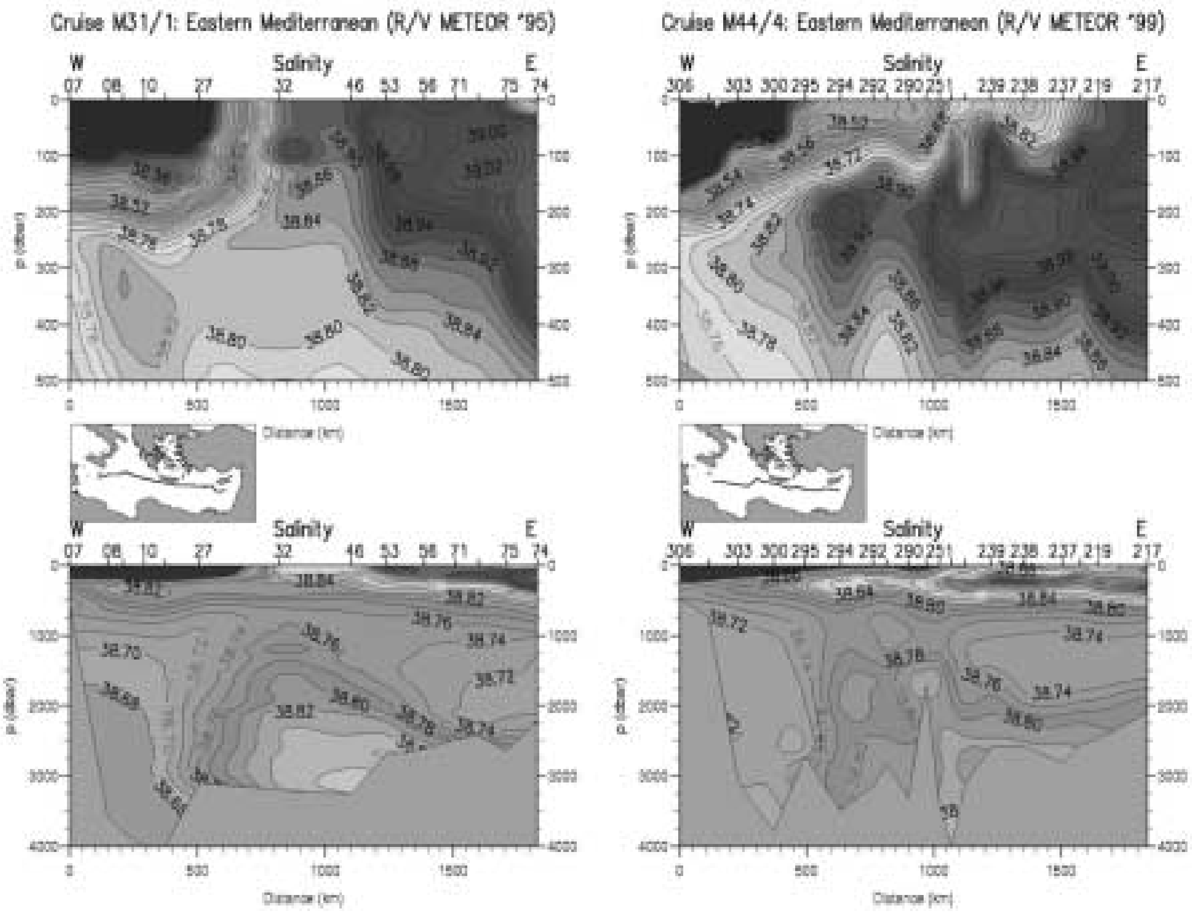

Fig. 2. Vertical distribution of salinity down to 500 dbar (upper panels) and for the whole water column (lower panels) in January 1995 (RV/ *Meteor* cruise M31) and in April-May 1999 (R/V *Meteor* cruise M44) along the west -east

intermediate layers. The MAW is largely accumulated in the Ionian Sea, while in the Levantine basin a very high salinity water dominates the entire water column. The same section occupied in 1999 shows a different situation. The MAW is found to intrude into the Eastern Levantine causing a freshening of the upper layer. In 1995, all the isohalines with S>38.90 are confined in the Levantine basin, while in 1999 they protrude much more westwards leaning from the surface to the intermediate layer, representing mostly the spreading pattern of the LIW.

INTERMEDIATE LAYER

Repeated CTD stations at Otranto Strait have allowed to identify in the intermediate layer a very saline core water (S > 38.95) comparable in terms of its salinity to the LIW in its source region (Ozsoy *et al.*, 1993). It is conceivable to consider a different source region for this high salinity core water. Basin scale observations conducted in January 1999, have definitely clarified that the source of this water is found in the Aegean.

The Cretan Intermediate Water (CIW) formed in the South Aegean, has been noticed in small patches in the vicinity of the Cretan Arc Straits by Schlitzer *et al.* (1991). In 1991, the CIW forms a large tongue in the Ionian outside the western Cretan Straits (Malanotte-Rizzoli *et al.*, 1999). At present, the CIW fills the intermediate layer previously occupied by the LIW with core characteristics θ=15.0-15.5°C, S=39.0-39.1. It spreads prevalently along a northward route on the 29.10 isopycnal and intrudes into the Adriatic Sea (Fig. 3). An important meridional front separates two regions in the Ionian. The CIW which would spill out the Cretan Straits occupies the eastern part. The western Ionian is occupied by less saline water mass probably branching off from the main path of LIW. The salinity increase recently observed in the South Adriatic (Manca *et al.*, 2000) is consistent with the dynamics in the Eastern Ionian Sea.

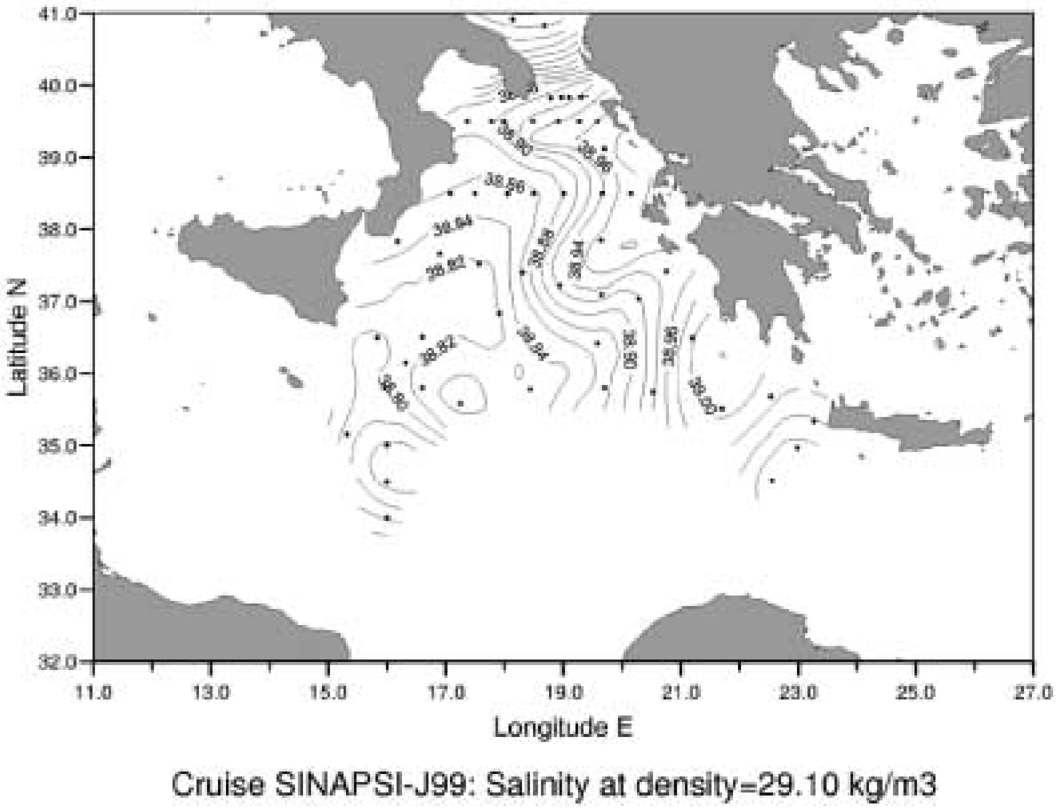

Fig. 3. Salinity distribution on the isopycnal surface 29.10 kg·m-3 in January 1999. The dots denote the station postions.

The above scenario is also supported by the oxygen distribution. The Fig. 4 shows the salinity and oxygen sections along the Greek coast following the spreading pattern of CIW, as shown in Fig. 3. The sections down to 500 dbar, depicted in the upper panels, provide a better view of the advection of salt into the Adriatic. The CIW source is detected by the highly saline core water (S > 39.0) at station T11 located in front of the Cretan Strait. Furthermore, the oxygen distribution renders possible to distinguish two saline core waters in the intermediate layer. The former, more ventilated, is the core water of Aegean origin prevalently northward bound towards the Adriatic Sea; the latter, due to an extended travel time, is "old" and intrudes into the Ionian through the Cretan passage (right end of the oxygen section) following the traditional path from the Levantine basin towards the Sicily Straits.

It is noteworthy to remark that the oxygen minimum layer (< 4.3 ml/l; Fig. 4, lower-right panel), associated with a nutrient maximum, is further elevated to 500 m, instead of the 1000 m observed in 1995 by Klein *et al*., (1999). It is shallow enough to flow into the Adriatic below the CIW. The oxygen minimum layer traced along a similar cross section in 1987, representative of the previous regime, was centered at about 1700 m (Souvermezoglou *et al*., 1992).

BOTTOM LAYER

The salinity distribution in the bottom layer trough the Eastern Mediterranean in 1995 and 1999 (see Fig. 2, lower panels) clearly shows the evolution of the dense water discharge from the Aegean. It is clear that the dense water of Aegean origin has drastically reduced its contribution to the bottom layer. However, the dense water already discharged is laterally advected both eastward in the Levantine basin and westward in the Ionian Sea, influencing the bottom layer as shown by the modification of water properties.

The spreading of Adriatic Deep Water (ADW) into the Ionian constitutes the return path of the Eastern Mediterranean closed deep circulation. The recent observations indicate that the classical picture of the water exchange pattern in the Otranto Strait, as determined during the MAST/MTP1 OTRANTO (1994-1995) and MAST/MTP2 MATER (1997-1999) projects, has not

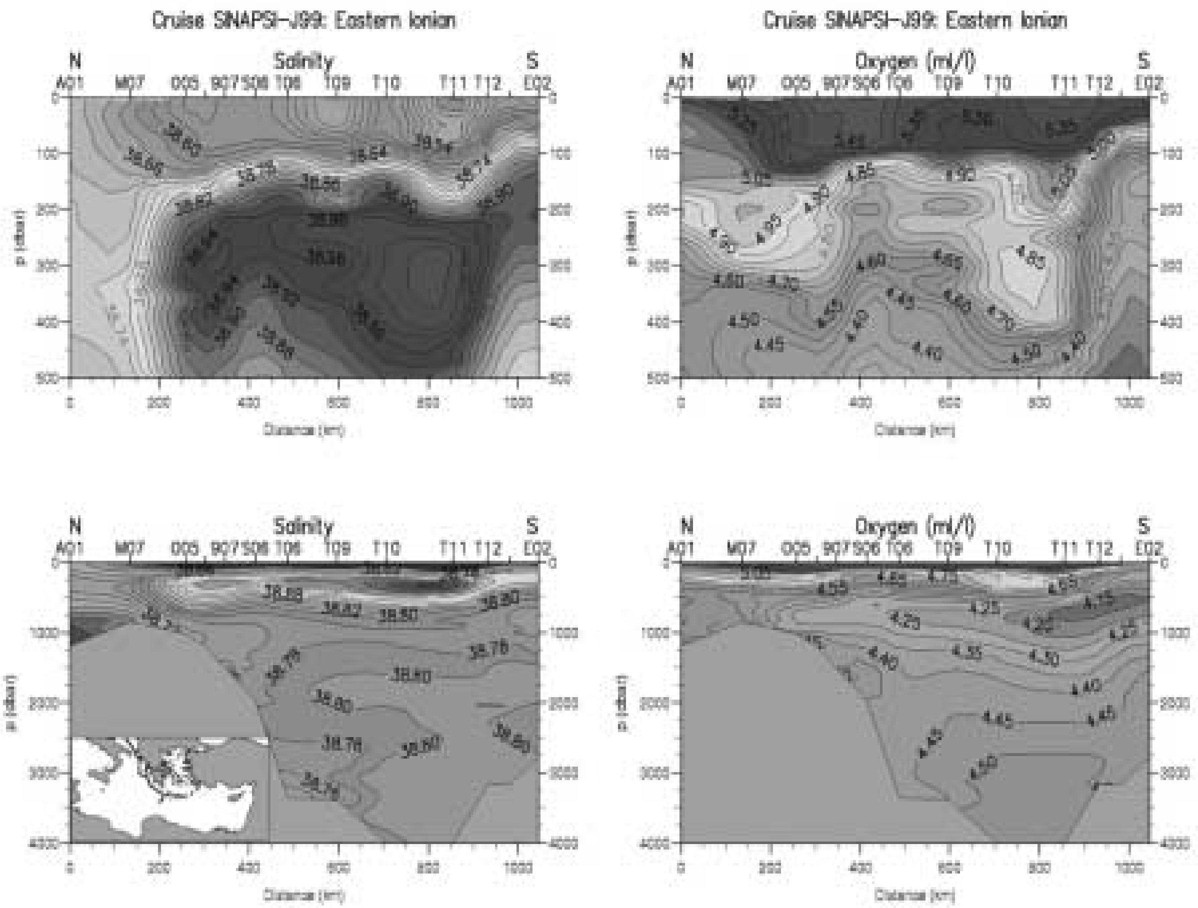

Fig. 4. Vertical sections of salinity and oxygen down to 500 dbar (upper panels) and for the whole water column (lower panels) in January 1999 following the traditional path of the saline core water intrusion into the Adriatic sea.

changed, but less dense waters (σθ ≅ 29.17-29.18 kg·m^{-3}) than those previously observed (σθ ≅ 29.20-29.22 kg·m^{-3}) overflows the Otranto sill into the Ionian. The vertical distributions of salinity and oxygen along the meridional Ionian section (Fig. 4) indicate that water masses with thermohaline properties such as those observed over the sill in the Otranto Strait (i.e. θ ≅ 13.5 °C; S ≅ 38.72; σθ ≅ 29.17 kg·m^{-3}) flow in a transitional layer at a depth of about 1000-1500 m. The bottom layer is occupied by the saltier and more ventilated water mass, identified as Aegean water, which spreads northwards.

CONCLUSIVE REMARKS

The main results of this study concern the modification of advection of MAW and LIW. The MAW, observed prevalently in the Ionian between 1987 and 1995, diverts its pathway and reaches the Levantine basin more abundantly.

The LIW dispersal path in the Ionian is altered and a new highly saline core water from the Aegean flows from the western Cretan Straits and intrudes into the Adriatic Sea. The increase of salinity in the Southern Adriatic may be effective in reiforcing the early leading role of the Adriatic Sea in dense water formation. On the other hand, a reduction of LIW in the Northern Ionian may enhance the traditional path of LIW from the site of origin towards the Straits of Sicily, with possible consequences for the Western Mediterranean.

In the bottom layer, no significant signature of further increase of salinity has been found around the Cretan Arc. The bottom water both in the Western Ionian and in the Eastern Levantine have changed their hydrological characteristics due to the lateral advection of denser Aegean water previously discharged.

Decadal variability of winter rainfall in the Mediterranean region

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The wintertime atmospheric circulation in the European region has experienced significant modifications in the last few decades. Multi-decadal trends are evident in the statistics of both upper-air fields and surface weather parameters. In recent years, most attention has been devoted to the inter-decadal variability of the North-Atlantic Oscillation (NAO), a large-scale anomaly pattern which affects the intensity and extension of the storm-track over the North Atlantic (Barnston and Livezey 1987, Thompson and Wallace 1998). It has been shown that the NAO affects the distribution of surface temperature and rainfall over the whole of Europe *(e.g.* Hurrell 1995); therefore, an observed trend in the amplitude of the NAO index is reflected in long-term variations of wintertime precipitation over the European and Mediterranean region (Valero *et al.,* 1996; Rodó *et al.,* 1997; Ulbrich *et al.,* 1999).

The NAO pattern is the main, but not the only, large-scale circulation pattern affecting the distribution of European rainfall *(e.g.* Wibig, 1999; Pavan *et al.*, 2000). This paper presents the results of a study on the relationship between European/Mediterranean winter rainfall and large-scale anomalies over the northern hemisphere in the period 1979-1995. A standard Principal Component analysis has been performed over the Mediterranean and over a larger European region, based on monthly precipitation anomalies computed from the dataset produced by Xie and Arkin (1996). Large-scale circulation anomalies associated to the leading empirical orthogonal functions (EOFs) of rainfall have been defined by the covariance patterns between the rainfall PCs and monthly-mean anomalies of 500-hPa height from the NCEP analyses.

Looking at the structure of the rainfall EOFs over the Mediterranean and the larger European region, one finds that the main centres of action in the EOFs are very similar for the two regions. Correspondingly, the two sets of PCs are highly correlated with each other, showing that winter rainfall anomalies over the Mediterranean are strongly linked to rainfall anomalies in other parts of the European continent.

The time series of the first two Mediterranean PCs are characterised by significant trends. In particular, the trend in the first PC (significant at the 99% level) implies a change towards drier conditions for most of southern Europe. Similar results for this period were also found in studies using much longer time series, such as those by Hurrel (1995), Mayes (1996), Kutiel *et al.* (1996) and Maheras (1988). The spatial distribution of the winter rainfall trends over Europe has also been computed by least squares estimates from time series at individual grid-points. Such a distribution is very similar to the pattern obtained by superimposing the trends of the first two PCs: the region with negative tendency covers most of Europe, with maxima located over Portugal, north-eastern Italy, the southern Adriatic and the Eastern Mediterranean. Conversely, the western side of Scandinavia exhibits a strong precipitation increase.

The large-scale circulation anomaly associated with the first rainfall PC resembles the negative phase of the North Atlantic Oscillation (NAO), consistent with the similarity between the first EOF of rainfall and the features described by Hurrel (1995). The similarity is confirmed by the correlation index between the first PC and Hurrel's simple NAO index, equal to -0.76.

Also the circulation pattern associated with the second rainfall PC has planetary features. It resembles the Eurasian pattern (EU) described by Wallace and Gutzler (1981), characterised by three main centres of action over Scandinavia, Siberia and Japan. The circulation anomaly corresponding to the third rainfall PC has a more regional nature, and resembles the composite anomaly pattern for European blocking, as described by Tibaldi and Molteni (1990) and Pavan *et al.,* (2000). Consistently with previous investigations, it was found that none of the patterns considered has a substantial correlation with El-Niño SST anomalies.

Variability in the Mediterranean Sea : connection with climatic patterns

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The Mediterranean is a bordering region that feels the dynamics of the circulation of both the mid-latitudes and the Tropics. The seasonal cycle regulates the transition from the winter regime, which is dominated by the mid-latitude westerly flow, although strongly modified by local orography, to the summer regime, when the westerlies weaken and a meridional circulation develops over the eastern basin. This paper summarizes some features of Mediterranean variability correlated with large-scale climatic patterns, and suggests a possible connection with the recent Eastern Mediterranean transient.

In winter (January-March) two major climatic patterns are strongly connected with the Mediterranean region, namely the North Atlantic Oscillation (Hurrell, 1995) and the Arctic Oscillation (Thompson and Wallace, 1998). Although not completely independent of each other, they are basically different, since the North Atlantic Oscillation is related to a regional sea level pressure gradient, while the Arctic Oscillation can be interpreted as the surface signature of the modulation in strength of the polar vortex. Both are correlated with sea level pressure all over the Mediterranean basin on interannual and multi-annual time-scales. In the Mediterranean the correlation between North Atlantic Oscillation and sea level pressure is maximal around Gibraltar ($C \approx 0.8$) and decreases eastwards. The correlation between the Arctic Oscillation and sea level pressure is maximal ($C > 0.85$) over the northernmost portion of the basin and decreases almost radially, remaining very notable ($C > 0.65$) over the whole Mediterranean Sea. Significant anti-correlation ($C \approx -0.5$) is found between the Arctic Oscillation and the meridional wind component over the Aegean Sea and part of the Levantine Basin, meaning that a positive phase of the Arctic Oscillation is connected with stronger northerly winds in those regions. The North Atlantic Oscillation is also found to be correlated with the water transport through the Corsica Channel (Vignudelli *et al.*, 1999).

In summer teleconnections are found between the Mediterranean region and the Indian monsoon and Sahel rainfall regimes on an interannual time-scale (Ward, 1992; Ward, 1996). The sea level pressure over the Eastern Mediterranean is anticorrelated with Indian monsoon, mainly in July-September ($C \approx -0.5$), while in the Western Mediterranean it is positively correlated with maximum in September-November ($C \approx 0.4$). The meridional wind component is anticorrelated with Indian monsoon over the central basin ($C \approx -0.5$) and eastern basin ($C \approx -0.4$). This means that a more active Indian monsoon is connected with lower sea level pressure over the eastern basin and higher over the western, and stronger northerly wind over most of the Mediterranean region. Concerning the teleconnection with Sahel rainfall, anticorrelations are found in July-

September with Eastern Mediterranean sea level pressure (C ≈ -0.4) and Central Mediterranean meridional wind component (C ≈ -0.6). The sea level pressure over the western basin is most correlated in September-November (C ≈ 0.5), suggesting that a more rainy season in the Sahel is likely to be followed by higher sea level pressure over the Western Mediterranean.

The Arctic Oscillation fluctuations might have played a role in the recent changes in the Eastern Mediterranean deep water characteristics observed by Klein *et al.* (1999). The changes, occurred after September 1987 and before January 1995, might be partly related to unusual winter atmospheric conditions observed during that period. Figure 1 shows the time series of Arctic Oscillation index and meridional wind component over the Adriatic and the Aegean Seas. It can be seen that large positive anomalies in the Arctic Oscillation occurred every year from 1989 to 1993 except in 1991, together with stronger than normal northerly winds over the Aegean Sea and prevailingly close to normal over the Adriatic Sea. This might have contributed to the formation of a relatively larger amount of deep waters in the Aegean Sea than in the Adriatic Sea.

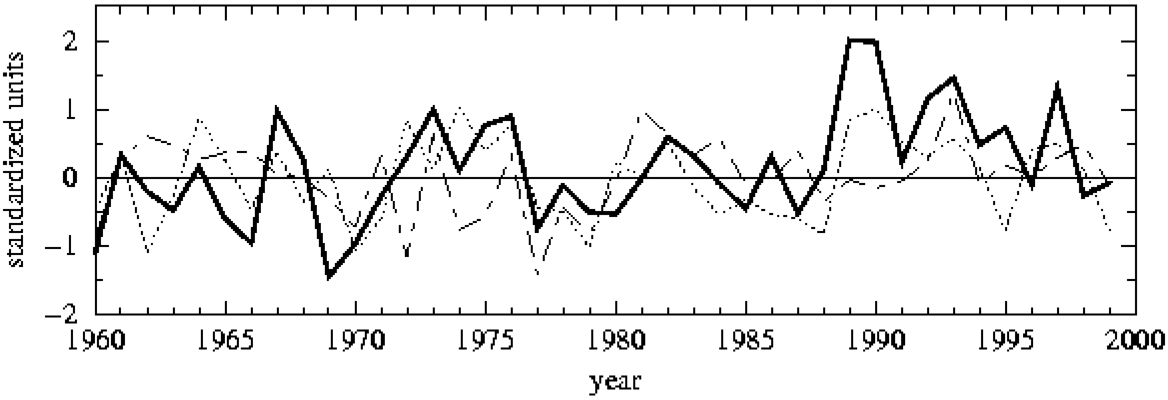

Fig. 1. Comparison between standardized January-March Arctic Oscillation index (solid line) and meridional wind component over the Adriatic Sea (dashed line) and over the Aegean Sea (dotted line). The wind time series are reversed for better visual comparison.

Although the events most directly connected with the Eastern Mediterranean Transient, and particularly the deep water formation, appear to have occurred in the wintertime, a crucial role might have been played by a preconditioning phase. One of the hypotheses on such a phase involves a salinity increase in the Aegean Sea partly due to the combination of high evaporation and low precipitation conditions just before the Transient started, and in fact, during the large positive Arctic Oscillation anomaly, annual precipitation was prevailingly well below normal. This may suggest that the Transient can be an indirect consequence of meteo-marine conditions established during all seasons, including summer.

Times series of biological data in the Adriatic Sea

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Time series of bacterioplankton, phytoplankton and zooplankton abundances, and of primary production are available from samples taken over 20 years by the Institute of Oceanography and Fisheries, Split, in the coastal and open Adriatic Sea (Table 1). Multivariate methods were used for extracting the main patterns of year-to-year changes in abundances (Principal components Analysis), and for discriminating between years and sites (Multidimensional Scaling). They identified increasing long term trends for all studied parameters, at both coastal and open areas, presumably as a result of eutrophication. In the open sea, ingression of Mediterranean water into the Adriatic Sea, and temperature were the dominant factors in controlling year-to-year fluctuations of plankton. On the other hand, long term fluctuations of plankton in the coastal area were chiefly controlled by man-induced factors, in particular the fluctuation of nutrients coming from the land as a result of human activities.

Table 1. Planktonic data sets

parameter		*period*
BACTERIOPLANKTON		**1968-1990**
PHYTOPLANKTON		
	Diatoms	1962-1982
	Dinoflagellates	1962-1982
	Coccolithophorids	1962-1982
PRIMARY PRODUCTION		**1962-1982**
ZOOPLANKTON		
	CopepodaCladocera	1962-1982
	Appendicularia	1962-1982
	Chaetognatha	1962-1982
	Thaliacea	1962-1982
	Medusae/Siphonophora	1962-1982
	Mollusca	1962-1982
	Decapoda	1962-1982
	Polychaeta	1962-1982

Relation to the environment

Table 2 presents the significant correlations between the 20-year fluctuations of different plankton groups (represented by PC1 and PC2 as two main patterns of fluctuation) and several environmental factors.

Table 2. Kendall rank correlation between first two principal components (PC1 and PC2) and environmental factors

	OPEN SEA STATION		COASTAL SEA STATION			
	DWS	ST	PH	P	SS	ST
PC1	0.59^{**}	–	0.46^{*}	0.51^{*}	0.71^{***}	–
PC2	–	0.85^{***}	–	–	–	0.52^{*}

*(DWS : deep water salinity; ST : surface temperature; PH : phosphate concentration; P : precipitation quantity; SS : surface salinity) *P < 0.05; **P < 0.05 ***P < 0.05.*

In the open sea area (about 100 m deep, and 50 km offshore), the dominant pattern of planktonic year-to-year fluctuations (PC1) displayed a good positive correlation with "deep-water" salinity (DWS) (salinity between 75 and 100m depth) (Solic *et al.*, 1997). Common maxima were recorded in 1975 and 1980, and common minima in 1971 and 1977. The relationship between fluctuations of plankton and DWS may presumably be attributed to the ingression of Mediterranean water which is characterized by higher salinity and nutrient concentrations in comparison with the open Adriatic (Buljan, 1953; Zore-Armanda, 1969, 1974).

The relationship between ingression years and increased frequency of "southerly weather type" (characterized by low atmospheric pressure, south-easterly wind and higher precipitation) was also reported (Baranovic *et al.*, 1993). The years 1967-1968 and 1980 were considered to be a period of marked ingression. Increase of salinity and nutrient levels were recorded from the Adriatic (Zore-Armanda *et al.*, 1987), resulting in a maximum phytoplankton population in 1968 (Pucher-Petkovic and Marasovic, 1980) and maximum primary production in 1969 (Pucher-Petkovic *et al.*, 1987). Maximum quantities of sardine eggs were also recorded in 1968/69 and 1969/70 (Karlovac, 1973). The next primary production maximum was reported for the year 1980 (Pucher-Petkovic *et al.*, 1987). Maximal total bacterial counts were found in the same year, as well as maximal bacterioplankton production (Krstulovic *et al.*, 1995). Two pronounced maxima in the 23-year time series of heterotrophic bacteria density were recorded in 1968 and 1980 (Solic and Krstulovic, 1991). The autocovariance function of trend-component free time series data shows that superimposed shorter (2.3 and 3.5 years, respectively) and longer (around 14 years) periods occurred just in these years (Solic and Krstulovic, 1991).

In this connection the phenomenon of mass occurrence of scyphomedusa (Pelagia noctiluca) in the Adriatic, beginning in 1977 and gradually decreasing up to 1986 when it disappeared (Vucetic, 1982, 1983, 1988), is highly important. This phenomenon was preceded by the abnormal presence of high saline water in winter 1976, again indicative of stronger advection of the Mediterranean water into the Adriatic (Vucetic, 1983). "Pelagia years" (1977-1986) coincide in time with the cycle of bacteria, phytoplankton and zooplankton with a peak in 1980 (Solic and Krstulovic, 1991; Baranovic *et al.*, 1993; Solic *et al.*, 1997). The next significant pattern of plankton fluctuations (represented by PC2) was in good correlation with seawater temperature. Common maxima were observed in 1963, 1971/72 and 1977-80 (thus, maximal values of both PC1 and PC2 patterns coincided in 1980), and common minima in 1966, 1975 and 1981/82.

In the coastal area (enclosed, shallow basin, Kastela Bay with an average depth of 23m, and maximal depth of 40m), a significant relationship was found between year-to-year changes in phosphate concentrations, surface salinity, precipitation quantities and PC1 of plankton abundance. A connection between all these environmental factors was evidenced. Kastela Bay receives fresh water from the river Jadro, which carries considerable quantities of nutrients into the bay. Moreover, an agricultural area extends along the northern coast of the bay, while the southern side is bound by the Marjan peninsula covered with a pine forest, so that precipitation waters also transport appreciable amounts of nutrients. Therefore, both higher phosphate concentrations and lower surface salinity were caused by a greater quantity of precipitation. Next in importance was the pattern of plankton fluctuations, which showed a good correlation with seawater temperatures, chiefly controlled in Kastela Bay by local meteorological conditions.

DISTINGUISHING BETWEEN NATURAL AND MAN-INDUCED CHANGES

Long-term fluctuations of plankton in the Adriatic Sea are due to the combined effect of a number of factors. Some of them are part of a natural process, while others are clearly linked to human activities (Table 3).

Table 3. Distinguishing between natural and man-induced changes

Environmental factors	*Patterns*	*Changes*
OPEN SEA		
Eutrophication	Increasing long-term trends	Man-induced
Ingression	PC1 (47% of variability)	Natural
Temperature	PC2 (21% of variability)	Natural
COASTAL SEA		
Eutrophication	Increasing long-term trends	Man-induced
Input of nutrients	PC1 (47% of variability)	Man-induced
Temperature	PC2 (21% of variability)	Natural

Increasing eutrophication was first identified in the coastal area, but extended into the open Adriatic from the late 1970s onward. However, in the open sea natural factors remained most influential in controlling year-to-year fluctuations of plankton. Thus, the water exchange between the Mediterranean and Adriatic seas, as well as seawater temperature, explain the greater part (about 80%) of variability (Solic *et al.*, 1997). On the other hand, long-term fluctuations of plankton in the coastal area were mainly controlled by man-induced factors, notably the fluctuations of nutrients of terrestrial origin (agricultural area, municipal effluents).

Possible causes, origin, evolution and some consequences of the Eastern Mediterranean Transient during the period 1987-1999

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INTRODUCTION

The Eastern Mediterranean, one of the poorly known sea-regions before the 80s, became the object of very intense research since 1985, coordinated by large international/European and national projects. It has been recognized as an ideal basin for studying fundamental oceanic and air-sea interaction processes of global importance (i.e. intermediate and deep water formation). The synthesis of the comprehensive data sets collected during the last 15 years revealed significant information on the hydrography, dynamics and their variability in space and time (POEM group, 1992; Ozsoy *et al.*, 1993; Malanotte-Rizzoli *et al.*, 1997; Theocharis and Kontoyiannis 1999; Balopoulos *et al.*, 1999; Klein *et al.*, 1999). Significant water mass (and salt) exchanges occur at the straits through which the Eastern Mediterranean communicates with the Western Basin (strait of Sicily) and the Black Sea (strait of Dardanelles), as well as the ones connecting the different sub-basins (Otranto strait and Cretan Arc straits) (Astraldi *et al.*, 1999b). Moreover, long term variations of some crucial hydrological parameters, as salt content, stratification, dissolved oxygen content, over large areas of the Basin are attributed to drastic runoff control of major rivers (i.e. the Nile, the Po, etc.) discharging along the coastline of the Eastern Mediterranean (Bethoux *et al.*, 1990).

THE THERMOHALINE CIRCULATION OF THE EASTERN MEDITERRANEAN AND ITS RECENT CHANGES

The Adriatic has been historically considered as the main contributor to the deep and bottom waters of the entire eastern Basin, thus driving the internal cell of the deep Eastern Mediterranean circulation. Until the late 80s, the horizontally homogeneous deep temperature and salinity values have indicated an almost perfectly repeating cycle in both water mass characteristics and formation rates. However, the Aegean has also been reported as a possible secondary, but sporadic, source of dense waters, lower intermediate and/or deep (Nielsen, 1912; Miller, 1963; Schlitzer *et al.*, 1991) that affected only the adjacent to the Cretan Arc Eastern Mediterranean region. Moreover, the Levantine Intermediate Water (LIW), the warm and saline water mass that is exclusively produced in the Levantine Basin, is one of the components of the external thermohaline cell and the main contributor of the Mediterranean outflow into the Atlantic. From 1991 onwards, research revealed the most important changes in the thermohaline circulation and water properties basin-wide ever detected since the existence of observations in the Basin (Nielsen, 1912). A shift in the formation site of the deep and bottom waters from the Adriatic to the Aegean Sea occurred (Theocharis *et al.*, 1992; Roether *et al.*, 1996; Malanotte-Rizzoli *et al.*,1999; Theocharis *et al.*, 1999a, Lascaratos *et al.*, 1999). Much denser than the previously existing deep eastern Mediterranean water mass, namely the Cretan Deep Water (CDW), has been produced by the new source; in the same time a new "intermediate type" water mass, namely the Cretan Intermediate Water (CIW) was produced in the south Aegean. These changes have altered the deep (internal/closed) and upper (external/open) conveyor belts of the Eastern Mediterranean respectively. This abrupt shift in the Mediterranean "ocean climate" has been named the Eastern Mediterranean Transient (EMT). Several hypotheses have been proposed concerning possible causes of this unique thermohaline event, such as (i) internal redistribution of salt (Klein *et al.*, 1999), (ii) changes in the local atmospheric forcing combined with long term salinity change (Theocharis *et al.*, 1999a), (iii) changes in circulation patterns (Malanotte-Rizzoli *et al.*, 1999) and (iv) variations in fresh water inputs (Black Sea outflow, Atlantic Water inflow). Regardless the percentage of contribution of each of the above proposed scenarios, there is still lack of a consistent and quantified theory of the EMT.

THE ORIGIN AND EVOLUTION OF THE THERMOHALINE CHANGES

In winter 1987, there was observational evidence that in the Kiklades Plateau of the south Aegean started the production of denser than the usual local deep water (σ_θ>29.2 kg/m^3). In the following years, a combination of continuous important salinity increase (1987-92) and significant temperature drop (1992-94) caused massive dense water formation and strong outflow through the Cretan Arc Straits towards the Ionian and Levantine basins. The density of this water reached the maximum value 29.4 kg/m^3 in the Cretan Sea during 1994-95 (Theocharis *et al.*, 1999b). Interestingly, the peak of the production rate, about 3 Sv, occurred in 1991-92 (Theocharis *et al.*, 1999c) when the 29.2 isopycnal raised up to the surface layer. During the same winter an almost complete overturning of the water column occurred in the proper Cretan Sea. The evolution of both deep-water characteristics and meteorological conditions outlines that during the two distinct periods, 1988-92 and 1992-94, two different forcing factors acted. The first phase is salinity driven. The overall salinity increase in the Cretan Sea was about 0.1 psu due to a persistent period of reduced precipitation over the Aegean and the eastern Mediterranean. This meteorological event might be attributed to larger scale atmospheric variability as the North Atlantic Oscillation (Hurrell, 1995). Moreover, the net upper layer (0-200m) salt transport into the Aegean from the Levantine was increased one to four times within the period 1987-94 not only due to the dry period but also to significant changes of the characteristic water mass pathways. In particular, the LIW was blocked in its traditional westward route by a strong multilobe anticyclonic structure that induces its recirculation in the Levantine Basin itself. As a result the LIW became more saline. This was a secondary source of salt for the south Aegean that has further preconditioned dense water formation. The second period is characterized by cooling of the deep waters by about 0.35° C, related to the exceptionally cold winters of 1992 and 1993. Thus, the Aegean became an effective source of deep waters, since within the period 1989-1995 its overall production was estimated more than 7 Sv (Roether *et al.*, 1996; Theocharis *et al.*, 1999a), which is three times higher than that of the Adriatic (Roether and Schlitzer, 1991). The new Aegean-origin deep water of the eastern Mediterranean is warmer (by about 0.2-0.5°C) and more saline (by about 0.18 psu) compared to the old EMDW of Adriatic origin.

A general circulation ocean model of the area, forced with ECMWF re-analysis data for the period 1979-1994 (Lascaratos *et al.*, 1999) quite successfully reproduced the event and confirmed the existence of the two distinct phases mentioned above with the salt preconditioning being the main driving force in the first, and the extreme cooling during the 1992 and 1993 winters being the main driving force for the second. Experiments conducted without the inclusion of the observed reduction in precipitation over the area, resulted in the production of very small amounts (0.1-0.2 Sv) of CDW during the first period (1988-1991) while during the second period (1992-1994), the formation rate increased to 0.3-0.8 Sv. Still, nevertheless, these values are almost half of those obtained by the model when the reduced precipitation signal was included

(0.8-1.2 Sv). We consider those results of Lascaratos *et al.*, 1999 as a clear indication of the importance of the salt preconditioning in triggering the whole event.

The period 1995-98 is characterized by continuous decrease of CDW production, from 1 to 0.3 Sv. The level of the CDW remained almost unchanged in the last three years within the south Aegean Sea and is found approximately at 600m. The deep outflow has also been weakened, especially from the western Cretan Straits. Interestingly, there is observational evidence that the waters formed in the south Aegean in the recent years have intermediate characteristics (warmer thus less dense, σ_θ~29.05-29.10 kg/m^3) due to mild winter meteorological conditions. Thus, the Aegean continuous to contribute with the CIW to the intermediate layers of the eastern Mediterranean. However, there is a differentiation of the Aegean contribution in the deep layers. The recent (1998-99) hydrological structure in the Cretan Passage and the eastern Ionian reveals that on top of the known very dense deep and bottom waters of Aegean origin (σ_θ>29.2 kg/m^3) there appear slightly less dense waters (σ_θ<29.2 kg/m^3) (Fig. 1). These warm, saline and well-oxygenated waters are considered the new Aegean contribution to the layers 1500-2000m of the eastern Mediterranean. It seems that this new outflow type comes from the upper layer of the still existing CDW in the Cretan Sea, as its level has been lowered down to almost the sill depths at the straits' areas. This CDW layer probably was enriched in recent years with some newly formed waters, as the slightly higher oxygen shows. It is worth noting that this outflow is more pronounced in the eastern straits, forms a distinct layer and spreads westwards.

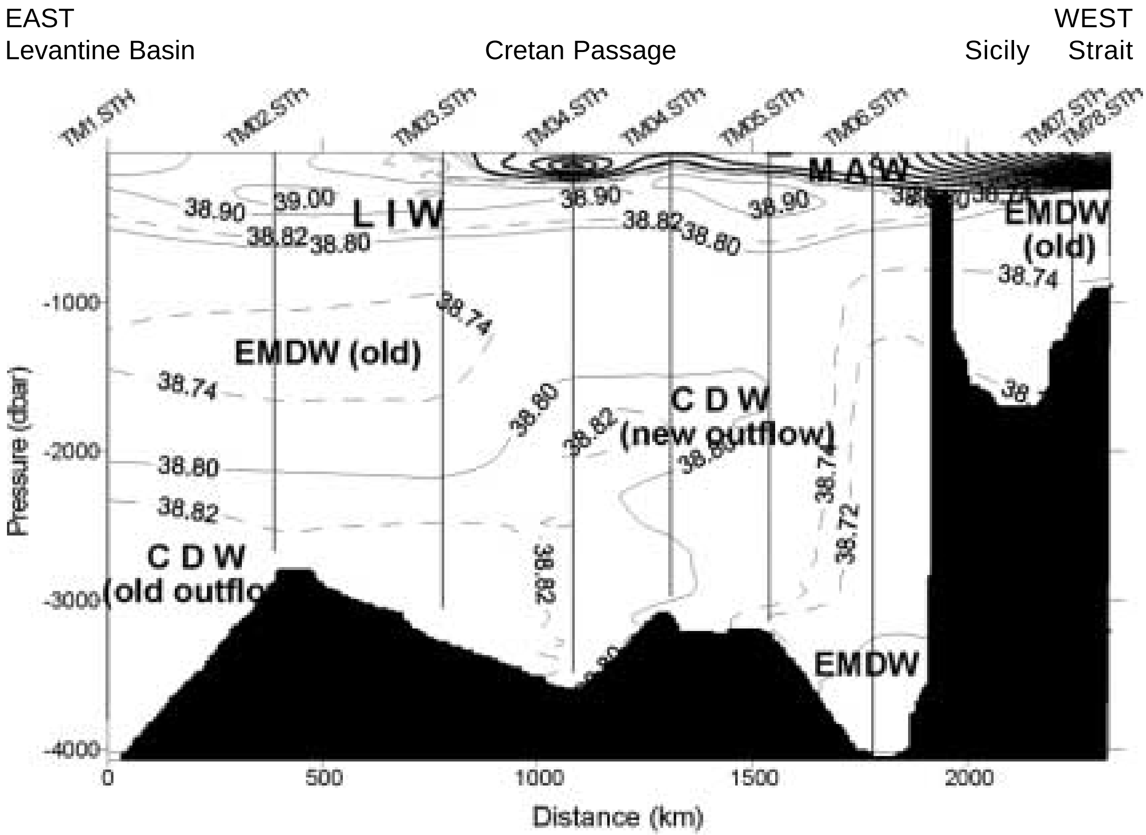

Fig. 1. Salinity E-W section in the Eastern Mediterranean. June 1999.

CONSEQUENCES AND FUTURE EVOLUTION OF THE EMT.

The spreading of the CDW has initiated a series of modifications not only in the hydrology and the dynamics of the entire basin but also in the chemical structure and some biological parameters of the ecosystem (Weikert, 1996; Souvermezoglou and Krassakopoulou, 1999). The dense enough newly formed (high oxygenated) CDW, has filled the deep and bottom parts of the eastern Mediterranean replacing the old EMDW of Adriatic origin, which has been uplifted several hundred meters. This process brought the poor in oxygen-rich in nutrients waters closer to the euphotic zone, especially in the vicinity of the Cretan Arc (E. Ionian, Cretan Passage and NW Levantine). Thus, the nutrients became potentially more readily available to the ecosystem, so that changes in primary and secondary production have already been reported. After 1992, the deep Cretan outflow started to be compensated by the intrusion into the south Aegean at mid-depths of old eastern Mediterranean waters that occupied outside the Aegean the layers between the LIW and EMDW (transitional, 500-1200m) and are found shallow enough in the vicinity of the Cretan Straits. These waters formed gradually a distinct intermediate layer (150-500m) in the south Aegean characterized by temperature, salinity and oxygen minima and nutrients maximum (Theocharis *et al.*, 1999b; Souvermezoglou *et al.*, 1999). This has enhanced the previously weak stratification and enriched considerably with nutrients one of the most oligotrophic sea world-wide. This new structure prevents winter convection deeper than 300m.

The changes of the Aegean contribution, after 1989, to the below-LIW horizons, caused among others a dilution of the LIW. Thus, a reduced advection of salt into the Adriatic occurred between 1987-95 due to the intrusion of this “diluted LIW” and the even less saline “old mid-depth waters”. This modification has a direct effect on the formation processes of the southern Adriatic (Klein *et al.*, 1999). On the other hand, in addition to the CDW there is also the CIW that outflows since 1991 from the Cretan Straits at intermediate layers (200-500m), the so-called LIW horizons. Then, spreading out mostly in the Ionian interior it replaces the LIW and reaches the Adriatic and Sicily areas (Malanotte-Rizzoli *et al.*, 1999). These changes in the intermediate layers have also influenced the adjacent Adriatic Sea (Manca, personal communication) and the Western Mediterranean Basin (Sparnocchia *et al.*, 1999).

The spatial homogeneity and time invariance of the EMDW properties for almost 100 years is well documented. On the other hand, the re-analysis of the available historical data (MEDATLAS database) in the area of the south Aegean since 1946 shows that during the last 50 years, waters with density around σ_θ 29.2 kg/m^3 were formed at least twice; the first in 1959-65 when the 29.2 isopycnal was raised up to 700m depth and the second in 1970-73 when this isopycnal reached 600-1000m depth. In both cases the deep-water salinity was about 39.0 psu, much lower than that of the present case 39.08 psu. These are indications of the likely inter-decadal time scale of such hydrological variations in the south Aegean. The intensity of the present event is justified by the combined effect of the extended dry period followed by the exceptionally cold winters that caused important anomalies in heat fluxes and fresh water budgets. Furthermore, the long-term salinity increase may have intensified the effect of atmospheric forcing.

Important issues can be addressed concerning further evolution of the EMT and its impact on the Western Mediterranean and the adjacent ocean. The simultaneous changes in both the upper and deep conveyor belts of the eastern Mediterranean may affect in many ways the processes and the water characteristics of the neighboring seas. The evolution of the production along with the outflow rates of the CDW outline the integration of the EMT cycle concerning its origin. However, the contribution of the Aegean to the intermediate and deep layers is still active. The variability in the intermediate waters can alter the preconditioning of dense water formation in the Adriatic as well as in the western Mediterranean. On the other hand, the changes in the deep waters can affect the LIW formation characteristics. Whether the present thermohaline regime is expected to return to its previous state in a period of time or to arrive to a new equilibrium through the series of states, evolving as a chain reaction that influences the various regions is still an open question.

Interdisciplinary observations from moorings and autonomous underwater vehicles: recent advances and a look toward the future

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Observations based on developments in instrumentation and supporting technologies have led to a majority of the discoveries and advances in ocean sciences (*e.g.* Dickey, 1991, 2000). A grand challenge of oceanography is to massively increase the variety and quantity of ocean measurements. Ocean measurements are expensive, but vital for effective stewardship, preservation, and utilization of the oceans and atmosphere. Many innovative technologies involving computing, robotics, communications, space exploration, and physical, chemical, biomolecular, and biomedical research are being developed at unprecedented rates for a plethora of applications. Many of these technologies will be most beneficial for oceanography. It should be emphasized that virtually all important environmental problems require interdisciplinary approaches and necessarily atmospheric, physical, chemical, biological, optical, and geological data sets. Ideally, the requisite data should be collected simultaneously (concept of synopticity) and span time and space scales to observe the relevant processes of interest. For global problems, this means that variability extending well over ten orders of magnitude in space, and much longer in time (for climate problems) is encompassed (*e.g.* Dickey, 1991, 2000). Present capabilities for obtaining needed atmospheric and physical oceanographic data are relatively well advanced in contrast to those for chemical, biological, optical, acoustical, and geological data. This is not surprising, considering the greater complexity and non-conservative nature of the chemistry and biology of the oceans. Nonetheless, remarkable advances are being made in these areas as well. In fact, several bio-optical, chemical, geological, and acoustical variables can now be made on the same time and space scales as physical variables; however many more are needed.

Detection limits, precision, and accuracy of ocean measurements are important. However, the oceans are naturally dynamic with large amplitude periodic and episodic variability, which is especially confounding for quantifying long-term trends and changes. Presently, limited numbers of variables can be directly measured in the marine environment, so it is important to carefully select those which are the most critical. Because of the paucity of data, interdisciplinary numerical models capable of synthesizing observations and predicting variability over broad time and space scales will be needed.

A MULTI-PLATFORM, INTERDISCIPLINARY APPROACH

Interdisciplinary sensor suites are critical for studying problems such as carbon cycling and variability, the role of biology in upper ocean heating, phytoplankton productivity, upper ocean ecology, population dynamics, and sediment resuspension. Many of the new sensors are relatively small and have modest power requirements. Thus, the deployment of an increasing number of these sensors from autonomous platforms is becoming practical (*e.g.* Dickey, 1991; 2000). Several major interdisciplinary oceanographic programs have adopted multi-platform approaches. These programs have utilized mooring arrays, drifters, voluntary observing ships (VOS), and satellite data. The Global Ocean Observing System (GOOS) will also follow this approach, allowing studies of El No-Southern Oscillation (ENSO) and interdecadal phenomena such as the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO), and others. Nesting of platforms can optimize utilization of these observational assets. Further, numerical modeling is central to these collective programs. Many of the societally important oceanographic problems, like their atmospheric counterparts, require forecasting and rapid information dissemination to decision-makers and the public. Thus, two important aspects are near real-time data telemetry and data assimilation modeling.

Below, brief summaries of present capabilities and future directions using two classes of platforms are presented.

MOORINGS AND BOTTOM TRIPODS

Present capabilities

Interdisciplinary moored and bottom tripod measurement systems and sensors are being used by the research community to study environmental changes in the ocean on time scales from minutes to years. An increasing number of bio-optical, chemical, geological and acoustical parameters are being measured from moorings. This work has led to discoveries of new processes such as primary production variability associated with ENSO and equatorial long waves, sediment resuspension through internal solitary waves, cloud-induced and diel fluctuations in phytoplankton biomass, phytoplankton blooms associated with incipient seasonal stratification, and frontal- and eddy-trapped inertial waves (*e.g.* Dickey *et al.*, 1998, 2000; Dickey and Falkowski, 2000). Measurements of nitrate, partial pressure of carbon dioxide (pCO2), and dissolved oxygen (DO) have enabled new insights into primary and new production and gas exchange across the air-sea interface (Tokar and Dickey, 2000). Interestingly, several diverse and often adverse oceanic regions have been studied using interdisciplinary moored systems. These range from the equatorial Pacific to high latitude areas south of Iceland and in the Southern Ocean. Moorings and bottom tripods have been used in both open ocean and coastal settings. Because of biofouling of sensors, useful data from moorings has often been limited to a few months in the open ocean and less in coastal waters; however, work is underway to mitigate this problem. Moored systems have proven their value in the research realm and need to be deployed in critical regions for studies of seasonal through decadal variability and longer term monitoring purposes.

Benthic processes may be studied and monitored using instrumentation deployed on bottom tripods. Bottom tripods and their instrumentation may be placed in virtually the same environments as moorings and essentially the same suite of sensors and samplers deployable from moorings can be used on bottom tripods. The chemical species and geological parameters of interest will vary depending on the type of environment (*e.g.* harbor, coastal, or open ocean).

Offshore platforms, including dedicated and oil production platforms, provide unique opportunities for conducting oceanic and meteorological research and monitoring. These often large and very stable platforms typically have space and facilities for manned research laboratories and are equipped with adequate power and other needed services making them ideal for oceanographic observations. They offer several advantages over shipboard platforms, including absolute stability in high sea states, suitability for time series measurements, and capability for housing personnel. It should be possible to launch autonomous underwater vehicles (AUVs) and other mobile sampling devices from these platforms for spatial sampling as well. Active platforms would not be preferable for all types of measurements because of possible chemical contamination and non-representative biology that may result from drilling operations.

Looking forward

Time series observations in the coastal ocean and at selected sites of expected high environmental consequence (*e.g.* equatorial Pacific, high latitude sites of water formation and/or CO2 uptake) or special long-term monitoring value (*e.g.* oligotrophic areas of the gyres of the Pacific and Atlantic Oceans, the Arctic region, the Southern Ocean, and near Antarctica) will require the aforementioned platforms (*e.g.* see Griffiths *et al.*, 1999). Optimal selection of locations will be essential because of costs and return of investment. Increased multi-use of platforms for interdisciplinary sensors and systems is imperative. For example, a mooring designed for a tsunami warning system has been used in the Pacific for measuring upper ocean parameters relevant to global climate change. There is also a need for essentially expendable moorings, which can be deployed in remote areas, which require excessive shiptime for recovery, and for special observational programs (*e.g.* in paths and wakes of hurricanes and typhoons and in harmful algal blooms).

Novel uses of the platforms will evolve (*e.g.* Griffiths *et al.*, 1999; Dickey, 2000)). For example, moored profilers – *e.g.* buoyancy or mechanically (*e.g.* traction-drive) driven for the open ocean; wave-driven in the coastal zone – have been and can be used to good advantage for situations requiring high vertical as well as temporal resolution data (*e.g.* including temperature, salinity, current, and bio-optical variables). This mode of sampling can be preferable to gliders used in "virtual mooring" mode (described in detail below) for high current regimes and where surfacing (*e.g.* under ice) is not possible. In addition, moored profilers have the advantage of measuring absolute velocity whereas virtual mooring gliders require additional position data to reference their relative velocity measurements. A variant of moored profilers is the "pop-up" system, which could be deployed as an expendable system with a telemetry module.

AUTONOMOUS VEHICLES

Present capabilities

New technologies have enabled the development of AUVs and three related types of unmanned oceanographic vehicles: untethered underwater vehicles (UUVs), autonomous surface vehicles (ASVs), and gliders (*e.g.* Griffiths *et al.*, 1999; Dickey, 2000). These can be roughly described as robotic platforms designed to execute functions normally performed by ships, submarines, and divers. AUVs and UUVs are designed for a diverse set of activities in coastal or open ocean waters and can carry sensor payloads for specific applications. They generally vary in size from about a meter in length to over 10 m and utilize battery or fuel cell propulsion. AUVs are pre-programmed to perform sampling along specified track lines, to dock for downloading of data and recharging of batteries or fuel cells, and to key on specific oceanic cues (*e.g.* adaptive sampling based on temperature and chemical gradients). ASVs operate similarly to AUVs, but are restricted to surface operations.

Novel autonomous sampling platforms called gliders are the newest class of platforms being tested. Gliders have design elements and attributes of both profiling floats and AUVs. Gliders use buoyancy control to move vertically through the water columns, but utilize wings and hydrodynamic shape to produce horizontal motion. They are intended to perform with two sampling options: 1) performing long transects (*e.g.* up to 10,000 km) in sawtooth pattern (down to 2000m) and 2) as "virtual moorings" executing vertical profiles at fixed location. In both cases, sampling strategies could be modified (adaptive sampling) and the gliders could be remotely commanded to sample new sections or selected sites.

Looking forward

At present, several specialized groups are developing and using autonomous vehicles and the numbers are expected to grow as mission length capabilities increase, costs decline, reliability improves, operation becomes more routine, and more sensors become available for various sampling needs. It is likely that major breakthroughs in fuel cell technologies (allowing longer missions in space and time), improved navigation and telemetry (via acoustic and satellite links) capabilities, and miniaturization of sensors will facilitate and accelerate widespread use of these platforms. It is anticipated that creative uses of the vehicles will involve networking and informational feedback loops to guide sampling programs (in some areas involving predictive models) and responses to extreme natural and anthropogenic driven events.

Modelling studies of the Eastern Mediterranean thermohaline changes

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The paper of Wu *et al.* (2000) has demonstrated that it is possible to simulate the production of salinity, temperature and tracer distributions in the Eastern Mediterranean which are strikingly similar to the early results obtained by the 1995 *Meteor* cruise (Klein *et al.*, 1999). The model used by Wu *et al.* has high resolution 1/8 by 41 vertical levels and covers the whole Mediterranean. Since this work was submitted several improvements to the model simulations have been added, including better representations of bathymetry and the CFC12 distribution (Stratford and Haines, 2000), and these new results were shown at the workshop.

Figures 1a-c shows temperature, salinity and CFC12 cross sections, and Figures 1d-f show the corresponding bottom water properties, in the Eastern Mediterranean south of Crete for the time period corresponding to *Meteor* cruise M5 in 1987. Figures 2a-f show the corresponding plots in 1995 corresponding to M31 data. The dates are determined by the CFC12 surface boundary conditions. The model simulation was based on the premise that the new deep waters are known to have been produced in the Aegean sea and that the proximate cause of deep water production is through winter cooling. The model was forced with a seasonal cycle of winds, and with surface temperature and salinity relaxed to climatological monthly values (salinity more weakly so). The model was forced initially for 37 years using surface T,S taken essentially from the MODB MED5 climatology. The final 17 years of this run includes a CFC12 tracer with concentrations representative of the years 1970-1987. Analysis of the water properties at this time (Fig. 1) show that all eastern deep water is forming in the Adriatic Sea, consistent with the observations of *Meteor* cruise M5 in 1987. Thereafter an additional winter cooling was added to the Aegean Sea only, corresponding to an additional surface temperature drop of 1-2C. No other pre-conditioning of any kind was added. The model run was continued for a further 8 years with evolving surface CFC12 conditions, to produce the 1995 results in Fig. 2.

One of the wider consequences of the new Aegean deep water is the uplift of the old intermediate water masses in the eastern basin which is most clearly seen in the salinity cross sections. Figure 2b shows a thinner and more depleted LIW salinity maximum, which has been lifted up compared to the distribution in Fig. 1b as the new Aegean water spreads out below. There are also impacts on the Adriatic deep water production which

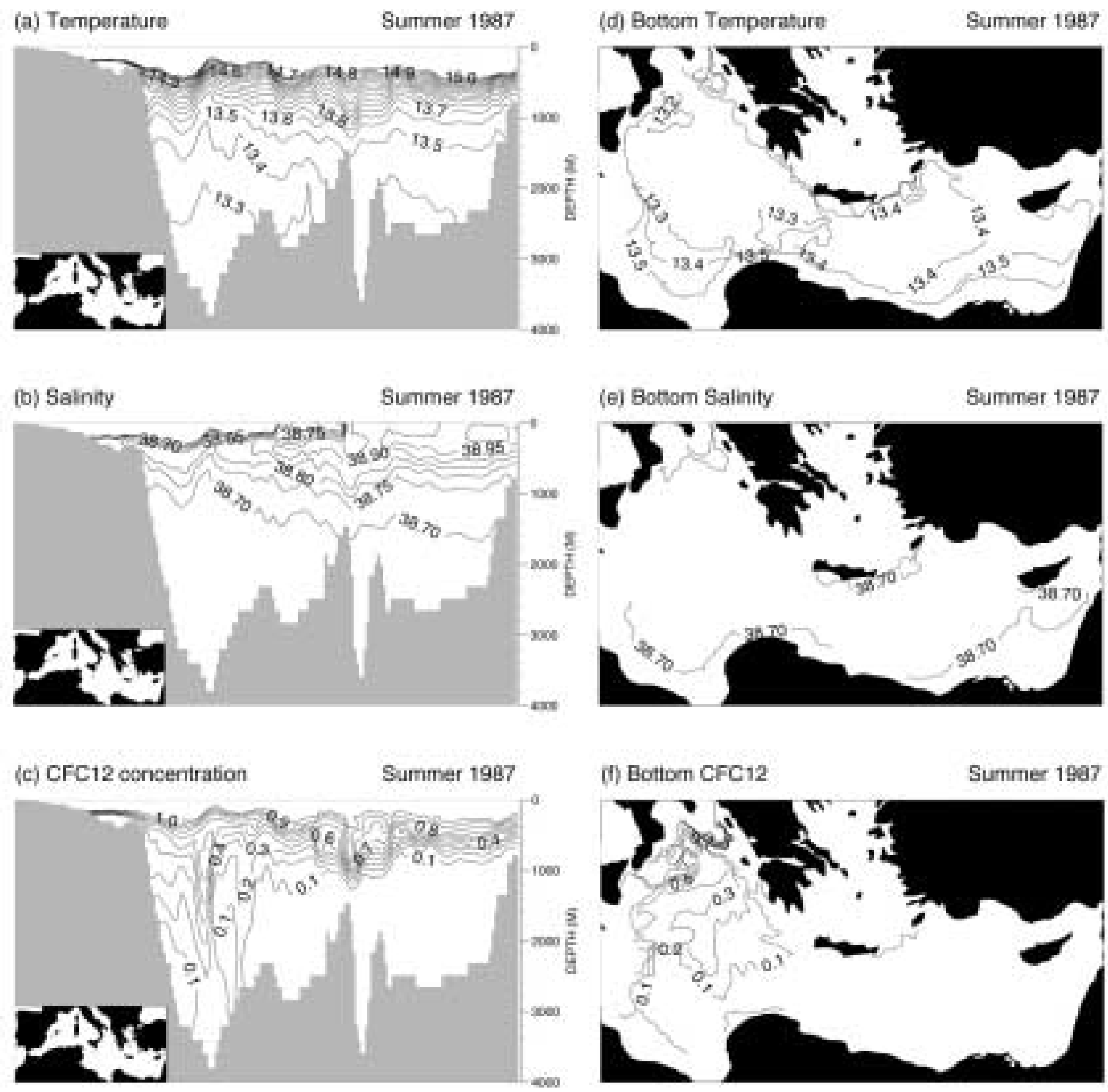

Fig 1. Modelled potential temperature (°C), salinity (psu) and CFC12 concentrations (nmol m^{-3}) for July 1987. The contour intervals are 0.1°C, 0.05 psu and 0.1 nmol m^{-3} respectively.

is greatly curtailed as the Aegean water formation takes over, due to the diversion of intermediate waters into the Aegean sea. These changes in water spreading pathways are described in detail in Wu *et al.* (2000). We are currently investigating the deep water pathways with an improved bathymetry data set and figure 3 shows a preliminary cross section of these results.

The results shown in Figs. 1 and 2 are quantitatively similar in many respects to those shown by Klein *et al.* (1999). However due to the fact that this model is forced by relaxing the surface properties, it is not easy to make an immediate deduction about the buoyancy fluxes causing the change. Therefore we performed careful air-sea flux and basin budget analyses of this model run. The air-sea heat loss over the Eastern Mediterranean increased on average from 5.3 Wm{-2} to 7.7Wm{-2} in the years with additional cooling. The net E-P over the eastern Mediterranean also increased from 61.3 cmyr{-1} to 67.9 cmyr{-1} during the cold years. Thus the increase in net evaporation does contribute to the higher salinity of the final state but the evaporation change is relatively small. If we compare the vertical distribution of salinity in the eastern Mediterranean before and after the extra cooling was applied we find that about 75% of the salt increase below the

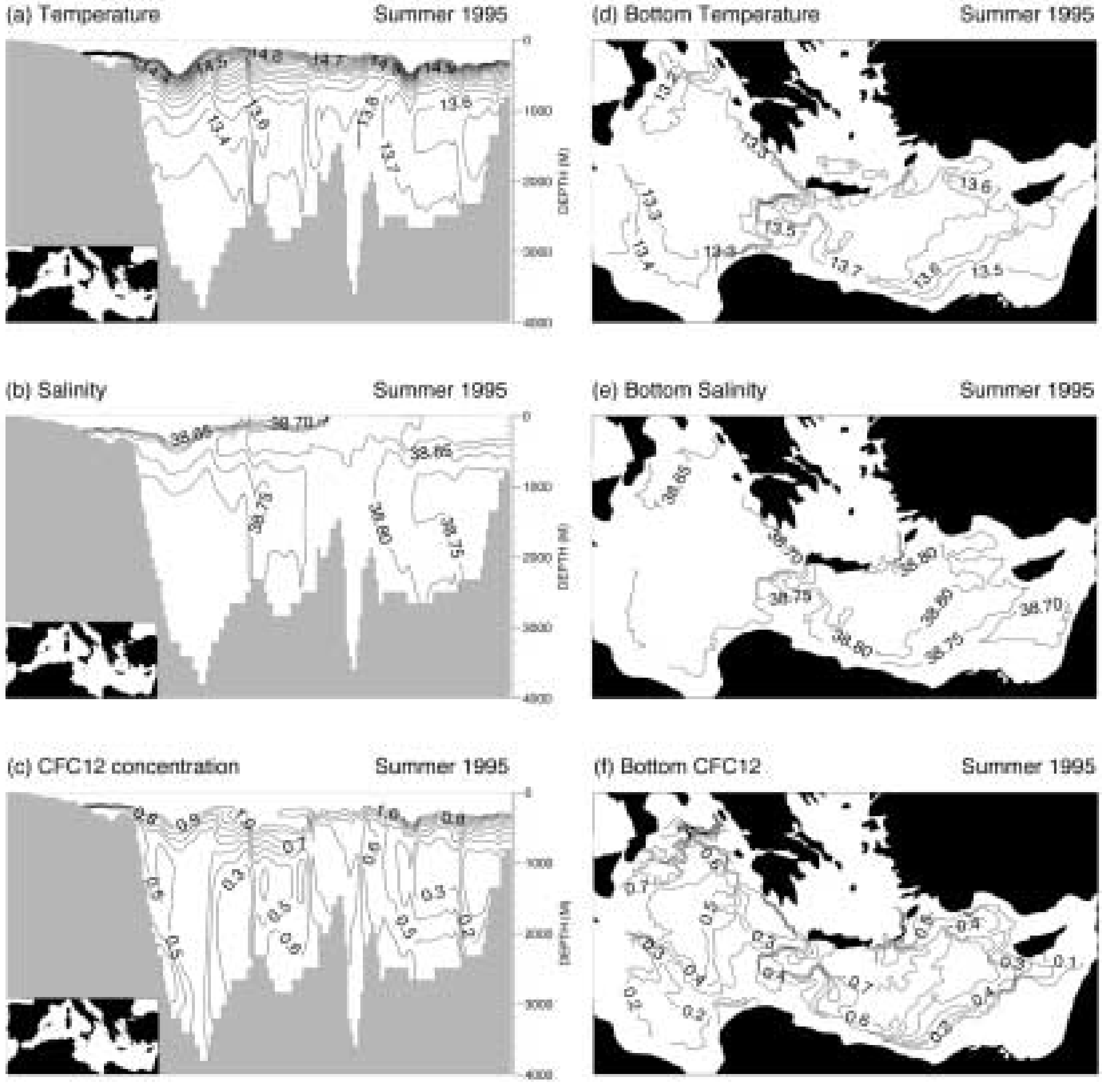

Fig 2. Modelled potential temperature (°C), salinity (psu) and CFC12 concentrations (nmol m^{-3}) for July 1995. The contour intervals are 0.1°C, 0.05 psu and 0.1 nmo ml^{-3} respectively.

1000m level is the result of salinity redistribution from the layer above 1000m. In this model the other 25% of the salinity increase comes from salt added at the sea surface, however we interpret this as meaning that 25% of the extra salinity is actually advected in from the western basin.

The latest observational analyses also suggest a role for Sicily exchange in changing the salt budget for the Eastern Mediterranean. We have therefore considered the problem of salt accumulation in the eastern Mediterranean from the point of view of a box model. It is easy to show that a relatively small increase in E-P over the basin and/or a small decrease in the rate of water formation can lead to quite a large rate of salt accumulation without any change to the salinity of the inflowing waters. Consider for example an initial 2 psu difference between the inflow and outflow waters and a 1 Sv exchange rate, with the basin in salt balance. Then if the E-P is increased by 10% with no other changes the salt accumulation rate can be shown to be 6.3 x 10^12 kg/yr. A 10% decrease in water formation rate to produce a smaller volume of higher salinity waters from the same E-P can lead to the same salt accumulation rate. Such a change in water formation rate could be triggered in a number of ways including, changes in wind patterns, Samuels *et al.*

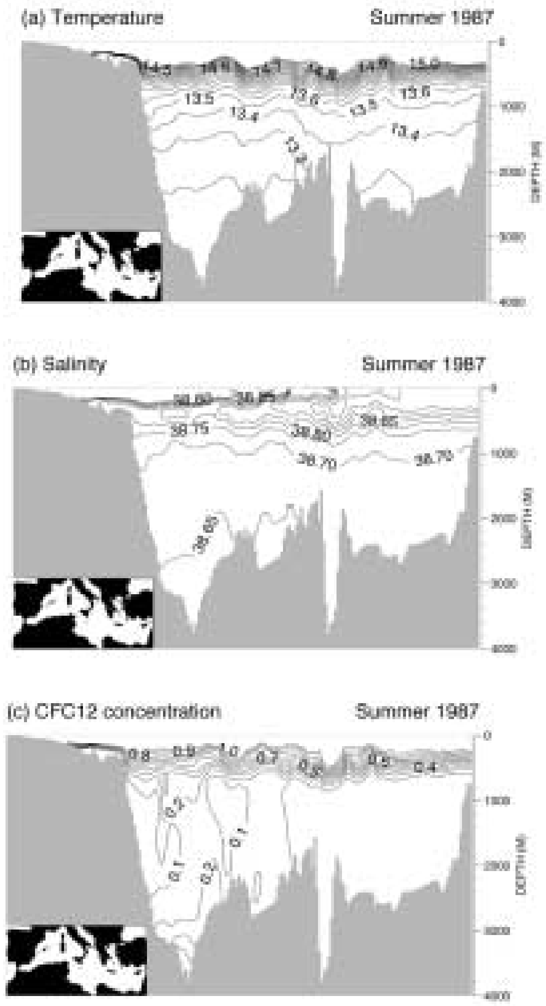

Fig 3. Modelled potential temperature (°C), salinity (psu) and CFC12 concentrations (nmol m^{-3}) for July 1997, with an improved topographic representation. The contour intervals are 0.1°C, 0.05 psu and 0.1 nmo ml^{-3} respectively. Note the high CFC12 values in the deepest part of the Ionian basin.

(1999), and changes in circulation patterns, Malanotte-Rizzoli *et al.* (1999), or additional winter cooling, which are not directly related to the E-P.

While these model results do not deny a role for long term changes in the E-P fluxes or river runoff in causing the switch in thermohaline circulation regime, they do present a strong case for extra Aegean winter cooling playing a key role. We believe it would be surprising if this were the only factor at work for there were surely previous very cold winters at many times in the past. The results show that it will require further very careful comparisons with observational data to identify the more subtle differences between our simulation and the observations which could throw light onto aspects of basin pre-conditioning.

Simulations of biological production in the Rhodes basin of the Eastern Mediterranean

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The biological production characteristics of the Rhodes basin of the Eastern Mediterranean are studied by a one dimensional, coupled physical-biological model. The model involves single aggregated compartments of phytoplankton, zooplankton, detritus as well as ammonium and nitrate forms of the inorganic nitrogen. It interacts with the physical model through the vertical eddy diffusivity which is calculated using the Mellor-Yamada level 2.5 turbulence parameterization.

The mixed layer waters of the entire summer and autumn seasons are extremely poor in nutrients, and characterized by only trace level nitrate concentrations of about 0.1 mmol/m^3. The nitrate depletion arises due to lack of supply from the subsurface levels because of the presence of strong seasonal thermocline/pycnocline. The zone of high stratification below the seasonal thermocline coincides with the strong nitrate variations (the so-called the nitracline). Approximately below 80-90 m depths, the nitrate attains its typical deep water values in excess of 5.0 mmol/m^3. This structure undergoes substantial modification during the winter months as the convective overturning mechanism brings the nitrate rich subsurface waters to near-surface levels. Under such conditions, nitrate concentrations attain their maximum values of 4.5 mmol/m^3 over the 400m deep homogeneous water column in February.

The phytoplankton structure exhibits a major algae production during the first half of March immediately after the cessation of the strong mixing, shallowing of the mixed layer and higher rate of solar irradiance penetrating to deeper levels. Since the water column was already replenished by nitrate, all these conditions favor phytoplankton bloom as an exponential increase of algae concentrations during the second week of March. High nitrate concentrations, built up in the water column during the winter, lead to generation of a very intense bloom with maximum biomass of about 3.8 mmol/m^3. It extends to the depth of 120 m, but its major part is confined to the upper 65 m because of the increasing role of self-shading effect on the light limitation. Following a week-long intense period, the bloom weakens gradually within the last week of March and terminates completely by the end of that month.

The early spring phytoplankton bloom initiates other biological activities on the living and non-living components of the pelagic ecosystem. Soon after the termination of the phytoplankton bloom, mesozooplankton biomass increases up to 2.2 mmol/m^3 during April. This period also coincides with increased detritus and ammonium concentrations supported by excretion and mortality of phytoplankton and mesozooplankton communities. The major detritus accumulation in the water column in fact proceeds termination of phytoplankton bloom at beginning of April.

Moreover, sinking particles are remineralized completely within the upper 300 m before reaching bottom of the model at 400 m depth. All the detrital material is therefore preserved within the water column without any loss from the system. This is the reason for which the bottom boundary was taken at 400 m whereas the pelagic planktonic processes are confined within the upper 100 m of the water column.

The role of remineralization responsible for transforming the particulate organic nitrogen to inorganic dissolved nitrogen is indicated by increased ammonium concentrations up to 0.7 mmol/m^3 in March-April period. Its eventual oxidation due to nitrification process leads to nitrate accumulation primarily in the mixed layer and to a less extent in the nitracline, and causes a short-term increase in phytoplankton biomass up to about 0.5 mmol/m^3 within the mixed layer during the first half of May. As in the previous case, this secondary bloom is also followed by a small increase in mesozooplankton biomass, as well as in detritus and ammonium concentrations. The surface-intensified phytoplankton bloom event continues below the seasonal thermocline for another month by consuming available nitrate and ammonium within the nitracline zone. The subsurface biomass diminishes gradually towards the end of July as the contribution of losses from mesozooplankton grazing and phytoplankton mortality exceeds production.

The annual phytoplankton structure exhibits another weak bloom from mid-December to mid-January. This is associated with the consumption of nitrate which are made readily available by the convective mixing initiated in the water column with the beginning of cooling season. Once again, it is followed by increase in mesozooplankton stocks in January-February. The annual primary production is estimated as 97 gC m^2/yr which is comparable with other productive basins of the Mediterranean, such as the Aegean and Adriatic seas and Northwestern Mediterranean.

The interannual variability of the Mediterranean Sea : from simulations to forecasting

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The Mediterranean Sea has been discovered in recent years to have large fluctuations in circulation and water mass structure partially due to atmospheric low and high frequency variability (Pinardi *et al.*, 1997b). The latter has been studied in connection to momentum and heat flux variability. The wind stress amplitude can change from year to year more than twofold (Korres *et al.*, 2000) and the heat flux can have annual mean value changes of more than 100% around the long term mean value of -10 W/m**2 (Castellari *et al.*, 2000). Interannual and multidecadal

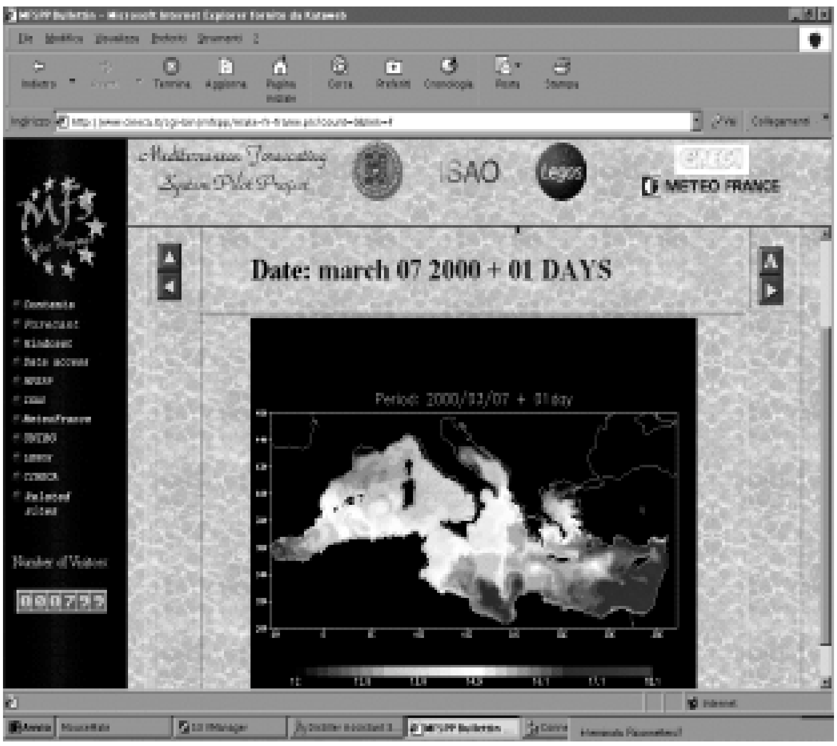

Fig. 1. The Mediterranean Forecasting System Pilot Project Bulletin page with sea surface temperature hindcast.

simulations of the atmospherically forced circulation in the Mediterranean have been carried out in order to elucidate the modes of ocean response to the forcing. It has been found that the atmospheric forcing can induce long term memory of past large atmospheric anomalies in the thermocline, that changes in surface heat fluxes can induce salt redistribution processes that will enhance the ocean response to the heat forcing and that large decadal changes in Levantine Intermediate Water properties can be induced that persists over a decade feedbacking on other components of the general circulation.

These modelling results is substantiated by data (Brankart and Pinardi, 2000) and it shows the importance of having a permanent observing system coupled with a modelling system for the hindcast of the Mediterranean Sea variability since events may change the structure of the circulation for many years or decades.

In the past three years a basin wide forecasting system has been set up in the basin which provides hindcasts and forecasts of deep ocean currents based upon Voluntary Observing System (VOS) XBT measurements on seven cross-Mediterranean tracks and satellite sea surface temperature and sea level anomalies. Results from the system will be shown and its capability to assimilate all these data sets evaluated. The results of hindcasts and forecasts are distributed on the Web (<http: \\www.cineca.it\~mfspp000>) as shown in Fig.1.

The effects of the North Atlantic Oscillation on European shelf ecosystems

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The dominant mode of climatic variability over the North Atlantic Ocean is the North Atlantic Oscillation (NAO) which is associated with changes in the winter surface westerlies across the ocean as far as Europe. One measure of this is the NAO index, the difference in atmospheric pressure between the Azores (or Portugal) and Iceland (Hurrell, 1995). Year to year changes in biological populations may be expected to show some relationship with this NAO index. However, the winter pressure difference between Portugal and Iceland is only weakly correlated with the annual mean pressure difference so that biological associations are likely to involve some process by which the populations are especially dependent on conditions in the winter. Fromentin and Planque (1996) have reported that the interannual variability of the copepod *Calanus finmarchicus* in the NE Atlantic and North Sea has been strongly correlated with the NAO index from 1958 to 1996. An important factor in this case is that this particular species of zooplankton overwinters in deep water in the ocean and returns to the North Sea at the start of the year. Stephens *et al.* (1998) have shown that the annual abundance of *Calanus finmarchicus* in the northern North Sea is strongly determined by winter flows, flows that are closely related to the NAO index. Reid *et al.* (1998) have recently described phytoplankton trends in the North Atlantic and North Sea which they have suggested could be associated with changes in the NAO perhaps via sea temperature changes originating in the winter.

One index of the ocean circulation in the North Atlantic is the latitude of the north wall of the Gulf Stream near the US coast (the GSNW index, Taylor and Stephens, 1980). This index from 1966 to 1999 has been constructed by means of principal components analysis and is available at <http://www.pml.ac.uk/gulfstream/>. Interannual variations of the GSNW index are in agreement with estimates of the large-scale transport of the Gulf Stream. As the Gulf Stream is driven by the wind pattern over the North Atlantic, its position will be linked to the NAO, but with a delayed response (Taylor and Stephens, 1998). The Stream is also influenced by ENSO events in the Pacific (Taylor *et al.*, 1998). Using the NAO index as a forcing function (and including all seasons), the year-to-year changes in the latitude of the Gulf Stream from 1966 to 1999 can be replicated in a simple numerical model (Taylor and Gangopadhyay, submitted).

The year-to-year changes in the GSNW series are strongly correlated with the abundances of plankton observed by the Continuous Plankton Recorder Survey around the British Isles (Taylor, 1995), and also with the abundance of zooplankton in Lake Windermere (George and Taylor, 1995). The series has also been shown to be correlated with the several of the roadside-verge populations at Bibury (Willis *et al.*, 1995). These teleconnections represent atmospheric connections which operate in the spring and involve fluctuations in the onset of thermal stratification. Recent work (Taylor *et al.*, submitted) has shown that years when the Gulf Stream is more southerly tend to have more incidence of blocking events to the west of the British Isles around the month of April. These events are the source of the teleconnections. The isobar patterns associated with these events indicate they will be accompanied by more northerly winds over the western Mediterranean during the spring. There is a potential for making limited forecasts of these processes.

Effects produced by the Eastern Mediterranean climatic transient in the Sicily strait and the consequences in the Western Mediterranean

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The income of a new water coming from the Aegean Sea to the bottom of the Eastern Mediterranean (EM) since 1987 (Roether *et al.*, 1996), has produced an uplifting of the old bottom waters and their progressive involvement in the intermediate circulation patterns of this basin. In order to verify the effects at the western basin boundary and the possible consequences in the Western Mediterranean (WM), we analysed the hydrographic data gathered from 1993 to 1999 in the Central Mediterranean region, between the Sardinia Channel and the Sicily Strait. This is a region with a very complicated bottom topography, directly influencing the water masses crossing it. In the western side, a deep channel with a sill at about 1900 m of depth, directly connects the WM with the Tyrrhenian Sea, thus allowing a free communication between the deep waters of the two basins. In the Sicily Strait, the sill is at about 430 m of depth and then imposes a strong constraint to the passage of deep waters of the EM.

Actually, two water types were seen to flow into the central Mediterranean region from the EM: the Levantine Intermediate Water (LIW) and the denser transitional Ionian Deep Water (tIDW) formed by the top level of EMDW in the Ionian. The latter is sucked through the shallow sills of the Sicily Channel by the overlying stream. While LIW recirculates in the Tyrrhenian Sea outflowing from the Sicily-Sardinia section and the Sardinia Channel, tIDW sinks in this basin and mixes with the resident Tyrrhenian waters at depth. It then represents a source of T and S for the Tyrrhenian Deep Water (TDW). At the opposite side, two water types coming from the WM flow into the Tyrrhenian through the Sardinia Channel: WM Deep Water (WMDW) and WM Intermediate Water (WMIW). Conversely, two water types outflow from this basin towards the WM: LIW and TDW. The latter results from a mixing of WMDW and tIDW.

The time series of hydrographic data in the Sicily Strait show (see Figure) that both Ø and S of the LIW core were subject to a significant and progressive decrease from 1993 to 1998, most intense in the first years of measurement. This induces an overall increase of the water density as well as the sinking of the LIW core to higher depths. The time series also show that in between 1998 and 1999, this tendency stops and both parameters tend to approach again the values measured at the beginning. It is interesting to remark that, during the first phase, water properties of tIDW did not modify significantly, and this can be considered an indication that the changes of LIW were mostly induced by a major percentage of this water in the LIW composition. This is also the response of the evolution of the LIW core in the θ-S diagram in the considered period, showing a drifting towards the position of tIDW in the next Ionian, and a significant reverse of its course at the end of 1998.

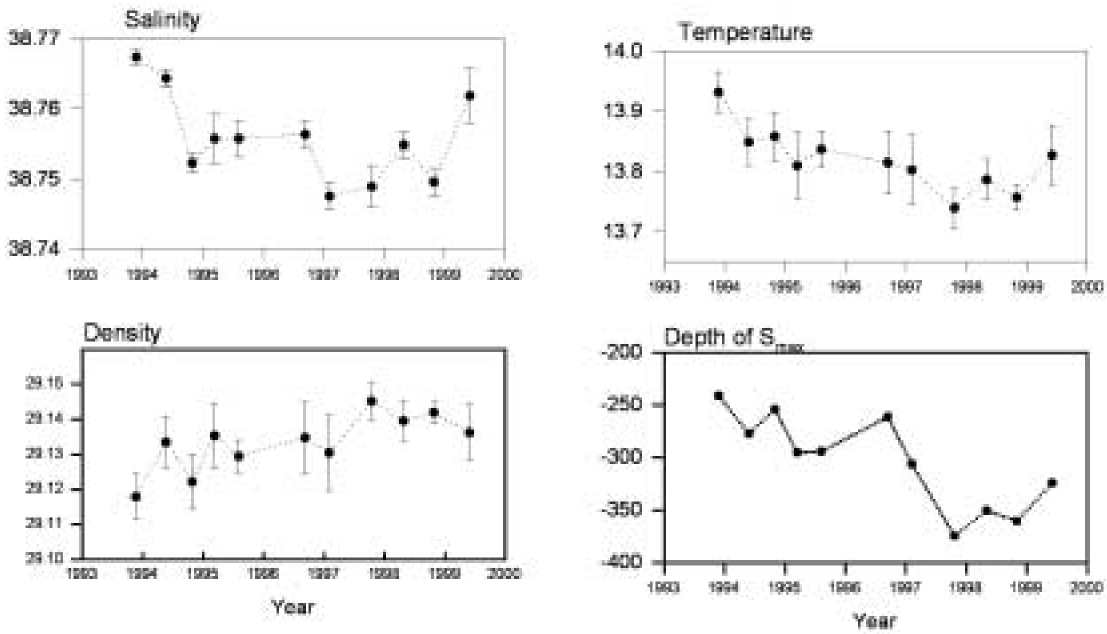

Fig. 1. Evolution of LIW characteristics.

The overall process is consistent with the general uplifting undergone by the deep waters of the EM as a consequence of the intrusion of the Aegean waters. Our data then indicate that the effects of the climatic transient have reached the western basin boundary at least in 1993, with a phase lag of not more than 6 years from the event. The data also show that, in between 1998 and 1999, a significant inversion of this trend happens, thus indicating a possible relaxation of the involved structure.

In order to verify the response of the Tyrrhenian Sea, we have considered the time evolution of the thermohaline properties of waters outflowing from the southern basin boundary at three crucial depths: 400-500 m (the average depth of the LIW core), 1000-1500 m (the region where tIDW finds an equilibrium depth over the local Tyrrhenian waters) and 2000 m (close to the sea bottom).

The analysis of the respective behaviours shows that, while T and S of LIW did not change significantly with time, at the intermediate depths the same parameters were subject to a progressive and significant increase. Though less evident, this tendency is also present in the waters at the bottom of the section. The overall result is rather surprising as it is in contrast with the evolution of the water properties in the Sicily Strait.

We have explained this apparent discrepancy, by attributing the increase of T and S of TDW to the contribution of heat and salt provided by tIDW while sinking in the Tyrrhenian. We can presume that this mechanism may be enhanced in the presence of denser waters, like those crossing the Sicily Strait in the last years, because of their tendency to deepen at major depths where the local temperature and salinity are even lower.

We could verify the effects of this process in the stepped structure characterising the region directly adjacent to the cascading of the Levantine flow. Our data in fact show that, in the last years, there has been a substantial and progressive increase of the mean temperature and salinity of the stepped profile, associated with a general reduction of the number of steps. While not relevant in the upper 600 m of depth, the increasing tendency appears to be higher between 1000 and 1500 m, that just corresponds with the final course of the tIDW produced by the transient.

As TDW directly feeds the WM, we can expect that the new signal will make feel its effects in the deep waters of this basin. It is likely then that, after the sudden acceleration of the existing trend provided in the fifties by the damming of the Nile (Rohling and Bryden, 1992), another significant increase will affect (is affecting) the positive gradient of T and S observed in WMDW.

Hydrological variability in the Channel of Sicily

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ABSTRACT

Monitoring long term hydrological variations in a place as suitable as the channel of Sicily, and especially with respect to the Eastern Mediterranean Transient consequences, is certainly something which must be done. Nevertheless, as suggested by adequate in situ and remotely sensed data sets, and demonstrated by Sammari et al. (1999), this is not an easy task since the mesoscale variability there is relatively large and must be resolved. We have taken the opportunity of the data analysis presented by Astraldi, Gasparini and Vetrano (AGV hereafter) in this volume to perform a similar analysis of our own data set and to present our own approach. We conclude that evidencing long term variations cannot be achieved with the sampling strategy presently used by all teams.

INTRODUCTION

The aim of the present paper is to discuss the possibility of monitoring long term variations of intermediate water masses hydrological characteristics, in a channel and with ship-handled CTD casts, since this is one of the easiest thing experimentalists can do with the presently available standard instrumentation.

As a preamble, let us specify that, especially in a channel, water masses are structured like veins flowing alongslope. Ideally, the most significant characteristics would be integrated values representative of the whole vein (which is too constraining in terms of instrumentation, time and money). Practically, the most convenient characteristics would thus be those of the water masses' cores (associated with some parameters extrema). With a theoretical vertical slope (Fig. 1a), this is something that can be done without any risks for the CTD.

Now, the slope is never vertical so that veins' cores are necessarily somewhere "on the bottom". Sampling the core (assuming it has been located) with a ship-handled instrument is thus "theoretically impossible" or at least "risky" for the instrument. Where the slope is steep (Fig.1b), a "local" vein core will be found easily since, a bit offshore (O(1 km)) the mean location of the "actual" core, some parameter extremum will be always identified by less extreme values above and below. Nevertheless, the "actual" core characteristics and location (O (100s m) with respect to the mean) will remain unknown. Where the slope is gentle (Fig.1c) and along a cross-slope section, a vein is roughly shaped as a drop of water on a flat bottom, so that extreme values will be encountered close to the bottom everywhere within the vein (i.e. over several km -10s km). Consequently, no "local" core will be found anywhere, and the "actual" core characteristics and location (O (several km) either shoreward or seaward from any isolated CTD cast) will remain unknown.

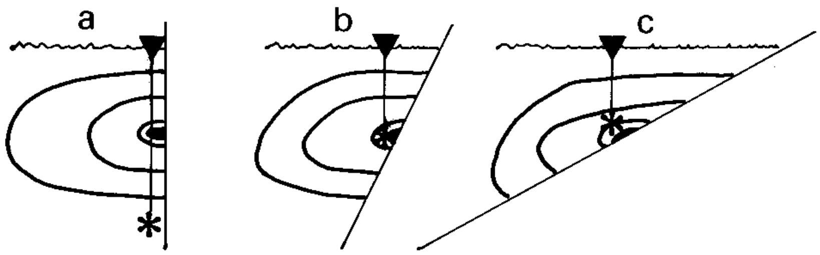

Fig.1. Sampling the core of a vein of intermediate water flowing alongslope with a ship-handled CTD, and without lowering the CTD too close to the bottom, is ideally possible with a vertical slope (a), practically acceptable with a steep slope (b), but impossible with a gentle slope (c). Additionally, locating the core of the vein along a gentle slope is very difficult.

Now, are these “theoretical difficulties” to sample a vein’s core, even along a steep slope, redhibitory to any monitoring of long term variations from ship-handled CTD casts? In other words, what is the variability of both the characteristics and location of a vein core at space and time scales smaller than “the long term”? Let us specify that this variability includes a “natural” part (heterogeneity of the characteristics along the core of a stable vein, instability of an homogeneous vein, both variabilities obviously occurring together), and a “forced” part (effects, on the intermediate layers, of the large variability in the surface layer at mesoscale). To answer these questions and specify the various variabilities, adequate data sets are not available yet. Therefore, our aim is just to illustrate the “effective difficulties” by analysing the most representative data sets available up to now.

AGV have been performing, since 1993, the most important work done up to now in the channel of Sicily. In addition to large surveys in the whole area, they have been monitoring some specific locations once to twice a year. The CTD data presented in their paper were collected at 37°20,3'N-11°36,0'E in the eastern part of the channel, i.e. at a place where the LIW vein can always be sampled (Fig. 2).

In order to deal with data as significant as possible, AGV avoided presenting isolated values and mainly computed averages over some depth interval. In order to consider LIW without taking into account any MAW values, they focused on data below the salinity maximum (itself

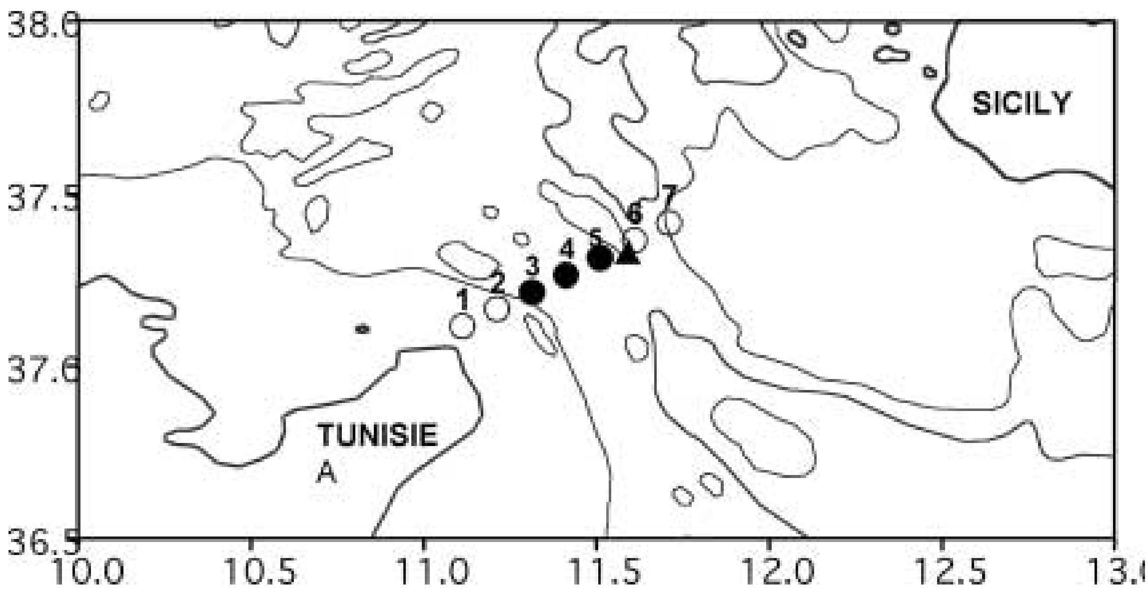

Fig. 2. The location of the AGV station (full triangle) is close to that of our station 5 (full dot). Stations 3 and 4 are also used to analyse the AIW characteristics while stations 1, 2, 6 and 7 are plotted just for the record.

located below the temperature maximum) they found. The salinity, temperature and density values they present are thus averages (with their associated standard deviation) computed over the 100-m depth interval below the depth of the salinity maximum (also plotted). This approach is probably one of the most cost-efficient which could be used with the technology and means presently available. The AGV figure is reproduced here as figure 3.

On our side, we have collected (with a SBE911+ CTD regularly calibrated by Seabird) analogous data at a nearby location (37°17,6'N-11°30,0'E, station 5 of the SI cross-channel section in Sammari *et al.*, 1999, Fig. 2). The major difference is that our data were collected 4 times in 1995 and 4 times in 1996, generally once to twice a month during both years to illustrate the importance of the mesoscale variability. We have obviously performed the same computations AGV did and, even though we cannot strictly compare absolute values (locations are ~3 nautical miles away), we can compare the average and standard deviation variabilities (the AGV values have been estimated directly from their plots). What we come with is discussed in section 2.

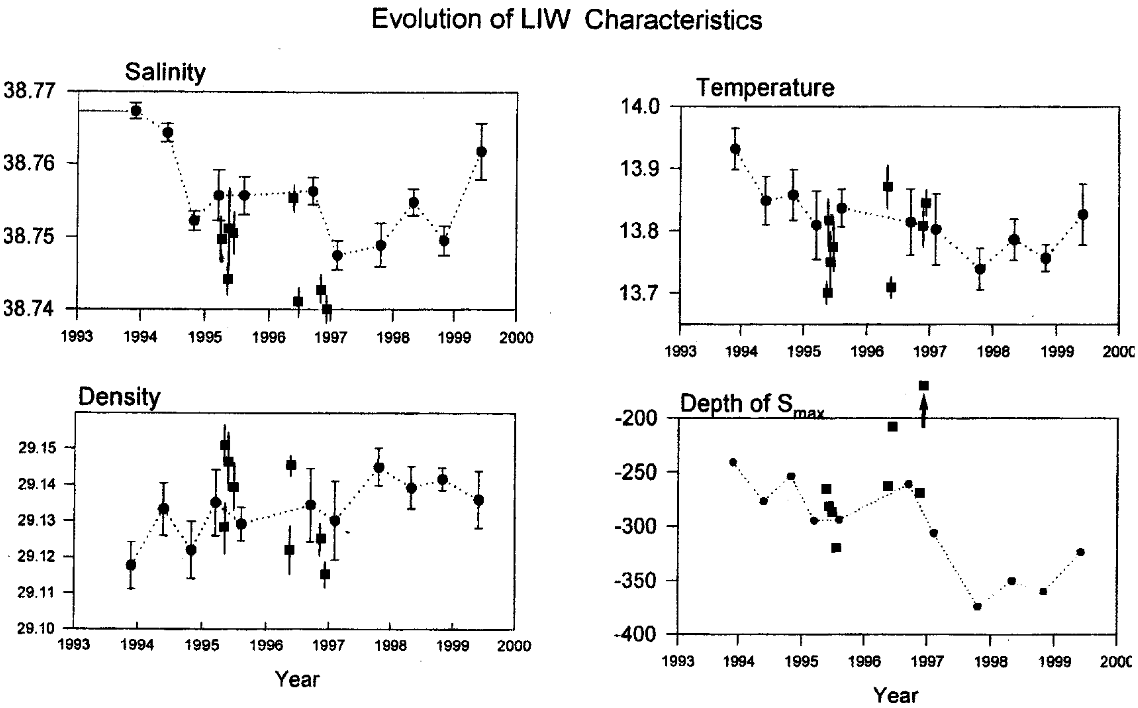

Fig. 3. This figure is the exact reproduction of the AGV one on which we have plotted our own data (full squares and associated standard deviations).

In addition, and to provide a complementary illustration of the relatively large importance of the mesoscale variability, we present an original data analysis about the AIW/tEMDW characteristics in section 3.

THE LIW DATA ANALYSIS

The AGV salinity averages range, over the 1993-1999 period, from ~38.747 to ~38.767 which represents a 0.020 interval (Fig. 3). Our averages have been plotted on the same figure and they range, over the 1995-1996 period, from 38.740 to 38.755, which represents a 0.015 interval not very different from the AGV one. Moreover, the AGV values during the same period as ours (i.e. in 1995-1996) range only from ~38.756 to ~38.757, thus giving the misleading impression that the values did not change significantly during that time.

The AGV temperature averages range from ~13.73°C to ~13.93°C, i.e. over a 0.20 °C interval. Ours range from 13.70°C to 13.87°C, i.e. over an almost similar 0.17°C interval. Again, the AGV values coinciding with ours only spread between ~13.81°C and 13.84°C (0.03 °C interval).

The AGV density averages range from ~29.118 to ~29.145 (0.027 interval) while ours range from 29.114 to 29.150 (coinciding AGV values only spread between 29.128 and 29.135, i.e. a 0.007 interval). The 0.036 interval we got from our 2-year data set is larger than the 7-year AGV interval!

The AGV depth of salinity maximum values range from ~240 m to ~370 m while ours range from 175 m to 320 m (coinciding AGV values only spread between 260 and 290 m, i.e. within 30 m only). Here again, our whole interval (145 m) is larger than theirs (130 m).

To be emphasized is the fact that the overall differences between the AGV values and ours are consistent with the general structure of the waters masses in the channel (see Sammari *et al.*, 1999, for instance; see also hereafter), assuming the AGV station is closer to the LIW core (itself located more to the east, just "on" the slope) than ours. Note also that standard deviations are similar for both data sets. Nevertheless, it is clear that the mesoscale variability, as we define the variability evidenced from our data set, is practically as large as the long term variability, as far as this would be indeed the variability evidenced from the AGV data set. Moreover, we strongly believe that even our once to twice a month hydrological survey is not fine enough (in both time and space) to correctly estimate the actual variability (i.e. both the mesoscale and the long term variabilities).

THE AIW DATA ANALYSIS

It is well known, at least since the Garzoli and Maillard (1976, 1979) data also reproduced by Guibout (1987) that, in addition to the LIW vein constrained along the eastern side of the channel, there is a colder and denser vein located along the western side of it. This vein is formed by the water referred to as transitional EMDW by authors following Pollak (1951), as transitional IDW by AGV, and as AIW by Sammari *et al.*, 1999. The latter acronym was proposed taking into account the facts that (i) this Intermediate (there) water mainly originates from the Adriatic and/or the Aegean (since it is relatively cold), (ii) that EMDW/IDW is a relatively vague acronym (which includes deep waters possibly formed in the Levantine basin, and thus relatively warm), and (iii) that transitional (between LIW and EMDW/IDW per se) is an adjective that could apply to any water located, on a Q-S diagram, on a line between two points representing water masses cores. In any case, let's call it AIW, at least since the work initiated by Salat (2000) has been completed.

The LIW core is located along a relatively steep slope (see Fig. 1b), so that defining a salinity maximum and performing averages over some depth interval could probably be significantly done from ship-handled CTD data (which could then allow monitoring LIW provided these data are collected close to its core). On the contrary, the AIW core is located along a relatively gentle slope (see Fig. 1c), so that AIW is roughly shaped, along a cross-slope section, as a drop of water on a flat bottom. Therefore, the deeper the measurement the lower the temperature, wherever the CTD cast is with respect to the core.

As an illustration of this problem, let's consider the minimum temperature values and their respective depths observed at stations 3 and 4 (37°12,3'N-11°19,6'E and 37°14,9'N-11°24,8'E, Fig. 2) and plotted in Fig. 4 (stations 3, 4 (and 5) are ~10 km apart). Even though the depths of the temperature minima (i.e. the maximum depths of the casts) are obviously constant at both

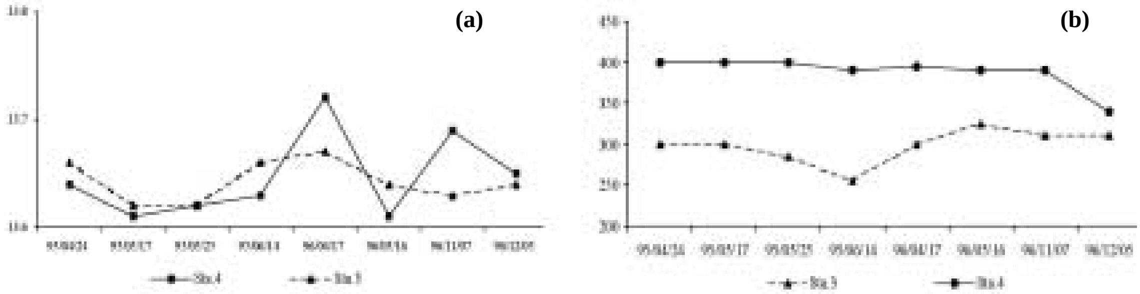

Fig. 4. Values of the AIW temperature minimum (a) at stations 3 (triangles) and 4 (dots) and values of the corresponding depths (b).

locations, it appears that the minimum/bottom temperature value is encountered sometimes at station 3 (at ~300 m) and sometimes at station 4 (at ~400m). It is thus clear that the location of the AIW vein is markedly variable at what we have called mesoscale, and that the AIW characteristics cannot be monitored from isolated values at fixed locations.

To monitor AIW, averaged values could be computed from ship-handled CTD data at fixed locations over some fixed depth interval. But this interval would have to be, ideally, as deep as possible, while a CTD can hardly be laid from ship on the bottom (!). Therefore, especially for monitoring AIW, performing ship-handled CTD casts is obviously not a reliable sampling strategy.

CONCLUSION

The problem of localizing the core of a vein along a slope, which has been shown to be crucial for AIW, is maybe less important for LIW since the eastern slope is steeper than the western one. Nevertheless, it is clear that it will never be possible, without using something like a tow-yo device managed down to the bottom, to be sure that the LIW/AIW core has been correctly sampled. Indeed, this core is necessarily located close to the slope, i.e. somewhere close to the bottom, and it must first of all be accurately located and estimated to perform significant averages analogous to those that have been described.

Now, even though devices more adapted than CTD’s (which will remain for a while the most cost-efficient instruments) would have to be operated from ships, it is clear that what we have called mesoscale variability will have to be more accurately resolved. This variability is expected to be induced not only by mesoscale dynamics (eddies, meanders, ...) but also by the natural heterogeneity existing within any water mass. To resolve this variability, it is clear that an almost permanent monitoring with moored CTD's and/or other devices (ideally able to provide information on the vertical) will have to be performed to get relatively significant results.

Therefore, we don’t believe that the variability evidenced up to now in the channel of Sicily is reliable since the available data sets do not resolve correctly the major variations time scales. Measurements adequately sampling the cores of the major water masses there are definitely requested on a nearly-continuous basis.

Acknowledgements

CM warmly thanks Isabelle Taupier-Letage for her very constructive comments and Frédéric Briand for his suggestion to draw Fig. 1.