WORKING PAPER

POTENTIAL IMPACT OF THE GREENHOUSE EFFECT ON THE MEDITERRANEAN SEA: OVERVIEW

Marco Zavatarelli

September 1988
WP-88-76

IIASA
International Institute
for Applied Systems Analysis

POTENTIAL IMPACT OF THE GREENHOUSE EFFECT ON THE MEDITERRANEAN SEA: OVERVIEW

Marco Zavatarelli

September 1988
WP-88-76

The author was a participant in the Young Scientists' Summer Program of 1987. He worked in the European Case Study of the Biosphere Project.

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

PREFACE

One of the objectives of IIASA's Study, *The Future Environments for Europe: Some Implications of Alternative Development Paths*, is to foresee long-term, broad-scale environmental transformations before they actually occur. Toward this goal, this paper focusses on the potential changes in the Mediterranean Sea owing to climatic change and chemical pollution. Hitherto, the Mediterranean Sea, especially the deeper, western half, has been relatively resilient to environmental changes. This is true in part, because of its great depth compared to, for example, the North and Baltic Seas, and in part because of the relatively low inputs from industrial wastes compared to the situation in northern Europe.

However, as explained by the author, plausible changes in climate may lead to large-scale environmental changes in the Mediterranean and the adjacent Adriatic Sea. Moreover, an expected rapid level of development on the southern coast of the Mediterranean, owing to population pressures and industrialization, could lead to increased inputs of chemical pollutants over and above those originating from development activities on the northern coast.

Finally, the author sets forth the possibility of utilizing the monitored changes in the Mediterranean Sea, sometimes defined as a "reduced scale ocean", for gaining insights into the physical and biological changes that may occur in the larger world ocean systems. Thus, this paper is relevant, not only to countries bordering the Mediterranean Sea, but also to more general concerns about responses of large marine systems to climatic change.

William M. Stigliani
Coordinator
Future Environments for Europe

TABLE OF CONTENTS

POTENTIAL IMPACT OF THE GREENHOUSE EFFECT ON THE MEDITERRANEAN SEA: OVERVIEW

Marco Zavatarelli

1. INTRODUCTION

1.1. General

The possible climatic variations linked to the predicted doubling of atmospheric concentrations of the so-called "greenhouse gases" by the middle of the 21st century (National Research Council; 1983) are expected to have profound effects on the biosphere. The concentration increase will directly affect the climate, vegetation and the global carbon cycle. The amplitude of these effects could be very strong and may occur over a relatively short time period. Consequently the transition to a new thermal equilibrium can be considered as an important "stress factor" acting on the biosphere.

As oceans are one of the key elements in Earth's climatic system, a variation in the atmospheric climatic parameters (temperature, moisture, wind regime, etc.) must involve also variations in the world's oceanographical systems. The importance of such variations will depend on the actual atmospheric warming that will occur (that, in turn, will depend on the future emissions of greenhouse gases). Furthermore, effects may vary depending on the different characteristics of the various basins forming the world's oceans.

Models developed by climatologists studying the greenhouse effect must treat the atmosphere and oceans as a coupled system. In such models the air-sea thermal coupling coefficients describe the transfer of heat from the atmosphere to the ocean, which acts like a flywheel for storing the thermal energy in the climate system (Dickinson, 1986), and determines the delay in the atmospheric warming.

For example the model developed by Schlesinger (1986), based on estimates of the increase in CO_2 concentration occurring between 1850 and 1980, showed that the oceans' sequestering of heat was responsible for the concomitant warming being about half that which would have occurred in the absence of the world ocean system.

In this report the approach to the problem is "reversed"; i.e., the greenhouse effect is considered as an accelerating factor for a global change in the oceans.

Moreover, the report focuses mainly on the Mediterranean Sea, from the point of view of the possible effects that climate change could have on the most important physical-oceanographical patterns. Of additional interest is the potential impact of sea level rise acting on the Mediterranean coastal areas.

The aim is to provide a general overview on these topics, examining the variations that the global warming could impose to the actual situation. It must be stressed that the considerations and the hypotheses made in this paper deal with the problem in a very general way. The complexity of the factors involved in global change, and the uncertainity about its patterns, coupled with the complexity of the Mediterranean physical system, did not permit a more profound analysis within the scope of IIASA's YSSP.

1.2. Organization of the Report

The objectives of the report are:

— To identify and define, on the basis of the scientific literature (models, scenarios), the possible general variations in the atmosphere-ocean system that may occur in future.

— To assess the climatologic and hydrologic characteristics of the Mediterranean Sea within the framework of the "greenhouse scenarios".

— To assess the possible problems arising from a sea level rise in the Mediterranean coastal areas.

— To evaluate other possible variations occurring during the expected climatic change.

To achieve these goals the paper is divided into nine chapters: the remainder of this introduction describes why a study of the Mediterranean is important for our overall understanding of the effect of global climate change. Chapter 2 describes and discusses briefly the forecast future climatic scenarios, and the related possible variations in the oceanographic parameters. In chapter 3 a general overview of the oceanography and climatology of the Mediterranean Sea is given. The hypotheses about the change in the Mediterranean oceanography, according to different scenarios, and the implications concerning the physico-chemical and biological characteristics, are developed in chapters 4 and 5 respectively. Chapter 6 is devoted to an analysis of the possible combined effects of warming and increases of pollution on the coastal ecosystem. In chapter 7 the well known sensitivity of the Mediterranean Sea (and particularly of the Adriatic Sea) to climatological factors is reviewed, and the possibility of utilizing the sea as a "sensitivity indicator" of climate change is discussed. Chapter 8 discusses the problems associated with sea level rise, whereas chapter 9 deals with other possible problems that could arise in the future.

1.3. Why the Mediterranean?

Because of its size, and oceanographic characteristics, the Mediterranean Sea is often defined as a "reduced scale ocean".

Since a study of the processes occurring in the Mediterranean can be conducted more easily than in the oceans, it has even been suggested that studies of the Mediterranean may provide invaluable insights on the features (both physical and biological) of the world ocean systems.

For example, the process of deep water formation, observed and studied in the northwestern Mediterranean basin, occurs also in open sea areas like the Labrador Sea and, perhaps even the Antarctic Ocean; moreover, the close link between its oceanography and climate may provide a "model" basin for the long term response of the sea to atmospheric and energy-exchange forcing.

2. GREENHOUSE EFFECT: THE FORECAST SCENARIOS

2.1. Greenhouse Gas Emissions

As briefly pointed out in the introduction, the real extent of future atmospheric warming will be dependent on the rate at which greenhouse gases are released to the atmosphere. The scientific evidence on CO_2 emissions can be summarized as follows (Hekstra, 1986):

— Atmospheric CO_2 will continue to increase by 0.5% yearly. Even if fossil fuel burning were to slacken, atmospheric CO_2 will continue to build up.

- Other trace gases emitted mainly by human activities (nitrous oxide, methane, CFCs and tropospheric ozone), collectively may affect climate as much as CO_2 alone. Concentrations of CFCs can be more easily influenced by policy measures.
- Recent scenarios for the emissions of CO_2 from fossils fuels tend to show less rapid growth than was generally believed a few years ago. However coal use is increasing again world wide.
- Depending on the choice of the CO_2 emission scenario (IIASA-high, IIASA-low or zero growth) the doubling of the preindustrial atmospheric concentration of CO_2 (280 ppm) will occur about the year 2043, 2068 or 2139, respectively.

2.2. Climatic Variation

2.2.1. Models and scenarios for climatic impact-forecasting

General circulation models (GCMs) are regarded as the most promising tools in climatic impact simulation studies (Hansen et al., 1981; Hekstra, 1986). In these models the atmosphere is represented by a three-dimensional mesh of points separated by about 5 lat. or long. and by about 1 km in the vertical dimension; the lower boundaries for the system are the Earth's continents and oceans.

A GCM becomes a complete climatic model with the addition of submodels describing oceans, soil moisture and snow cover. Such sub models are considerably oversimplified; oceans, for example are in reality as complex a dynamical system as the atmosphere, and their surface temperature can only be properly obtained by coupling ocean models to the atmospheric GCMs (Dickinson, 1986).

In addition to the oversimplification of the coupled submodels, a major disadvantage of the GCMs is that the grid points are in general too large for accurate climatic impact forecasting on a regional scale.

Moreover, it must be stressed that in climatic impact simulation studies, the quantity of short wave energy that Earth receives from the Sun is assumed as constant; hence, a change in solar activity could lead to different patterns of climatic variation.

Another method for devising future scenarios is based on the use of historical climatic data, looking at the climate of the warmest years compared with the characteristics of the coldest years (Lough et al., 1983; Palutikof et al., 1984.) This method uses the natural variability of climate, and allows the development of a set of different scenarios, dependent on the selection criteria of the warm and cold periods.

The analyses of past climates to generate future scenarios have been utilized by Flohn (1980, 1981), who examined previous warm periods in the Earth's history (the Medieval-warm period, the Holocene warm period, the last interglacial period and the late Tertiary period). The climatic characteristics of each period were correlated to the atmospheric CO_2 concentrations necessary to have induced the examined climates.

2.2.2. Atmospheric warming

GCMs have estimated annual temperature increases from a doubling in CO_2 concentration of between about 1.5 and 4.5° C (Schlesinger, 1986; Bolin et al., 1986).

On a seasonal basis, Jäger (personal communication, 1987) has provided the following ranges in temperature change for different latitudinal parts of Europe:

Winter:			
-0.5° C	to	+4.0° C	Mediterranean
+4.0° C	to	+6.0° C	Central Europe
+5.0° C	to	+10.0° C	Northern Europe
Summer:			
+2.0° C	to	+6.0° C	Mediterranean
		+2.0° C	Central and Northern Europe

However, forecasting of mean temperature variation is not a sufficient tool for a complete and reliable understanding of effects from climatic change, since the mean value of temperature is the result of the interactions of many different (and difficult to predict) parameters, like wind regime, daily temperature, evapotranspiration processes, precipitation etc. The combined variations of these factors could compensate or aggravate the effects induced by the mean global warming.

The general study of possible climatic variations developed by Flohn (1980, 1981, 1982) stresses as one of the most striking consequences of global warming, the occurrence of an ice-free Arctic Ocean together with a heavily glaciated Antarctic continent. This situation, increasing the existing climatic asymmetry between the two hemispheres in the general circulation system, could cause the northward shift of the arid climatic belt, with a septentrional limit at between 35 and 45 lat N. Consequently the Mediterranean climate could be replaced (totally or partially) by an arid climatic system.

However, despite the general consensus about a global warming in the next 100 years, the hypothesis of a regional (or general) cooling in Europe cannot be disregarded: see for example the scenarios prepared by Lough et al. (1984) (particularly the scenarios A and C), suggesting a possible future cooling over the Mediterranean region in the transitional period before ocean warming is complete.

2.2.3. Ocean warming

The oceans' role for providing thermal inertia and heat to the atmosphere is often represented by proxy measurements of the sea surface temperature, although it is the heat transport and content of the oceans, and the heat flux to and from the atmosphere, that are crucial to understanding the oceans' role in climate.

An increase of CO_2 concentration, if it causes atmospheric warming, will warm the oceans; hence one might expect the sea surface temperature to increase by about the same amount as the air surface temperature. Normal ocean processes would mix this surface signature to greater depths; the resulting change in the oceans' density structure would raise the sea level and, perhaps, change some features of the oceans' circulation. These changes would probably be regional in nature (marginal seas, regions of water mass formation), because the processes which would redistribute the heat are known to have such characteristics.

Analysis of historical data series suggests that variation of air temperature, measured over sea surface, and the corresponding variations of sea surface temperature, track reasonably well (Barnett: 1984, 1985). Hence, the mean variation of air temperature should be strictly followed by a similar variation in the mean sea surface temperature.

On the contrary, the mixed layer warming is more slow; at least 25 years are needed to adjust the ocean mixed layers to about 70% of the changed mean surface temperature (Cess and Goldenberg, 1981; Hekstra, 1986).

A study on the heating of ocean waters (from present time to the year 2080) in the 0–1000 m depth range and in the 60 N–80 S latitudinal range, has been carried out by Revelle (1983), utilizing as the actual "image" of the thermal state of the oceans the data reported by Sverdrup et al. (1942), and as future sea surface temperature the projection made by Flohn (1982). Revelle reported on the increase in temperature in the Mediterranean latitudinal range, of between 3.5 and 5.0° C in the surface layers, and between 0.5 and 1.5° C in the 1000 m deep layers. However, these values are only indicative of the mean Atlantic and Pacific Ocean temperature characteristics; the pattern of heating the Mediterranean Sea could be totally different.

2.3. Sea Level Rise

A possible sea level rise is regarded as one of the most important consequences of the greenhouse effect. In the past century the relative sea level seems to have risen by about 20 cm (Barnett, 1983); the factors involved in this phenomenon are thought to be essentially two: thermal expansion of upper ocean water and polar ice melting.

At the 1985 Villach Conference thermal expansion was considered to be the most important factor acting on future sea level rise (Bolin et al., 1986); nevertheless, analysis of historical data series (Gornitz, 1982; Barnett, 1985) indicates that this factor can explain, at most, only a part of the observed sea level rise. The Netherlands Health Council (1985), arrived at the same conclusion, and a future rise of between 42 and 69 cm is predicted, with the contribution from thermal expansion of about 8–16 cm.

The contribution of polar-ice melting to the global sea level rise is still open to question; concerning the next 100 years, there is general agreement about the possible complete melting of the Arctic ice floes, while a collapse of the Antarctic ice sheet is not thought to be imminent (at least not in the next 100 years).

Another contribution to the global sea level rise could be the melting of small glaciers: actually, although the range of error is large, the contribution of these glaciers appears to account for a third to half of the observed value (Meier, 1984).

However, models developed to assess the possible future sea level rise show large differences in both the low and high scenarios. These differences depend on the different methods used in the construction of the models and on the relative importance attributed to the different elements potentially acting on sea level rise (SLR). The results of the models are summarized below:

SLR (cm)	Author	Year
42-69	N.N.H.C. (1985)	2085
70	Revelle (1983)	2080
38-213	Hoffmann et al. (1983)	2075
20-165	Robin (1986)	2080

Notwithstanding the large variation in forecast ranges, a sea level rise of about one meter by the year 2100 seems not unlikely. Even considering the possibility of an ice-free Arctic ocean, the sea level rise will not exhibit the dramatic rise (5 m or more) obtained by projections dealing with the possibility of the Antarctic ice melting. Nevertheless, even the more modest rises in sea level cited above are sufficient to raise serious problems in many coastal areas (chapter 8). The increase of sea level will be probably very slow during the first few decades, but thereafter rates may be progressively increasing; the increase will probably not be clearly detectable until approximately the year 2020 (Thomas, 1986).

3. THE CURRENT OCEANOGRAPHIC AND CLIMATIC CONDITIONS OF THE MEDITERRANEAN SEA

In this chapter a brief account of the principal characteristics of the Mediterranean Sea is given. In order to discuss the possible effects of climatic change on the sea, the general features, the climatology, and the most important oceanographical patterns are briefly summarized. For a more detailed description see Lacombe and Tchernia (1972) and Miller (1983).

3.1. General Characteristics

The Mediterranean Sea is a sill basin separated from the general oceanic system by the Gibraltar Straits and from the Black Sea by the Bosphorus. In turn, it is subdivided into a series of smaller basins, the most important being the Siculo Tunisian sill, which divides the eastern part of the Mediterranean from the western basin. In many respects these two parts exhibit distinctive hydrographical conditions.

These two main eastern and western basins are divided by various sills and channels into many sub-basins. For the purpose of this report we shall focus on three major areas: the northwestern basin comprising the Gulf of Lion and the Ligurian Sea (western Mediterranean), the Adriatic Sea, and the Levantine basin (eastern Mediterranean). Each of these areas is characterized by strong vertical movements of water masses under the influence of the seasonal climate.

The complex system of channels and sills inside the basin plays a very important role in the development of the oceanographical characteristics of the individual seas forming the Mediterranean. The waterflows through each channel are constricted vertically and laterally by the topographical features; moreover, in order to maintain the conservation of mass, the circulation between sub-basins is complicated by the requirements for return flows (Bethoux, 1980.)

3.2. Climatology

The climate of the Mediterranean basin is characterized by diversity; desertic and arid regions border the eastern and southern coasts, while in the northwestern part climatic conditions are more wet, especially in winter. Generally speaking summers are dry and winters are humid.

Atmospheric circulation in summer is mainly dominated by the Azores anticyclone, which extends its influence over the whole of western Europe; the resulting intensive heating generates a field of relatively low pressure responsible for the generation of antycyclonic winds blowing over the whole basin.

In winter, meteorological depressions coming from the north Atlantic move over the basin from west to east (and often halting over the northern part of the basin). This pattern causes heavy precipitation on the northern coasts, and the occurrence of cold and violent winds: Mistral and Tramontana (Gulf of Lions and Ligurian Sea), Bora (northern Adriatic Sea).

3.3. Oceanography

The Mediterranean Sea's physical oceanography is determined by climatology; the water loss due to evaporation is greater than the gain of freshwater provided by direct precipitation and by river discharge (comprised of the water inflowing from the Black Sea). Hence, if the Mediterranean Sea were not connected to the general ocean system, the mean sea level would be lowered by about one meter ($\pm$ 30%) every year because of its negative water budget (Tixeront, 1970; Lacombe and Tchernia, 1972; Bethoux, 1979.)

The water deficit is replenished by the flux of water coming from the Atlantic Ocean through the Gibraltar Straits; in this way the water volume is maintained. The continuously inflowing water and the evaporative losses might suggest a progressive increase in the mean salinity, but the Mediterranean's salinity value seems to be constant through time. The maintenance of water and salt budget in a steady state is provided by the existence (at the Gibraltar Straits) of two superposed fluxes of water: a surface inflow and a deep outflow. These two fluxes have different volume and salinity characteristics; generally speaking the inflowing volume is about 4.7% greater than the outflowing volume, and introduces into the Mediterranean Sea a quantity of salt equal to the quantity exported by the outflow, whose salinity is about 4.7% greater than in the inflowing waters.

Through these superimposed fluxes the Mediterranean Sea maintains (at least on time scales of societal interest) its water, salt and heat budgets in a steady state, acting like a "machine" transforming the Atlantic water into a typical, dense and saline "Mediterranean" water. This transformation is the most important hydrologic feature in Mediterranean oceanography; because of this process this Sea is a concentration basin, like all the tropical and subtropical enclosed seas (Gulf of California, Red Sea). The circulation patterns at the straits can be defined like a reversed estuary circulation.

In order to provide a link between the two fluxes, the functioning of this hydrological engine requires the existence of vertical water movements; in these processes the Mediterranean Sea fully reveals its strong connections between hydrology and climate.

The transformation mechanism is spatially and temporally differentiated; i.e., different areas of the sea have different functions, and the mechanism in winter differs from that in the summer. According to Lacombe and Tchernia (1972) it is possible to distinguish two phases:

1) Summer pre-transformation
2) Winter final transformation.

1) In summer the Atlantic water is pre-conditioned for the large transformation occurring in the winter. The warming of surface layers resulting from the absorption of solar radiation is greater than the heat loss from long wave radiation and evaporation (heat budget > 0). This situation leads to the formation of a thermocline (20–40 m depth) acting like a screen limiting the exchanges between the surface and the underlying waters: surface layers over the thermocline increase in temperature and salinity (caused by evaporation), but the density structure is dominated by temperature maintained at equilibrium near the surface of this water mass.

2) In winter the heat budget is reversed (< 0). Evaporation and heat release are strongly enhanced because of the influence of different factors: sea surface temperature can exceed air temperature by about 8° - 10° C, the occurrence of strong dry winds is another important factor enhancing evaporation. The high salinity surface layers are no longer in equilibrium with the underlying water mass (because of the cooling) and vertical convection movements start, providing the renewal and the ventilation of deep waters.

This phenomenon influences the whole basin in three well defined geographical areas:

a) Southeastern Aegean Sea and the Rhodes-Cyprus area (Levantine basin);
b) Northern Adriatic Sea;
c) Gulf of Lions, Ligurian Sea (northwestern basin).

a) In this area the warm surface waters are mixed with the less saline Atlantic waters under the thermocline. The result of the mixing is the formation of the "Levantine waters" that spread throughout the whole eastern basin and into the western basin where, after mixing, they form the "Intermediate waters", lying at a depth between

250 and 400 m. This water mass forms the main part of the outflow at Gibraltar (about 90% of the outflowing volume).

b) The shallow continental shelf and the deep part of the northern Adriatic Sea are the place of formation, under the influence of the Bora wind and the cold and dense water (Franco et al., 1982); the dense waters formed in the shallow part sink in the south depression of the Adriatic and are not involved in the water exchange through the Otranto Sill (the limit between the Adriatic and the eastern basin). On the contrary, in the deep part intensive convective mixing form dense waters that are carried through the Otranto Sill, becoming the main source of the deep water mass for the whole eastern basin (Ovchinnikov et al., 1987.)

c) Under the action of the Mistral and of the Tramontana, the surface waters are mixed with the intermediate waters. The resulting water mass sinks down to great depth (up to 2000–2500 m depth) forming the deep waters of the western basin.

The sunken water mass is replaced at surface by deep waters less dense and richer in nutrients. This exchange regulates the ventilation of the deep part of the basin and the fertilization of surface waters, a crucial phenomenon for primary production in the Mediterranean.

3.4. Evaporation: The Link Between Mediterranean Climate and Oceanography

The Mediterranean oceanographic characteristics leading to the transformation of the water described above are mainly dependent on air-sea exchange processes, and evaporation is the major factor dominating the process (section 3.3). The evaporation pattern depends on seasonal climate: the summer heating of the eastward moving Atlantic water (the summer pre-transformation) determines the evaporation, but the associated loss of heat is compensated by the incoming radiation. Hence the water's slow downwelling is due primarily to a loss of fresh water which increases the salinity value, rather than to a heat loss.

In winter the strong and intensive vertical movements determining deep water formation are due predominantly to the evaporative heat loss rather than to the increase in salinity. Interestingly, the winter evaporation results in a loss of buoyancy that is two orders of magnitude less than the annual large-scale loss of buoyancy over the Mediterranean (Bryden and Stommel, 1984); but it occurs quickly over a small area (see section 4.2), and forms a comparatively small volume of dense deep water, rather than a large volume of slightly modified intermediate water. For these reasons the water mass formed in winter can sink to great depths.

This situation is well documented in a study of the monthly mean evaporation over the Mediterranean Sea made by Colacino and Dell'Osso (1977), who calculated the mean evaporation values for the different Mediterranean basins, examining the nature and causes of some "anomalous" values.

For example, the calculated evaporation value for the western basin is 969 mm/y, but for the Gulf of Lion region the mean annual value is 1561 mm/y: the difference between the values explains very well the importance of the Mistral in this area, and highlights once more how deep water formation depends on the general atmospheric circulation system.

This discussion has briefly described the current characteristics of the Mediterranean Sea: the challenge is to understand how these features may change with the expected large-scale changes in climate.

4. SOME POSSIBLE CLIMATIC SCENARIOS AND THEIR EFFECT

Considering the current characteristics of the Mediterranean Sea described in the preceding section, and taking in account the forecast scenarios (chapter 2), two hypotheses about change in the Mediterranean can be made: the first one deals with the possibility of a cold Mediterranean region during winter, whereas the second projects a warmer Mediterranean, considering also the non-uniform latitudinal variations in the greenhouse warming.

4.1. First Hypothesis: Cold in Winter, Warm in Summer

The low-scenario temperature change given by Jäger for the Mediterranean latitudes forecasts for the winter season, not a mean seasonal warming, but on the contrary a slight cooling of 0.5° C. The corresponding low-scenario value for the summer period is a a 2° C increase in the mean temperature value.

One consequence of the increased temperature difference between the cold and the warm seasons might be an intensification of the processes currently determining the physical oceanographical features of the Mediterranean Sea (chapter 3). The basis of this increase would be an increase in the evaporation processes both in summer and in winter: in summer the enhanced evaporation would be caused by atmospheric warming, while in winter the warmer sea surface water coming in contact with the colder winter air would likewise tend to increase evaporation. This process could be strongly enhanced if the winter cooling were to be associated with lower atmospheric pressure over the Mediterranean and higher atmospheric pressure over central and northern Europe, as presented in one of the scenarios prepared by Lough et al. (1983) and Palutikof et al. (1984) (scenario C). This increase in the latitudinal pressure gradient could cause an increase in the number of depressions coming from northern latitudes and moving through the Mediterranean. Because events of this kind are associated with the occurrence of the cold and dry winds blowing over the deep-water formation areas, evaporation in these areas could increase. This in turn could intensify the "anomalous" evaporation in basins such as the Gulf of Lion (section 3.4) and hence, to a first approximation, improve the functioning of the Mediterranean "engine". As a result, the water deficit should be increased and, in order to maintain a steady state in the water balance, a major inflow volume and an increase in the outflow salinity (or volume) would be required. Thus, the thermohaline circulation will be enhanced, and the residence time of water in the Mediterranean basin would be reduced.

In conclusion, one may regard this hypothesis as a "stable" scenario, because the projected changes indicate an intensification of the current characteristics. On the contrary, the increase in the number of depressions occurring in a "colder" Mediterranean set in a warmer world could result in a more "stormy" sea. This possibility, considered together with the potential sea level rise, could cause major problems in the coastal areas (chapter 8).

4.2. Second Hypothesis: Decrease in Winter Evaporation

A second scenario is based on a differential winter warming between north-central Europe and the Mediterranean region. As the forecast warming is higher in central latitudes (section 2.2.2), a latitudinal decrease in the temperature gradient could be expected. The consequence could be a weakening in the general wind regime (Sibley and Strickland, 1985). Generalizations are difficult to make, but, for example, several upwelling phenomena exist because of the coincidence of properly oriented winds and coastlines, and it cannot be assumed that after a shift in wind patterns such coincidences will persist.

Applying this assumption to the Mediterranean Sea, it appears clear that, once more, the critical zones that could be affected by variations in the wind regime and in the atmospheric circulation are the areas where the intermediate and deep waters are formed.

In the northwestern basin, for example, the occurrence of Mistral depends not only on the general winter weather system, but also on the orographic continental morphology, as the wind is funnelled over the Gulf of Lions by the Alps and the Pyrenees.

The occurrence of deep water in winter under the influence of wind in the northwestern Mediterranean Sea was observed and described by the MEDOC Group (1970). Their analysis clearly demonstrates that the sinking of surface water (the so-called "violent mixing phase") occurs over a short time and space scale (a few days, a few square kilometers). In particular the time scale of these events is so short that it practically does not affect the mean slow upward movement of water masses during the winter season observed by Seung (1980) and Lacombe et al. (1981). In this way the described "anomaly" in the evaporation patterns (section 3.4) is translated into a hydrological "anomaly", causing a strong increase in the density field of the surface waters, and consequently a buoyancy loss resulting in its sinking.

Bryden and Stommel (1984) calculated the critical value of the buoyancy loss necessary to initiate the violent mixing phase and the successive spreading to the deep; the calculated value (for a Mistral event) is about 4.6 g/cm^2. This value could be thought of as a transition state between a ventilated and a stagnant deep water mass. Bunker (1972) observed a buoyancy loss of about 5.0 g/cm^2 during a Mistral event. This value corresponds to the 28 year mean value calculated by Bunker and Goldsmith (1979), although single seasonal values of about 8.6 g/cm^2 have been observed.

The observed value (5.0 g/cm^2), just a little higher than the critical theoretical value, is sufficient to determine deep water formation. If this value corresponds to the long term average value, it is reasonable to assume that the occurrence of more mild winters in the Mediterranean region may cause a possible reduction (or a slackening?) in the Mistral events due to the reduced latitudinal temperature gradient. This change in turn may have a negative influence on deep water formation.

The same considerations can be applied to the deep water formation process occurring in the northern Adriatic Sea. According to the recent paper of Ovchinnikov et al. (1987) the mechanism there follows the same patterns described by the MEDOC Group. However, changes could be even more easily affected in the Adriatic since it has already been demonstrated that the deep water formation in the sea is quite sensitive to year-to-year fluctuations in the winter environment (Zore Armanda, 1963; Buljan, 1953; and Buljan and Zore Armanda, 1976). Moreover, considering this sensitivity, one interesting question to ponder is whether the Mediterranean Sea as a whole, and particularly the Adriatic basin, may be utilized as an indicator of the effects of climate change on oceanographic systems. This hypothesis is discussed in chapter 7.

Given the possibility that a shift in the winter wind regime could change the oceanographical patterns of the Mediterranean, what would be the new physiognomy of this Sea? Generally speaking, as discussed above, the winter evaporation process caused by the heat release from the sea surface to the atmosphere could be affected. Moreover, a shift towards more arid conditions, accompanied by an increase in the sea surface temperature will enhance the evaporation associated with the transfer of fresh water from the sea to the atmosphere as water vapor (section 3.4). This increase, if compensating the reduction in winter evaporation due to a changing wind regime, will cause a totally different pattern of deep water formation, as the phenomenon of sudden sinking could be replaced by a more slow downwelling movement of the surface water masses. The amplitude of the vertical movements could affect the deep water characteristics, since reduced winter sinking coupled with the slow downwelling would not allow a mixing of the entire water column to the great depths attained today. Hence the renewal of deep waters could be affected. The implications of this variation for the ventilation of deep waters and for the effects on biological production are discussed in chapter 5.

4.3. Other Factors Involved in the Change

The two hypotheses developed above are, obviously, an oversimplification, since they do not take into account many other factors likely to be changed by a global warming. The most important, to which serious consideration should be given, is the feedback effect that the Mediterranean's waters will have on the regional atmospheric system; this interaction could have an important role in reducing or amplifying the effect of climatic change.

Another important factor that should be considered is changes in the freshwater input via changes in precipitation and river runoff, and changes in the water exchange between the Mediterranean and Black Sea.

Variations in precipitation and river discharge are complicated since they involve not only the climatic changes in the Mediterranean Sea, but also over the entire Mediterranean watershed.

To a first approximation, the hypothesis of a "colder" Mediterranean winter (section 4.1) could be characterized by an increase in precipitation, leading to an increase in the discharge of major rivers. This major freshwater contribution could partially compensate for the possible increased deficit from increased winter evaporation in the Mediterranean.

On the other hand, the occurrence of a warmer Mediterranean climate could result in reduction in precipitation and in river runoff. However, since the Alps are part of the Mediterranean watershed (Ambroggi, 1977, Fig. 1), these reductions could be compensated for by an enhanced melting of alpine snows feeding the two major European rivers discharging in the Mediterranean (Po and Rhone). These changes could have strong local effects: for example in the northern Adriatic, freshwater discharge from the Po influences the salinity distribution patterns, causing lower salinity values in spring-summer and higher values in winter, when retention of water as snow reduces the discharge volume (Buljan and Zore-Armanda, 1976; Franco, 1983). Hence, increased freshwater runoff in winter could probably serve to enhance the stability of the surface water mass, because, together with the increased temperature, it could act to reduce the sea water density, and contribute to a reduction in the winter mixing.

5. IMPLICATIONS OF THE POTENTIAL CHANGES IN THE MEDITERRANEAN'S OCEANOGRAPHY

5.1. Oxygenation Problems

The aim of this section is to discuss the potential for anoxia in the Mediterranean Sea, or at least an alteration in the deep water oxygen balance, given the second scenario described in section 4.2.

Currently, the vertical circulation supplies enough oxygen to the deep layers to maintain an oxygenated environment in the water column as well as in the surface sediments at the bottom of the basin.

The two main deep oxygen sources in the eastern and western basins are the two areas of deep water formation in the deep northern Adriatic Sea and in the northwestern basin respectively (see chapter 3 and Wust, 1961.)

Nevertheless, deep sediment cores sampled in the eastern Mediterranean, suggest that a different situation occurred during several periods of the late Quaternary. The cores present a sequence of black, grey and brown layers indicating that sedimentation patterns were drastically different in the past. The most remarkable features are the black layers: the so-called sapropels. They are rich in organic matter, and it is well known that the presence of high organic matter in sediments indicates a lack of oxygen available in the water column; if the oxygen content is lower than a minimum value, the fraction of organic detritus being incorporated in the sediments increases. Hence the sapropel layers indicate periods of lowered oxygenation in the deep eastern basin.

Various working hypotheses have been developed to explain the formation of sapropels: strong influx of fresh water derived by the melting of the glacial ice sheets arriving into the Mediterranean via the Adriatic, the Aegean and the Black Seas; enhanced rainfall; influx of less saline Atlantic waters accompanying a strong sea level rise; and thermal stratification induced by a warming of the upper layers faster than the warming of the local deep layers. (See Vergnaud-Grazzini et al., 1977.)

All these hypotheses indicate the formation of lighter waters in the Mediterranean upper layers (more warm and/or less saline) inhibiting the vertical convective water exchange. This point of view is well synthesized by Mangini and Schlosser (1986), who point out that a climatic change able to produce an increase in temperature of about 0.7° C or a decrease in salinity of about $0.2^{o}/oo$, in the Adriatic basin could be sufficient to stop the advective supply of oxygen to the deep basin, since it will produce a water mass overflowing the deeper waters. If the advective oxygen supply is cut off, the amount of available oxygen will rapidly decrease since the time scale for diffusive oxygen renewal is considerably larger. Hence, sapropel occurrence will be favoured during any climatic change toward more humid and warmer conditions. This has happened during the onset of interglacial periods (in fact the corresponding sapropel layers are well correlated), although there is also paleoclimatic evidence for sapropel formation during cold periods.

Thus, climatic change leading to an increase in the sea temperature and an alteration in the winter weather system causing milder winters could tip the system toward a reduced (or slackened) deep water formation, and lower oxygen concentrations in the bottom waters.

A warming trend, more than a reduction in the salinity, may be the major factor determining the change in oxygen concentration, although an increase of the river discharge into the Adriatic could also contribute. For example, Van Straaten (1972) has attributed the formation of sapropels in former times to a rise in winter temperature, leading to a thermal stratification and interruption of the deep water ventilation.

However, it must be stressed that the extent and the amplitude of any variation will depend on the character of the climatic change. Some paleoclimatic data indicate that changes in oceanographic-atmospheric interactions occur as sharp jumps rather than in a smooth and gradual way (Broecker et al., 1985; Broecker, 1987.)

5.2. Biological Production Problems

In this section the discussion is focussed on the possible effects that a global warming in the oceans (and particularly in the Mediterranean) could have on the marine primary production.

5.2.1. Abiotic factors acting on primary production

According to Sibley and Strickland (1985), the abiotic factors that could be affected by climate-induced warming are:

1) Temperature;
2) Vertical stability versus turbulence;
3) Vertical circulation;

4) Horizontal circulation.

1) As a general rule an increase in water temperature will increase the metabolism of all species.

2) The balance between turbulence and vertical stability has important and opposite effects on primary production. A strong stability favours high photosynthetic rates, since the floating organisms are retained near the surface where there is sufficient light to maintain the photosynthetic activity, rather than to be mixed to greater depths where light is a limiting factor.

   On the other hand primary production requires a nutrient supply, and stability is related to reduced mixing, which limits the replenishment of nutrients from the lower layers, leading to nutrient depletion as phytoplankton utilize all the available nutrient stock.

   The turbulence-stability balance affects also the phytoplankton species composition, that, in turn can affect the higher trophic levels (Greve and Parsons, 1977).

3) Vertical circulation determines the exchange of water and nutrients between surface and deep waters. This exchange represents the principal pathway by which nutrients are supplied to the upper layers. Coastal upwellings and areas of divergence are highly favorable for primary production since phytoplankton cells are retained within the euphotic zone, and are provided with high nutrients stocks for sustaining population growth.

4) Planktonic organisms are very susceptible to horizontal transport (currents, eddies, internal waves), since it affects the spatial distribution together with the vertical transport.

5.2.2. Mediterranean production and some potential changes

Because of its low nutrient levels the Mediterranean Sea is an oligotrophic system: by analogy with terrestrial ecosystems, it is comparable to the arid and semidesertic areas. Its primary production patterns depend particularly on the vertical circulation for the transport of the nutrients from the deep to the upper layers.

According to Margalef (1984) it is possible to distinguish two principal ecological seasons: a "warm" semester (May–October) and a "cold" semester (November–April). The "warm" period is physically characterised by the processes leading to the "summer pre-transformation", whereas the "cold" one is determined by the "winter final transformation" (section 3.3).

From May to October the water's thermal stratification reduces (or blocks) the transport of nutrients from the lower layers. Conversely, in the "cold" period the entire water column is mixed, causing the fertilization of the surface waters (Coste et al., 1972; Jacques et al., 1973.)

The formation of deep water and the importance of wind in this process have been already discussed. It is important to note that biological production is essentially dependent on the energy involved in the mixing process. Margalef (1984) defined the external energy influencing the primary production as "exosomatic", in contrast to the electromagnetic energy necessary for photosynthesis. The connection between the exosomatic energy and biological production explains why the coldest years are in general the most productive ones.

Accompanying the changes in the water-mass stability and nutrients availability are changes in species composition of phytoplankton. In general, the period of maximum fertilization is dominated by populations of diatoms, successively substituted by coccolithoforids, and finally, when the stratification of the water column begins and the nutrient stock is near depletion, by dinoflagellates (Margalef, 1984; Jacques and Treguer, 1986.)

However, a new fertilization event occurring in a later stage could start the process anew.

If the vertical circulation is altered by a climatic change causing increased stability of the surface water masses and a reduction of nutrient supply, the end result could be a reduced pelagic primary production. Moreover, there could be a shift in the phytoplankton species composition, subsequently affecting the higher trophic levels (Greve and Parsons, 1977) with a possibly negative effect on fisheries resources.

On the contrary, in the coastal areas the opposite effects could predominate. Increased nutrient inputs from anthropogenic sources together with the increased stability of the water masses (coastal waters have in general higher temperature than offshore) could favor an increase in the primary production (more nutrients supply and more water stability). This situation could give rise to increased episodes of eutrophication and anoxia in coastal waters (chapter 6).

6. CLIMATIC CHANGE AND POLLUTION

The oligotrophic structure of the Mediterranean Sea has been the most important factor in maintaining a relatively good "ecological health", in spite of the increasing land-based pollutant inputs (Helmer, 1977; UNEP, 1977; Jacques and Treguer, 1986.)

In fact the Mediterranean offshore waters seem to be still relatively unaffected by the strong pollution increase that has occurred in recent years (Tolba, 1986.) In some coastal areas however, local eutrophication episodes are occurring with increasing frequency as a result of increasing inputs of sewage disposal and nutrients from rivers (UNESCO, 1982.)

The greatest area affected by these problems is certainly the shallow northern Adriatic, where the direct sewage outfall of many coastal cities and the high nutrient concentrations discharged by the river Po cause anomalous algal blooms (red tides) and occasionally mortality of benthic organisms (Fonda Umani, 1985; Benovic et al., 1987.) Another area affected by these phenomena is the Saronikos Gulf in Greece (Zankanellas, 1979.)

The abiotic factor that contributes most, together with the pollutant inputs, to the development of such phenomena is the stability of the surface waters at conditions of high temperature and/or low salinity. Moreover, an enhanced thermal stratification prevents the exchange between the atmosphere and the bottom coastal waters. In the presence of high concentrations of organic matter and nutrients, oxygen depletion or, in the extreme case, anoxia may occur.

On the basis of these considerations, the possibility exists that a warming of the coastal waters, if coupled with an increase in coastal ecosystem pollution in areas already affected, could intensify effects such as eutrophication, red tides, anoxia, and toxification. Moreover, these effects may spread to other zones currently unaffected.

7. MONITORING THE MEDITERRANEAN (ADRIATIC) SEA AS AN INDICATOR OF CLIMATIC CHANGE

7.1. General

Miller (1983), in his review of the physical characteristics of the Mediterranean Sea, points out:

> "...if one could screen out the seasonal effects it might be possible to use the Mediterranean Sea like an indicator or predictor of climatic change."

Keeping in mind the described dependence of the Mediterranean Sea on climate (chapter 3), this suggestion might be quite valid. Therefore, in this section we investigate how climatic change may be reflected in changes in the oceanographical parameters of the Mediterranean waters. We will do this using a "bottom-up" approach whereby climatic change "in progress", can be used to deduce its effects on the Mediterranean hydrological system.

7.2. Where and What to Monitor

Monitoring the Mediterranean Sea may seem, at a first glance, a relatively simple problem, if compared, for example, with problems that could occur in monitoring the Atlantic ocean; moreover it could provide very useful insights about general oceanographic problems. Nevertheless, an accurate, extensive and coordinated monitoring program has never been achieved (Lacombe et al., 1981; Tolba, 1987).

The use of the Mediterranean as an indicator of climatic change requires the identification of the appropriate parameters to monitor, and the areas in which to conduct long term investigations.

To a first approximation, one might assume that the best place in which to investigate long term variations in the oceanographical characteristics is the Gibraltar Straits. A climatic variation, for example sea level rise, will be surely reflected there by a change in the water fluxes entering and leaving the Mediterranean.

However, the implementation of a monitoring system at Gibraltar is fraught with many problems (both oceanographical and otherwise).

A way to check changes in sea level could be through the records provided by a network of a tide gauges. An analysis of such data over a long time horizon, along the Mediterranean coast could be perhaps very useful, although the problems described by Barnett (1983, 1985) about the statistical significance of data should be kept in mind. However, a well designed recording network could overcome these problems, and installation of this system could be realized (international problems permitting) in a relatively simple way.

Such a network could also build on the well known sensitivity of the Adriatic Sea to the interannual variability of meteorological and climatological parameters. Considering the second hypothesis of climatic change in the Mediterranean (section 4.2), and Flohn's (1980, 1981) scenario concerning the melting of arctic ice (section 2.2.2), it is interesting to note the potential utilization of the Adriatic Sea as an indicator of such changes.

Zore Armanda (1972) has related the long term variations in the occurrence of dense deep water in the Adriatic in winter, to corresponding meteo-oceanographical conditions over the north Atlantic Ocean. Over a period of approximately 20 years the salinity of the Adriatic has varied in relation to the amount of icebergs and sea ice around Iceland. The highest salinities occur at the same time as the maximum ice quantity and the year to year variations most often correlate in the same direction.

The author suggests that the quantity of ice in the north Atlantic is related to the position of the polar front (the border between the subtropical and subpolar water, corresponding to the 10° C isotherm in the 0–200 m layer), which "predetermines to a considerable degree the paths of the cyclones over the north Atlantic and the intensity of their activity".

If this relation applies over a long period of time, it means that in the years in which the north Atlantic has low ice coverage, cyclonic activity will decrease and there will be a less intensive penetration of cold polar air over Europe. This situation will have as a consequence a reduced production of dense Adriatic bottom waters.

The occurrence of an ice-free Arctic Ocean would surely affect on the Adriatic Sea, leading to a reduced production of dense bottom waters. This effect could be monitored in a (relatively) simple way; by periodical surveying with oceanographical research vessels (not much different from the program started in the 1911–1914 period by the Italo-Austrian commission for the study of the Adriatic Sea). However, the Adriatic could be monitored in a more exhaustive way through infra-red imagery remote sensing (satellites). Since the sinking of water depends on the heat loss caused by evaporation under the action of the wind, identification of a long term reduction in the heat release from the sea surface could give precise indications about a progressing climatic variation.

8. COASTAL AREAS AND SEA LEVEL RISE

8.1. Mediterranean Sea Level

The sea level in the Mediterranean Sea is considerably lower than in the Atlantic Ocean, because of the continual inflow of Atlantic water. As a general rule the Mediterranean sea level decreases from west to east (Miller, 1983).

The analysis of archeological remains of flooded areas in the northwestern Mediterranean suggests that from year 300 B.C. to year 150 A.D., the sea level rose about 7.5 cm/century. At 0 A.D. the mean sea level was about 0.5 m below current levels. Eustatic changes are estimated to have contributed not more than 0.15 m (Pirazzoli, 1976.)

In examining the effects of sea level rise in the Mediterranean, particular consideration should be given to the northern Adriatic Sea, where strong sea level variations are induced by tides (remarkable in comparison to the Mediterranean tidal range), storm surges and seiches (under the action of wind). These factors can cause fluctuations of up to one meter (Franco et al., 1982). Moreover, the eustatic variations in sea level cause a rise more rapid than that in the world's oceans: for example the sinking of Venice results from an observed sea level rise of about 2.6 mm/y, while for the whole basin the value is ranging between 2.57 and 7.40 mm/y (Buljan and Zore Armanda, 1976.)

8.2. The Physical Impact of a Sea Level Rise

The most important direct effects of a significant sea level rise are: coastal erosion; shoreline inundation owing to higher normal tides levels plus increased temporary surge levels during storms; and saltwater intrusions, primarily into estuaries, deltas and ground water aquifers (Sorensen et al., 1984).

It is necessary to stress that the potential problems caused by sea level rise will be closely connected with both future coastal management and previous development in the coastal areas. For example, the delta of a river whose bed had been intensively exploited from the point of view of sand pre-elevation will be much more affected by a variation in sea level because of the reduced solid transport feeding the delta sand bars. In the same way an intensively exploited coastal aquifer could be more sensitive to saline contamination.

8.3. Erosion and Inundation

The processes involved in shore erosion, and the resulting extent, depend largely on the type of shore being inundated.

It is very difficult to assess, in a precise manner, the effect of sea level rise on coastal erosion. The simplest method is the inundation concept, where the preexisting contours above the shorelines are used to project new shorelines. In such a system the slope of the coast is the controlling factor, as shorelines with steep slopes will have a weak horizontal displacement; on the other hand, gently sloping shores will experience a much broader area of inundation.

This methodology can be quite accurate when dealing with immobile substrates or rocky shores. However, the analyses become more complicated when dealing with mobile substrates, because not only a flooding process but also an erosion action is involved (with landward movement of the shore profile). In these cases the inundation concept can be considered as a rough and conservative method of estimation. An accurate forecasting of the sea level rise effects can be obtained only through accurate, and spatially limited case studies using a methodology similar to those utilized by Kana et al. (1984) and Leatherman (1984).

8.3.1. Sandy beaches

The erosion of sandy beaches under current conditions is caused primarily by waves carrying sand offshore during storms and by lateral shoreline transport occurring without compensation of the sand removed by new available sand.

With a significant sea level rise there will be an acceleration of beach erosion in areas already eroded, and possibly the emergence of new vulnerable areas that were not previously subjected to erosion. The reasons for this are:

1) Higher water levels allow erosion by waves and currents to act farther up on the beach profile. Such activity could cause a readjustment of that profile, resulting in a net erosion of the beach and deposition of sand on the nearshore bottom.
2) Beach profiles are generally concave, increasing in steepness near the shore. At higher sea level, waves can get closer to the shore before breaking, and this new pattern may cause increased erosion.
3) Deeper water decreases wave refraction and thus increases the capacity for lateral shoreline transport.
4) Higher sea level could change the source of sediments, for example by decreasing river transport to the sea as the mouth is flooded.

The adjustment of a sandy beach to sea level rise may be described by the so-called Bruun rule (in Titus, 1985). This rule states that the entire profile of the beach must rise by the same amount as the sea. The material (sand) necessary to raise the beach profile is generally supplied by the upper (not submerged) part of the beach through erosion. The result is the landward shift of the beach profile.

However, higher sea level can also act locally to diminish erosion if more material is made available through lateral transport of sand by wave attack on previously untouched erodible cliffs.

8.3.2. Cliffs

Cliffs along the coastline are often (but not always) protected by narrow beaches that may be temporarily breached by a storm, allowing waves to attack the base of the cliff. Depending on the nature of the rock, this action may cause erosion, undermining the stability of the cliff face. In general, a rising sea level may greatly increase the exposure of the base of the cliff to wave action, resulting in an increased rate of erosion.

8.3.3. Estuaries and deltas

Estuaries and deltas in general are formed by the deposit of fine particulate matter, and are characterized by very flat shore profiles. Rising sea level will flood the shoreline, causing loss of land owing to inundation.

8.4. Storm Surges

The term "storm surge" refers to any departure from normal water levels due to the action of storms (Kana et al., 1984). This variation can either be a rise in the level (excess of water flooding the shoreline) or a lowering (recession of water from the coastal area).

The surge (h) is related to the water depth (H) by to the empirical formula (Hekstra, 1986):

$$\Delta h/h = -\Delta H/H \ .$$

Thus, with a rising sea level the extent of surging decreases slightly; e.g., 1 cm for a sea level rise of 50 cm. The increased statistical chance of flooding occurring with a positive variation in sea level, hence, seems to be slightly compensated by a reduced chance of surging. However, generalizations are difficult to make since the actual effects that a storm surge will have on a specific coastal area depends on the local characteristics and circulation patterns. (See section 8.3 and Sorensen et al., 1984.)

A storm at higher sea level could produce a particularly worrysome side-effect on estuaries and bays. In addition to the cited erosion and flooding problems, the storm could cause a "backwater effect" leading to flooding of the rivers draining into the bay or estuary. For urban settlements in these areas, the backwater effect can cause storm water systems to malfunction, and, if heavy rains are associated with the storm, extensive flood damage.

8.5. Saltwater Intrusion

Many investigations have focussed on the potential movement and extent of salt water intrusion owing to sea-level rise. A brief summary is presented here.

8.5.1. Saltwater intrusion into aquifers

The basic theory assumes that an equilibrium condition exists between the saltwater offshore and freshwater flowing from the upland area towards the sea. Because saltwater is 1.025 times denser than the freshwater, the saltwater/freshwater interface lies below sea level, and its position depends on the height of the freshwater over the sea level. For example, where the depth of coastal aquifers is lowered by the withdrawal of water, the location of the saltwater front is controlled by the pumping patterns and intensity of water removed from the aquifer rather than by the density balance. When the existing water levels in principal aquifers are already several tens of meters below sea level, a rise in sea level would be of less consequence than a slight increase in the withdrawal rate. On the contrary, in areas where the existing water level is within a few meters of mean sea level, the impact of sea-level rise could be significant; if the sea level were to rise more than one meter, all coastal aquifers would be affected to some degree.

Another element that must be taken into account is the potential effect of coastal erosion. If the position of the freshwater/saltwater interface is close to the shoreline, the erosion effect will cause a shift of the interface landward toward the new shoreline.

8.5.2. Saltwater intrusion into estuaries

During extended droughts, decreased river flows allow the saline water to migrate up the estuary. A rise in sea level will also cause saltwater migration upstream. The intrusion of saltwater by these processes could endanger ground water supplies, if the water level in the aquifer is below mean sea level. In this case, if water is withdrawn, the salt water would recharge the aquifer.

The remaining part of this chapter focusses mainly on potential problems arising along the Italian coastal regions, estuaries, deltas and ground water reservoirs. The aim is to assess the areas in which the most critical problems may occur owing to an increase in sea level.

8.6. The Effects of a Sea Level Rise in the Mediterranean (Italy)

As stated above, the determination of the extent of sea level rise is a complicated problem. As a first approximation, using the inundation concept, all the coastal areas whose heights over the current sea level fall within the ranges of the forecasted increase are potentially threatened by the effects of flooding and increased erosion. These effects may be coupled with the effects of storm surges, particularly in the case of a climatic variation involving a reduction in the Mediterranean winter mean temperature caused by an increased occurrence of meteorological perturbations moving over the northern Mediterranean. (See section 4.1.)

One may think that these effects would be of less importance where the coast profile is steep and rocky (e.g. the Ligurian coast), but the actual hydrogeological situation and the position of the human settlements along such coasts must be carefully considered, since even in these areas erosion phenomena, both natural and "man made", are already acting. Moreover in the regions where the coastal areas are constrained between sea and mountains (Henry, 1977), the human settlements and their infrastructures (railways, roads etc.) are very close to the shoreline and hence vulnerable to erosion. In these cases a positive and significant sea level rise could put into question the "immortability" of these sites, many of which have existed since classical times. (For a discussion of the "immortality" of sites, see Weinberg and Marland, 1986.)

On the other hand, coastal areas with flat or gently sloping profiles, as in the northern Adriatic Sea and the Tyrrhenian Sea near Tuscany, will be susceptible to erosion and flooding problems. In these kinds of coastal areas a predictable loss of land could occur. A sea level rise of about 1.5 meters will produce, on the average, a coastal retreat of 150 meters (Bruun, 1986).

In any case, toxic waste dumps located in coastal areas susceptible to sea level rise could cause serious problems if the rising waters cause a release and dispersal of the toxic materials. Little information currently exists in Italy on the locations of such sites, and a survey should be conducted whereby coastal waste dumps are evaluated in relation to possible disturbance by sea level rise.

Where erosion and occasional floodings already occur, an aggravation could be expected, by which effects could be extended to neighbouring zones yet unaffected. Water circulation patterns and meteorological conditions could catalyse such extended effects. For example, in the northern Adriatic, during the decade 1950–1960, major storm occurrences, coupled with geological subsidence could have contributed to the increased erosion of the river Po's delta (Bruun, 1986; Marabini, 1985.) (See section 8.7.)

In every case considered, disregarding the type of shoreline, a sea level rise will pose serious problems for harbors, piers, and other kinds of coastal structures, both existent and likely to be built.

In the future, environmental impact assessments that take into account sea level rise should be conducted for all coastal construction. For some of the proposed plans, for example, the project destined to avoid the "acqua alta" phenomenon in the lagoon of Venice (Paskoff, 1987), the economic stakes are enormous.

Other problems owing to sea level rise could occur in lagoons and wetlands, or in general, in all the shallowest marine areas along the Italian coast. The Italian lagoons (e.g., Venice and the Marano Lagoon in the Adriatic), salt marshes, wetlands and brackish lakes near the sea (e.g., the Orbetello lagoon and the Burano lake on the Tyrrhenian coast) are typically separated from the open sea by sand bars and dunes. Sea-level rise could cause the destruction or landward retreat of these sandy barriers. This situation could pose difficult management problems, especially in those cases in which landward movement would encroach on natural reserves or protected areas. Moreover, if the upland area behind the protected area will not permit this shift owing to the presence of cultivated areas or human settlements, the natural zone will be completely destroyed. At a first glance this problem may appear to be of marginal importance. However, it should be stressed that wetlands are one of the most productive of all ecosystems; their biological production equals or exceeds that of any other natural or agricultural system. About one half of the total production is available to terrestrial animals and to coastal fisheries. Moreover, these areas serve also as nursery grounds for many fish species, some of which are commercially significant. Furthermore, wetlands remove pollutants from sewage effluents and ground- and surface waters. Also, they provide protection from coastal storms by mitigating against the effects of erosion.

Based on these functions it has been calculated that in the USA, marshes provide an annual return equal to about 5,500 U.S. dollars per acre (Park et al., 1986.) For all these reasons the U.S. Environmental Protection Agency is already planning and preparing for mitigation against the possible landward movement of the protected natural saltmarshes as a response to sea level rise (Titus, 1985; Gilbert, 1986.) A similar project should be planned also along the Italian and Mediterranean coasts (at least for the protected areas).

8.7. The Sea Level Rise Effects on River Po Delta

The river Po delta is located in the northern Adriatic Sea basin, which, because of geological phenomena, should be quite sensitive to rapid and strong sea level rise (See also section 8.1.)

The sinking of the delta, caused by subsidence, is estimated to have been about three meters during the last 2500 years, with an increasing rate of sinking during the 1950–1960 decade (Grego and Mioni, 1985; Marabini, 1985).

Moreover, the delta exemplifies long term interaction between man and the natural environment. The first "management" action was undertaken by the ancient republic of Venice in 1600 in order to avoid excessive discharge of sediments into the lagoon. Since that time the action of man on the delta's natural evolution has been continuously present. The delta's morphology and hydraulic system have been altered significantly through land reclamation and regulation of the surface water system in an effort to prevent land from dropping below sea level.

During the period from 1600-1950, the delta grew by 25 km with a growth rate of about 7 km/century in spite of the subsidence phenomena. From the 6th century B.C. to 1600 A.D. the calculated growth rate was only 450 m/century. On the contrary, after 1950 the area started to shrink. The causes are thought to be natural subsidence (increased by extraction of natural gas during the 1960's), and reduced transport of solids caused by exploitation of sandy bed materials for human use (Dal Cin, 1983), although the latter activity seems to have decreased in recent years. Nevertheless, sea level rise, acting in conjunction with a sediment-dynamics not yet in equilibrium, and coupled with the natural sinking of the delta's area could cause an escalated erosion of the delta.

Considering that a large part of the delta's landscape is below the mean sea level, ranging between -4 and +1 m relative to the sea level (Bonifazi, 1985; Marabini, 1985), an erosion of the external sand barriers separating the open sea from the internal delta's areas may have serious consequences. Among these are extensive flooding, major penetration of sea water into the delta's channels, and the destruction of nursery grounds for commercially important fish species in the lagoonal zones (Gandolfi et al., 1985.)

The extent of saline intrusion into the delta's branches depends on the volume of water transported by the river and the tidal conditions. Also the recently increased subsidence has increased the extent of the intrusion, with serious consequences for the quality of the ground water. The maximum intrusions (up to 17 km) generally correspond to times when the volume of transported water is low. Hence, the major factors that could maximize sea water intrusion are: erosion of the delta, and a reduction in the water transported by the river.

The salinization of river water could have serious consequences if it is used for irrigation (Kovda, 1983). This activity could cause further salinization of soils, which, according to Szabolcs (1974) and Bonifazi (1985), are already considerably affected by salt in the areas surrounding the delta. From an ecological point of view, the salinization of river water and subsequent salinization of soils will in effect cause a large degradation of the delta's ecosystem (Park et al., 1985).

The considerations stated above for the river Po are also applicable for the other Mediterranean rivers discharging into the sea through a delta system. In particular a rising sea level of one meter could produce quite strong effects on the Nile delta, whose water flow and solid transport are considerably reduced artificially by the Aswan high dam. The reduction of solid transport is causing rapid erosion in the delta, which has reached a maximum value of about 100 m/yr. Considering only the inundation concept, a one meter sea level rise would cause the flooding of an area corresponding to 12–15 % of the total Egyptian arable land, supporting 16% of the total population (Broadus et al., 1986).

8.8. Saline Contamination of Groundwater (Italy)

The Mediterranean littoral zone is formed, almost entirely, by different kinds of sedimentary rocks and alluvial deposits that, for the most part, constitute ground water reservoirs. These may have a connection with the sea via coastal and submarine springs or, conversely, through salt-water intrusion. These reservoirs can serve several functions including: seasonal regulation of surface waters, interannual regulation of the hydrology during years of heavy rainfall, supply and distributon of water for societal uses, including emergency supplies during water shortages, and storage of surplus water by artificial recharging (Ambroggi, 1977).

Considering the possible climatic change toward more arid conditions, these reservoirs may be of more vital importance in the future. However, a rise in sea level could alter the freshwater/saltwater interface with subsequent salinization of these reservoirs. Vulnerability to salinization depends on the connection of the reservoir to the sea (via a submarine spring), the exploitation level of the reservoir, and the geological characteristics of the substrate in which the reservoir is embedded. According to a recent report on the ground water characteristics of Italy (Commissione delle Comunita Europee, 1982) it is possible to develop a general assessment of the reservoirs potentially exposed to contamination by saline water.

The most vulnerable reservoirs may be those that are currently contaminated by saline water in varying degrees and extent. Such is the case for numerous Italian aquifers in Calabria, Puglia, Liguria, Marche, Abruzzo, Sicily, and Sardinia. In these regions the extent of the saline intrusion is quite variable (from a few hundred meters to several kilometers), and it is caused either by direct sea-water penetration into the coastal aquifers, or by penetration through lagoons, channels and estuaries.

The most exposed aquifers appear to be those in the areas of Murge and Salento in Puglia. Direct saline intrusion occurs in the entire coastal area in the Murge region with a landward ingression variable within 4 and 7 km. The saline intrusion is caused also by the presence of various submarine springs in the Gulf of Taranto, which sustain a net influx of sea water during high tides. In the Salento region, the intrusion is present in the entire aquifer; moreover, in this aquifer the particular hydrogeological conditions cause an upward movement of the salt water, a factor that accelerates the contamination.

These aquifers are highly exploited and currently the salt content is already a factor limiting their use. Continuing exploitation, coupled with increased contamination owing to sea level rise, may render these aquifers completely unsuitable for human use in the future.

Saline intrusion from lagoons and channels into the rivers occurs along the Adriatic coast (Veneto and Emilia) in the estuary of the Po river and Tuscany (Maremma region). In these cases the salinization of the aquifers is in general coupled to soil salinization and will be increased by the sea level rise.

9. LARGE-SCALE CHANGES IN THE MEDITERRANEAN: SUGGESTIONS FOR FUTURE RESEARCH

As stated in IIASA's study, *The Future Environments for Europe: Some Implications of Alternative Development Paths*, the European continent represents the region of the Earth with the longest history of intensive development and human pressure on the environment. This general fact certainly applies to the coastal areas around the Mediterranean Sea. For many centuries the sea has received inputs of pollution from numerous societies that have settled on its shores. Population pressure and industrial development have caused a progressive increase in the land based pollutant loading, currently estimated to be 10 billion tons/yr of domestic and industrial wastes (Helmer, 1977; Osterberg and Keckes, 1977; Tolba, 1987). In the future the sea may no longer be able to sustain continued inputs of pollutants on this scale. Early warning of this loss of resilience has occurred as local cases of eutrophication and anoxia; the areas affected by these phenomena may spread in the future (See Chapter 6).

It should be stressed that the environmental future of the Mediterranean Sea will depend on the evolution of economic and social development in the 18 countries bordering its coast. Moreover, differences in patterns of development between the countries bordering its northern and southern coasts will be large. A UNEP (1977) study has identified major sources of pollution that may increase in the future. These include: oil, chemicals, domestic and agricultural wastes. In terms of demography and economics the "center of gravity" of the Mediterranean region currently exhibits a distinct northward shift. For example 65% of the Mediterranean population lives on the northern shores and produces 90% of the pollutant load from domestic wastes.

Future patterns, however, are likely to change. The "Plan Bleu" preliminary report (UNEP, 1983; Antoine, 1977) indicates that population growth in the future will occur mainly in countries bordering the southern coast, and particularly in urban centers located on the coast. Such a change in the demographic pattern will be accompanied by changes in development activities such as industry, land-use, energy use, etc. Subsequently, these activities will exert a strong environmental effect on the Mediterranean coastal waters. Rivers are a major transporter of pollutants into the sea. Thus, future management of the catchment basins of the rivers discharging into the Mediterranean will be extremely important.

In order to predict possible future environmental impacts, one idea may be to obtain a relation between past demographic trends and pollutant loadings (at least for the domestic wastes) for the Mediterranean as a whole and for the different basins. This relationship may be used to extrapolate pollutant loadings in the future, considering the land extending for about 20 km inland, as well as the areas within the drainage basins of the rivers discharging into the Sea (Helmer, 1977). The assessment of the future fertilizer loads discharged into the Mediterranean should take in account possible land-use changes, increases or decreases in the use of fertilizers, and the potential utilization of new agricultural technologies.

In this way some scenarios could be generated. In order to provide an upper bound for development activities one may extend the "northwestern model" to the entire Mediterranean coastal zone (UNEP, 1983). That is to say, one may assume a similar level of socio-economic activity for the entire region as currently occurs in the countries bordering the northwestern Mediterranean (Italy, France, Spain, Monaco, Malta). This scenario implies strong economic development in the southern Mediterranean countries. (See Henry (1977) for an historical perspective of this development pattern.)

Alternatively, a lower bound scenario could be generated based on the assumptions made in the "surprise-free" scenario of Svedin and Aniansson (1987). Here it is assumed that differences in socio-economic activities of developed and less developed nations remain unchanged in the future. Thus, the northward shift in the "center of gravity" of activities in the Mediterranean region alluded to above remain unchanged.

To obtain a picture of the environmental effects that various scenarios of development could have on the Mediterranean Sea, it is necessary to describe the scenarios in the context of an environmental/oceanographic framework. In the case of nitrogen and phosphorus inputs, a mass balance approach could be developed. A first attempt in this direction has been made by Coste and Minas (1981) who used the UNEP data (1977) to calculate the hypothetical increase of phosphorus concentration in the next hundred years. Another possible analysis could be based on the assessment of biological oxygen demand (BOD) in order to calculate the capacity of the Sea for recycling organic waste inputs in the future.

REFERENCES

AMBROGGI R.P. (1977). Freshwater resources of the Mediterranean basin. *Ambio* 6:371–373.

ANTOINE S. (1977). A "Blue Plan" for the survival of the Mediterranean region. *Ambio* 6:332–335.

BARNETT T.P. (1983). Recent changes in sea level and their possible causes. *Climatic Change* 5:15–38.

BARNETT T.P. (1984). Longterm trends in surface temperature over the oceans. *Monthly Weather Review* 112(2):303–312.

BARNETT T.P. (1985). Longterm climatic change in the observed physical properties of the oceans. In: *Detecting the Climatic Effects of Increasing* CO_2, Eds.: M.C. Mc Cracken, F.M. Luthers. U.S. Dept. Energy, DOE/ER 0235, pp. 91–107.

BENOVIC A., JUSTIC D., BENDER A. (1987). Enigmatic changes in the hydromedusan fauna of the northern Adriatic Sea. *Nature* 326:597–599.

BETHOUX J.P. (1979). Budgets of Mediterranean Sea. Their dependence on the local climate and on the characteristics of Atlantic waters. *Oceanologica Acta* 2(2):157–163.

BETHOUX J.P. (1980). Mean water fluxes across sections in the Mediterranean Sea, evaluated on the basis of water and salt budgets and observed salinities. *Oceanologica Acta* 3(1):79–88.

BOLIN B., DOOS B.R., JÄGER J., WARRICK R.A. Eds. (1986). *The Greenhouse Effect, Climatic Change and Ecosystems.* New York: SCOPE series, no. 29. John Wiley and Sons Publ.

BONIFAZI A. (1985). Indagine sulle produzioni agrarie del delta del Po e su alcuni fattori che la determinano. *Nova Thalassia* 7 (Suppl. 2):385–407.

BROADUS J.M., MILLIMAN J.D., EDWARDS S.F., AUBREY D.G., GABLE F. (1986). Rising sea level and damming of rivers: possible effects in Egypt and Bangladesh. In: *Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 4: Sea Level Rise.* Ed: J.G.Titus. E.P.A., Washington, D.C., pp. 165–190.

BROECKER W.S. (1987). Unpleasant surprises in the greenhouse? *Nature* 328:123–126.

BROECKER W.S., PETEET D.M., RIND D. (1985). Does the ocean-atmosphere system have more than one stable mode of operation? *Nature* 315:21–26.

BRUUN P. (1986). Worldwide impact of sea level rise on shorelines. In: *Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 4: Sea Level Rise.* Ed: J.G.Titus. E.P.A., Washington, D.C., pp. 99–128.

BRYDEN H.L., STOMMEL H.M. (1984). Limiting processes that determine basic features of the circulation in the Mediterranean Sea. *Oceanologica Acta* 7(3):289–296.

BULJAN M., ZORE ARMANDA M. (1976). Oceanographical properties of the Adriatic Sea. *Oceanogr. Mar. Biol. Ann. Rev.* 14:11–98.

BUNKER A.F. (1972). Wintertime interactions of the atmosphere with the Mediterranean Sea. *Journal of Phys. Oceanogr.* 2:225–238.

BUNKER A.F., GOLDSMITH R.A. (1979). Archived time series of Atlantic meteorological variables and surface fluxes. *W.H.O.I. Techn. Rep.* 79-3, 29 pp.

CESS R.D., GOLDENBERG S.D. (1981). The effect of ocean heat capacity upon global warming due to increasing atmospheric carbon dioxide. *Journal of Geophys. Res.* 86:498–502.

COLACINO M., DELL'OSSO L. (1977). Monthly mean evaporation over the Mediterranean Sea. *Arch. Met. Geophys. Biokl.* 26A:283–293.

COMMISSIONE DELLE COMUNITA EUROPEE (1982). Studio sulle risorse in acque sotterranee dell' Italia. *EUR 7944 IT.*

COSTE B., MINAS H.G. (1981). Influence des apports continentaux sur le regime et le bilan des sels nutritifs de la Mediterranee. *Thalassia Jugoslavica* 17(2):103–108.

COSTE B., GOSTAN J., MINAS H.J. (1972). Influence des conditions hivernales sur les productions phyto- et zooplanctoniques en Mediterranee nord occidentale. 1. Structures hydrologiques et distribution des sels nutritifs. *Mar. Biol.* 16:320–348.

DAL CIN R. (1983). I litorali del Delta del Po e delle foci dell'Adige e del Brenta: caratteri tessiturali e dispersione dei sedimenti, cause dell'arretramento e previsioni nell'evoluzione futura. *Boll. Soc. Geol. Ital.* 102:9–56.

DICKINSON R.E. (1986). Impact of human activities on climate - a framework. In: *Sustainable Development of the Biosphere.* Eds.: W.C. Clark, R.E. Munn. Cambridge: Cambridge University Press, pp. 252–289.

FLOHN H. (1980). *Possible Climatic Consequences of a Man Made Global Warming.* IIASA, Laxenburg, RR–80–30, 80 pp.

FLOHN H. (1981). *Life on a Warmer Earth: Possible Climatic Consequences of a Man Made Global Warming.* IIASA, Laxenburg, RR–81–03, 66 pp.

FLOHN H. (1982). Climate Change and Ice Free Arctic Ocean. In: *Carbon Dioxide Review.* Ed: W.C. Clark. Oxford: Oxford University Press, pp. 145–199.

FONDA UMANI S. (1985). Hydrology and red tides in the gulf of Trieste (north Adriatic Sea). *Oebalia* 11:141–147.

FRANCO P. (1983). L'Adriatico settentrionale: caratteri oceanografici e problemi. *Atti V Congr A.I.O.L.*, pp. 1–27.

FRANCO P., JEFTIC L., MALANOTTE RIZZOLI P., MICHELATO A., ORLIC M. (1982). Descriptive model of the northern Adriatic. *Oceanologica Acta* 5(3):379–389.

GANDOLFI G., IOANNILLI E, VITALI R. (1985). Caratteristiche biologiche delle comunita' ittiche, studi sulle migrazioni e aspetti quantitativi delle attivita' alieutiche del delta del Po. *Nova Thalassia* 7 (Suppl. 2):281–309.

GILBERT S. (1986). America washing away. *Science Digest* 94(8):28–35.

GORNITZ V., LEBEDEFF S., HANSEN J. (1982) Global sea level trend in the past century. *Science* 215:1611–1614.

GREGO G.A., MIONI F. (1985). Aspetti morfologici ed idrologici del delta del Po. Confronto con il passato. *Nova Thalassia* 7 (Suppl. 2):27–87.

GREVE W., PARSONS T.R. (1977). Photosynthesis and fish production: hypothetical effects of climate change and pollution. *Helg. Wiss. Meeres.* 30:666–672.

HANSEN J., JOHNSON D., LACIS A., LEBEDEFF S., LEE P., RIND D., RUSSELL G. (1981). Climate impact of increasing atmospheric CO_2. *Science* 213:957–966.

HEKSTRA G.P.(1986). Will climate change flood the Netherlands? Effects on agriculture, land use and well-being. *Ambio* 15:316–326.

HELMER R. (1977). Pollution from land-based sources in the Mediterranean. *Ambio* 6:312–316.

HENRY P.M. (1977). The Mediterranean: a threatened microcosm. *Ambio* 6:300–307.

HOFFMANN J.D., KEYES D., TITUS J. (1983). Projecting the future sea level rise: methodology, estimates to the year 2100, and research needs. *U.S. G.P.O. n. 055-000-0236-3.* Gov. Printing Office.

JACQUES J., MINAS H.G., MINAS M., NIVAL P. (1973). Influence des conditions hivernales sur les productions phyto- et zooplanctoniques en Mediterranee nord occidentale. 2. Biomasse et production phytoplanctonique. *Mar. Biol.* 23:251–265.

JACQUES G., TREGUER P. (1986). *Ecosystemes Pelagiques Marins.* Masson, Paris.

KANA T.W., MICHEL J., HAYES M.O., JENSEN J.R. (1984). The physical impact of a sea level rise in the area of Charleston, South Carolina. In: *Greenhouse Effect and Sea Level Rise: A Challenge for the Next Generation.* Eds.: M.C. Barth, J.G. Titus. New York: Van Nostrand Reinhold Co.

KOVDA V.A. (1983). Loss of productive land due to salinization. *Ambio* 12:91–93.

LACOMBE H., GASCARD J.C., GONELLA J., BETHOUX J.P. (1981). Response of the Mediterranean to the water and energy fluxes across its surface on seasonal and interannual scales. *Oceanologica Acta* 4(2):247–255.

LACOMBE H., TCHERNIA P. (1972). Caracteres hydrologiques et circulation des eaux en Mediterranee. In: *The Mediterranean Sea: A Natural Sedimentation Laboratory.* Ed.: J. Stanley. New York: Dowden, Stroudsboury and Ross Inc., pp. 25–36.

LEATHERMAN S.P. (1984). Coastal geomorphic response to sea level rise: Galveston Bay, Texas. In: *Greenhouse Effect and Sea Level Rise: A Challenge for the Next Generation.* Eds.: M.C. Barth, J.G. Titus. New York: Van Nostrand Reinhold Co., pp. 151–178.

LOUGH J.M., WIGLEY T.M.L., PALUTIKOF J.P. (1983). Climate and climate impact scenario for Europe in a warmer world. *Journal of Climate Appl. Meteorol.* 22:1673–1684.

MANGINI A., SCHLOSSER P. (1986). The formation of eastern mediterranean sapropels. *Mar. Geol.* 72:115–124.

MARABINI F. (1985). Alcune considerazioni sull'evoluzione del delta del Po. *Nova Thalassia* 7 (Suppl. 2):443–451.

MARGALEF R. (1984). Le plancton de la Mediterranee. *La Recherche* 15:1082–1094.

MEDOC GROUP (1970). Observation of formation of deep water in the Mediterranean Sea. *Nature* 227:1037–1040.

MILLER R.A. (1983). The Mediterranean Sea. A. Physical aspects. In: *Estuaries and Enclosed Seas (Ecosystems of the world: 26).* Ed.: B.H. Ketchum. New York: Elsevier Scientific Publ. Co., pp. 219–238.

NATIONAL RESEARCH COUNCIL (1983). *Climate Change: Report on Carbon Dioxide Assessment Committee.* Washington, D.C.: National Academy Press.

NETHERLANDS HEALTH COUNCIL (1985). *Report on* CO_2 *Problem. Part 1.* Min WVC/VAR Series 19 E.

OSTERBERG C., KECKES S. (1977). The state of pollution of the Mediterranean Sea. *Ambio* 6:321–326.

OVCHINNIKOV I.N., ZATS V.I., KRIVOSHEYA V.G., NEMIROVSKY M.S., UDODOV A.I. (1987). Winter convection in the Adriatic and formation of deep eastern Mediterranean waters. *Annales Geophysicae* 5B (1):89–92.

PALUTIKOF J.P., WIGLEY T.M.L., LOUGH J.M. (1984). *Seasonal Climate Scenarios for Europe and North America in a High* CO_2 *Warming World.* U.S. Dept. Energy, DOE/EV/10098-5.

PARK R.A., ARMENTANO T.V., CLOONAN C.L. (1986). Predicting the effects of a sea level rise on coastal wetlands. In: *Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 4: Sea Level Rise.* Ed: J.G. Titus. E.P.A., Washington, D.C., pp. 129–152.

PASKOFF R. (1987). Les variations du niveau de la mer. *La Recherche* 191:1010–1019.

PIRAZZOLI P.A. (1976). Sea level variations in the north-west Mediterranean during Roman times. *Science* 194:519–521.

REVELLE R.R. (1983). Probable future change in sea level resulting from increased atmospheric carbon dioxide. In: *Climate Change: Report on* CO_2 *Assessment Committee.* Ed: National research Council. Washington, D.C.: National Academic Press, pp. 433–447.

ROBIN G. de Q. (1986). Changing sea level. In: *The Greenhouse Effect, Climatic Change and Ecosystems.* Eds.: B.Bolin, B.R. Doos, J. Jaĝer, R.A. Warrick. New York: John Wiley and Sons, pp. 323–362.

SCHLESINGER M.E. (1986). Equilibrium and transient climatic warming induced by increasing atmospheric CO_2. *Climate Dynamics* 1:35–51.

SEUNG Y.H. (1980). Low frequency vertical motions in the MEDOC area of deep water formation. *Oceanologica Acta* 3(4):441–447.

SIBLEY T.H., STRICKLAND R.M. (1985). Fisheries: some relationships to climate change and marine environmental factors. In: *Characterization of Information Requirements for Studies on* CO_2 *Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health.* Ed.: M.R. White. U.S. Dept. Energy, DOE/ER–0236, pp. 95–143.

SORENSEN R.M., WEISMANN R.N., LENNON G.P. (1984). Control of erosion, inundation and salinity intrusion caused by a sea level rise. In: *Greenhouse Effect and Sea Level Rise: A Challenge for The Next Generation.* Eds: M.C. Barth, J.G. Titus. New York: Van Nostrand Reinhold Co., pp. 179–214.

SVEDIN U., ANIANSSON B. Eds. (1987). *Surprising Futures.* Swedish Council for Planning and Coordination of Research; Rep. 87/1.

SVERDRUP H.U., JOHNSON M.W., FLEMING R.H. (1942). *The Oceans.* Englewood Cliffs, New Jersey: Prentice Hall.

SZABOLCS I. (1974). *Salt Affected Soils in Europe.* M. Nijhoff-the Hague and Research Institute for Soil Science and Agricultural Chemistry of the Hungarian Academy of Sciences, Budapest.

THOMAS R.H. (1986). Future sea level rise and its early detection by satellite remote sensing. In: *Effects of Changes in Stratospheric Ozone and Global Climate. Vol. 4: Sea Level Rise.* Ed: J.G.Titus. E.P.A., Washington, D.C., pp. 19–36.

TITUS J.G. (1985). Greenhouse effect, sea level rise and coastal zone management. *Coast. Zone Management Journal* 14(3):147–171.

TIXERONT J. (1970). Le bilan hydrologique de la Mer Noire et de la Mer Mediterranee. *Cah. Oceanogr.* 22(3):227–237.

TOLBA M.K. (1987). An urgent role to save the Mediterranean (statement at the fourth meeting of contracting parties to the Barcelona convention, Genova, Italy, September 1985. In: *Sustainable Development. Constraints and Opportunities,* pp. 185–189.

UNEP (1977). *Preliminary Report on the State of Pollution of the Mediterranean Sea.* UNEP/.11/INF.

UNEP (1983). *G.C.S.: Rapport Preliminaire de Synthese de la Premiere Phase du Plan Bleu.* UNEP/IG.43/INF.3.

UNESCO (1982). The review of the health of the Oceans. *Reports and Studies*, n. 15.

VAN STRATEN L.M.J.U. (1972). Holocene stages of oxygen depletion in deep waters of Adriatic Sea. In: *The Mediterranean Sea: A Natural Sedimentation Laboratory.* Ed: J. Stanley. Dowden, Hutchinson and Ross Inc., pp. 631–643.

VERGNAUD GRAZZINI C., RYAN W.B.F., CITA B.M. (1977). Stable isotopic fractionation, climate change and episodic stagnation in the eastern Mediterranean Sea during the late Quaternary. *Mar. Micropaleont.* 2:353–370.

WEINBERG A.M., and Z. MARLAND. (1986). Longevity and infrastructure. Personal communication, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

WUST G. (1961). On the vertical circulation in the Mediterranean Sea. *Journal of Geophys. Res.* 66(10):3261–3271.

ZANKANELLAS A.J. (1979). Oxygen deficient and organic carbon fields expansion in Elefsis Bay, Greece. *Mar. Poll. Bull.* 10:11–13.

ZORE ARMANDA M. (1963). Mixing of three different water types in the South Adriatic. *Rapp. P.V. Reun. Comm. Int. Explor. Sci. Mer.* 21(4):203-205.

ZORE ARMANDA M. (1972). Response of the Mediterranean to the oceanographical/meteorological conditions of the north Atlantic. *Rapp. Comm. Int. Mer Medit.* 21:203–205.