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PHYSICAL OCEANOGRAPHY ASPECTS AND CHANGES IN CIRCULATION AND STRATIFICATION

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LOW FREQUENCY ATMOSPHERIC FORCING FUNCTIONS AND SEA RESPONSE IN THE NORTHEASTERN MEDITERRANEAN

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In order to understand what would be the sea response in the Eastern Mediterranean to predicted climatic changes it is necessary to have a detailed description of both forcing functions and the response over the entire subtidal frequency range. Appart from the fact that it is predicted that the mean air temperature will increase by 1.5 - 4.5 °C before the end of the 21st century followed by a sea level rise up to 140 cm, the forcing, variable at shorter time scales like atmospheric pressure and wind variations at the synoptic scale, will certainly be influenced by changes in climat. Therefore, the sea response at those time scales will also be affected. It is very likely that there will be a general northward shift of the atmospheric circulation pattern.

Some authors assume that this shift will be from 300 to 500 km (KUHN, 1987) along the meridian which will certainly influence the path and frequency of passage of midlatitude cyclones over some parts of the Mediterranean area. It is still not clear whether there would be any important changes in the wind regime which is now mostly related to the passage of atmospheric disturbances. The wind affects not only the sea level changes but it is also very important in generating the vertical convection and deep water formation processes. It is well known that e.g. the deep water in the center of the South Adriatic gyre is formed during outbreaks of the cold NE wind (bura) (ZORE-ARMANDA, 1972, OVCHINIKOV et al., 1985). These are, thus, short-lived phenomena which have time scales of several days. Their spatial scales are of the order of several tenths of miles (OVCHINIKOV et al., 1985). The Adriatic Sea is considered as one of the most important sources of the Eastern Mediterranean deep water.

It has already been documented that year-to-year fluctuations of the water exchange between the Adriatic and Ionian Seas are related to climatic conditions of a wide area of the North Atlantic and Europe (ZORE-ARMANDA, 1972). Evidences were presented that these fluctuations were well correlated with the time variations of the meridional component of the atmospheric pressure gradient over the Eastern Mediterranean. Also the occurence of heavy ice in polar regions, related to the position of great baric centers seems to regulate such factors as the frequency and strength of instrusions of the cold and dry continental air into the Eastern Mediterranean (ZORE-ARMANDA, 1971). It has also been shown that, on one hand, a strong and sudden outbreak of cold, dry Asian air over the Adriatic Sea resulted in such rapid evaporation rates that water column evidently overturned (HENDERSHOTT and RIZZOLI, 1976). The horizontal density gradient set up by evaporation is an important source of the large scale wintertime circulation. On the other hand, transients in the residual circulation in the Northern Adriatic are shown to be strongly affected by the bura wind (ZORE-ARMANDA and GACIC, 1987; KUZMIC et al., 1987). Therefore, any appreciable change in the seasonal distribution of the bura wind frequency will result in changes of the volume of the formed deep Adriatic water as well as in changes of the circulation pattern in the Northern Adriatic. Also the ammount of the South Adriatic water will affect the exchange between the Adriatic and Ionian Seas.

As far as the sea level is concerned, the variability in the low frequency range (periods in the tidal to several weeks interval) represents an energetic part of the sea level spectrum in the Mediterranean. Number of authors (KASUMOVIC, 1958; MOSETTI, 1971; PAPA, 1978; GODIN and TROTTI, 1975; GACIC, 1980) have reported that sea level variations in the Adriatic and other parts of the Mediterranean at time scales from one to ten days are primarily due to surface pressure changes related to synoptic atmospheric disturbances. Therefore, changes in sea level in this period range depend on a number of cyclones passing over the area. On the other hand, sea level variations at time scales of ten days to several weeks have been explained in terms of the influence of atmospheric planetary waves (ORLIC, 1983). Departures from isostatic response are due to the influence of local winds (PALUMBO and MAZZARELLA, 1982) or to constriction of straits which prevent sufficient water transport between connected basins (GARRETT, 1983; GARETT and MAJAESS, 1984). CREPON (1975) showed that the responses of a rotating fluid is never barometric. It may be quasi barometric if the space scale of the atmospheric disturbance is smaller than the barotropic radius of deformation. Also the larger the bottom friction is, the closer to barometric is the response.

The sea level slope between connected basins dictates water exchange between them if it is not due exclusively to differences in the atmospheric pressure between the two areas. Therefore, studies of the sea level response to the atmospheric forcing are rather important from the point of view of the barotropic water exchange between connected basins. It has been shown that the mean flow is mostly driven by the density differences between adjacent water bodies (DEFANT, 1961). On the other hand, shorter period fluctuations (2-10 days) are barotropic and generated by the sea level slope along the strait (SCHUMACHER et al., 1982). These are produced by large-scale meteorological forcing and this has been observed in a number of places around the world ocean. Even though evidences on variations of the water exchange between connected basins in the Mediterranean (like e.g. the Adriatic and the Ionian Seas or Eastern and Western Mediterranean) at synoptic time scale practically do not exist, it is very likely that these variations are rather strong. Evidences have been presented in a recent paper by ZORE-ARMANDA (1985) that there is a good correlation between the longitudinal sea level slope in the Adriatic Sea and the alongshore current at the time scale of several days.

LACOMBE (1961) pointed out that an isostatic response of the Mediterranean would require, by continuity, a strong fluctuating flow through the Strait of Gibraltar. CREPON (1965) concluded that in the Western Mediterranean the ration of atmospheric pressure to the sea level was consistent with an inverted barometric response. He also found a high correlation between cross strait sea level differences and the minus atmospheric pressure over the area, which is consistent with the geostrophic balance of the inflowing water. CREPON (1965) and LACOMBE et al. (1964) found, in contradiction with the mass conservation requirement, that in the Western Mediterranean, the sea level rather than the rate of change of the sea level is related to the inflow at Gibraltar. GARRETT (1983) explained that fact by a simple model in terms of the barotropic response to eastward propagating cyclones over the area and the exchange of water with the Eastern Mediterranean through the Sicily Strait. He also predicted that the Eastern Mediterranean should react nonisostatically to the moving atmospheric perturbations. GARRETT and MAJAESS (1984) showed for one station in the Eastern Mediterranean (Katakolon, Greece) that the response of the sea level to atmospheric pressure is non-barometric at the time scale of about four days, while at time scales larger than four days and smaller than three days an almost barometric response occured. A near barometric response at low frequencies occurs because there is enough time for the sea level to adjust. On the other hand, high-frequency changes have space scales smaller than the basin scale. Therefore, an internal adjustment takes place and the flow through straits is not required. GARRETT and MAJAESS also computed the cross-spectrum between the atmospheric pressure variations at one station in the Eastern Mediterranean (Andravidha - Greece) and at another station in the Western Mediterranean (Cagliari - Italy). It was shown that there was some coherence only for frequencies less than .005 cycles per hour. For higher frequencies coherence is very poor.

The lack of coherence between the Western Mediterranean and the Adriatic Sea was noted in the non-tidal sea level vatiations by RICKARDS (1986) on the basis of two-month time series. At the same time it was demonstrated that sea level variations in the Adriatic Sea were well correlated with the passage of synoptic atmospheric perturbations.

Attention in this part of the discussion is focused on the time variability of the sea level from two days to several weeks but less than the seasonal time scale i.e. scales in which it is expected that the influence of atmospheric forcing will prevail. The main objective is both to present the results giving the horizontal space scales of the subtidal sea level and atmospheric pressure variability in the Northeastern Mediterranean (LASCARATOS and GACIC, 1988) and to examine the correspondence between space and time scales. The response of the sea level to atmospheric pressure forcing in the subtidal frequency range is also a sybject of this discussion. On the basis of these results it will be possible to conclude whether the sea level slope between different parts of the area is simply due to the barometric response or there are some departures from it which can induce water circulation.

Time-series of one year of sea level data from eleven stations in the Northeastern Mediterranean (Adriatic, Ionian and Aegean Seas) have been analysed in terms of the local atmospheric pressure oscillations having time scales from one day to several weeks but shorter than the seasonal scale. The summer and winter season have been analysed separately. An EOF analysis of both the sea level and atmospheric pressure resulted in the separation of lower frequency oscillations of planetary wave time scale expressed by the first mode from the higher frequency synoptic time scale variability included in the second mode. The first mode is related to the in-phase sea level of atmospheric pressure variations in the entire area, while the second mode represents variations for which the Adriatic Sea is out of phase wiht respect to both the Ionian and Aegean Seas. Only those first two modes represent a regionally coheret signal subtracting more than 90% of the total variance from both sea level and atmospheric pressure. Sea level EOFs are closely related to respective atmospheric pressure modes in both space and time. Departures from the isostatic response, evident in the low frequency range of atmospheric planetary waves, are not due to geostrophic control in straits. It has been shown that the second mode time depedence is related to the surface pressure changes induced by the cyclonic activity in the study area. The location of the zero-crossing of the atmospheric pressure second mode over the area of Otranto Strait is being explained in terms of prevalent cyclone paths over the area of the Northeastern Mediterranean as presented by OSZOY (1981). Therefore any appreciable shift of the cyclone path over the Mediterranean will result in a change of the shape of the second sea level EOF. The major fraction of the variance of the sea level slope between the Adriatic and the Ionian Seas is related to the second mode i.e. generated by the atmospheric forcing at the synoptic time scale. Therefore, if the sea level slope is not exclusively induced by the atmospheric pressure forcing through the isostatic response, appreciable variations of the water exchange between the two basins can be expected at those time scales. The sea level slope related to variations at planetary wave time scales and longer is very small since the typical length scale of the forcing function is much larger than the Northeastern Mediterranean. Therefore, the water flow fluctuations at long time scales starting from planetary wave scale, cannot be explained in terms of the sea level slope but in terms of density differences as already pointed out by ZORE-ARMANDA (1968) on the basis of studies in the Adriatic Sea.

At time scales longer than the synoptic and planetary, both sea level and atmospheric pressure spectra display important energy content. Energy is present at seasonal, annual and interannual time scales. The relative importance of those parts of the spectrum is different for each of those signals. For example in Eastern Mediterranean, the annual variability of the sea level is very important compared to the other parts of the spectrum. This is due to the strong steric effects of sea water in the area. Important heating during summer season compared to strong cooling and evaporation in winter, result in strong annual variability of the sea water density.

The relative importance of each part of the spectrum of sea level is not static but shows important year to year variations As it was previously mentioned, sea level variations are closely related to circulation patterns and exhanges through straits.

These variations are produced by year to year variations of the forcing functions. The exact mechanism by which the sea level spectrum would respond to changes of the spectra of the forcing functions such as atmospheric pressure, wind, etc., themselves induced by climatic changes, is not obvious at all. It becomes even less evident if one accounts for the feedback mechanism, that is the forcing that sea water exerts and especially SST to atmospheric climate. The expected climatic changes for the next hundred years will certainly affect the sea level spectrum. Some insight as to what those effects could be, should come from detailed studies of shorter period interannual fluctuations of the El Nino type.

Detailed studies of long climatic series have indicated that climatic changes,statistically described as a more or less linear trend, in some cases occur stepwise, with a short and rather rapid transition between two different modes, each of them including relatively minor fluctuations These "jumps" have in common that the difference of the average of consecutive periods (in the order of 15-30 years) reaches or exceeds twice the standard deviation of the individual periods. They occur at a regional (not local) scale (FLOHN and WEBER, 1986). They are therefore quite important events on relatively short time scales and are quite suitable for the study of sea water response to atmospheric forcing. Such events seem to occur in the Eastern Mediterranean. THEOCHARIS et al., 1985, observed a very important (0.8 ppt) decrease of salinity (integrated in the 0-60 meters layer) inside the Saronikos Gulf during the years 1980-1982 compared to that of the period 1972-1976. Their computations were based on the results of 46 cruises in the area. This salinity decrease can be schematically attained by the replacement of the upper 1240 mm of the water column by fresh water. No rivers or important streams flow into the gulf. Precipitation in the area of the gulf during 1976-1982 was found to exceed the mean value of the last 30 years by approximately 200 mm. Higher precipitations (up to 200 mm) were also observed along the coasts of the greek mainland. Thus they concluded that precipitation could at maximum be responsible for 30% of the overall observed salinity decrease. Assuming no major changes in evaporation, they conclude that the salinity decrease was not induced by a phenomenon of local scale or even of the scale of western Aegean but that it might be attributed to a larger scale one related to salinity changes in the Black Sea source water advected to the Western Aegean.

FLEMMING and WOODWORTH (1988), studied the monthly mean sea levels in Greece during 1969-1983 using data from 16 tide gauge stations in the Aegean and Ionian seas. They observe an overall drop of sea levels in the area during the mid-1970's. The result of an EOF analysis they performed on the data shows clearly that the time series of the first Principal Component of mean sea level variations (in-phase oscillations over the entire area) has minimum values between 1973 and 1977 and maximum values between 1969-1970 and 1979-1982. It is interesting to note that the low mean sea level period coincides with the high salinity period observed by A.THEOCHARIS et al., (1985), while the high mean sea level period of 1979-1982 coincides with the low salinity period.

It can be expected that the impact of such large scale climatic variations of the order of a few years, is not restricted to the observed salinity and sea level changes but influences also other parameters such as horizontal density gradients, evaporation rates etc., and would therefore have an impact on general circulation, on production rates of deep and intermediate waters etc.

The study of the impact of such climatic "jumps" on the Eastern or even the whole Mediterranean Sea regime, should appreciably help to investigate the possible effects of the predicted large scale climatic changes for the future 150 years.

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TEMPORAL VARIABILITY OF THE LEVANTINE INTERMEDIATE WATERS IN THE EASTERN LEVANTINE BASIN

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As its name implies the talk is about the characteristics of the spacial and the temporal distribution of the Levantine Intermediate Waters (LIW) in the Levantine Basin in general but in the southeastern Levantine Basin in particular. The data come from a five year series (1979-1984) of 20 Israeli cruises known as the MC (Marine Climate) series. Each of these cruises lasted for about ten days and was planned so as to occupy the same grid of 28 stations situated at 0.5^{o} intervals in a rectangular domain defined by the latitudes of $32^{o}00'$ and $34^{o}30'$ N, and by the longitudes of $32^{o}30'$ and $34^{o}30'$ E. This data set was described in greater detail in Hecht, Pinardi and Robinson (1988).

The climatological temperature and salinity profiles show that for this region the variability diminishes considerably with the depth and that at about 1500 decibars it is below the level of the accuracy of our measurements. In the shallower section of the salinity profile one can see the distinct imprint of the main water masses of the region: at about 7 decibars the high salinity - 39.08 - Levantine Surface Waters (LSW); at about 74 decibars the low salinity - 38.86 - Atlantic Waters (AW); at about 242 decibars the subsurface maximum - 38.97 - of the Levantine Intermediate Waters (LIW). The bulk of the waters are the Levantine Deep Waters (LDW) which begin at about 700 decibars and have temperatures and salinities below 13.8^{o} and 38.74 respectively.

On the climatological temperature profile, the temperatures related to those characteristic salinities do not seem to be particularly conspicuous.

In an attempt to investigate the annual cycle of the various water properties, I arranged the cruise profiles in the order of the midday of the cruise irrespective of the year in which the cruise was carried out. Thus we have a representative for every month of the year except January and April. Although these cruises were carried out at practically random intervals one is amazed to see the regularity with which each one of them fits into its seasonal slot. The development of the temperature profile follows without a hitch from the mixed column oceanic winter low temperature in March ($16.0^{o}C$), through a short spring transition period and to its peak temperature ($27.2^{o}C$) and steepest thermocline of the oceanic summer in August, thereafter declining through the autumn transition period towards the winter minimum. Other profiles, such as the S/T diagrams and the Brunt-Vaisala frenquency profiles, follow as regular a pattern as the temperature profiles. We can follow the development of the local water masses throughout the year from the oceanic winter when one can see the sole presence of the LDW and LIW to the peak of the oceanic summer when we have already the LSW and the AW. The regularity of the salinity profiles, if it exists, it is less easy to grasp. In general one can follow the increase in the sea surface and upper layer salinity as well as the formation of the halocline from the winter to the summer. However the development is not as smooth and as monotoneous as that of the temperature. The lowest salinity was observed during MC12 of May 1979 (or perhaps it was attained during the missing April) and the highest one was observed during MC24 of October 1984. However one conspicuous feature stands out and that is the presence of the subsurface salinity maximum, or the presence of LIW, throughout the year.

Since it is the salinity variability which we will investigate in greater detail it is important to verify the accuracy and the repeatability with which it was measured. As pointed out before, the very deep waters of the Eastern Levantine basin exhibit practically no variability. Looking at the cruise average of the salinities at depths of 1000, 1500 and 2000 decibars one can not fail to observe the invariance of those measurements.

The simplest way to determine the extent of the LIW layer is to find the subsurface salinity maximum on the climatological salinity profile and to define the layer by its standard deviation. In our particular case the value is 38.966 $\pm$ 052 at 242 decibars. The depths at which one finds a salinity of 38.92 are 125 and 340 decibars and the respective temperatures are 16.3 and 14.8°C. Obviously, such a determination could not possibly give us any indication on seasonal variations. Moreover, the S/T diagrams indicate that in at least one case the upper limit of the LIW layer is ambiguous. Another possibility, is to accept the 38.92 salinity as the limiting values of the LIW layer but to determine the depths of this salinity for each cruise average salinity profile. The results indicate some seasonal variations of both the layer depth and the layers thickness. There are difficulties in determining the upper limit of the LIW on the average salinity profile of some of the cruises (MC25, MC22 and MC21). As for the rest, I cannot identify any particular seasonal regularity. The averages of the upper and lower limiting depths are 159 and 333 decibars respectively. Finally, a third approach, could be to determine the maximum salinity and the extent of the LIW layer for each cruise. Only one cruise - MC21 - does not seem to have a recognizable salinity subsurface maximum and therefore one cannot determine there neither the presence nor the extent of the LIW. As for the rest of the cruises, once more, there does not seem to be any clear seasonal regularity. For this case, the averages of the upper and lower limiting depths are 168 and 300 decibars respectively.

If we accept that there do not seem to be any identifiable seasonal regularities then the differences between the limiting depths does not seem to be very significant and I would opt for the third method as seemingly more defensible. Moreover, there does not seem to be any advantages in organizing the cruises in the manner in which we did. Thus, let us look at the limiting levels of the LIW on a regular sequential series of cruises. Both LIW layer determination methods appear to indicate the presence of a discontinuous jump on the 9 cruises following December 1982. This trend seems to be less pronounced at the lower boundary of the layer but quite clear at the upper boundary. Moreover the actual value of the subsurface salinity maximum shows a clear increase.

As pointed out before, we are quite confident as to accuracy of our salinity measurements. Nevertheless, before we come out with a definite statement, we would like to investigate this feature with great care. Furthermore, we intend to try to determine the extent of the LIW layer and the quantities of the LIW on a station by station basis.

The production and spreading of the LIW is just one aspect of the mass and salinity balance in the Mediterranean Sea. However, since these waters spread through the Gibraltar into the Atlantic Ocean and affect the circulation of the Atlantic the LIW is a very important contributor to global circulation. Obviously, the other water masses of the Levantine basin will have to be investigated as well.

These variations could be an outcome of climatic variations. If indeed they are the result of climatic changes they can be a very sensitive way to monitor and follow the development of such changes and one can hardly exagerate the need for the continuation of such time series and with international support and co-operation extend them to cover the entire basin.