GLOBAL CHANGE AND ECOSYSTEMS

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Report on the Design of a future coupled physical Ecosystem Model *(D6.2)*

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1. Introduction

This report focuses on the system identification issues related to the design of a coupled physical-ecosystem numerical model for the Mediterranean-Black Sea basins at both the “global” and the regional scales. The report is organised as follows: in section 2 the objectives that coupled activities, at the regional coastal scale, should achieve are listed. In section 3 the general characteristics that the system should have to fully capture the Mediterranean and Black Sea coastal and open Sea variability are revised. Section 4 describes the structure of the modelling system. Finally, section 5 lists a series of recommendations

2. Objective

Modelling (and forecasting) the spatial and temporal variability of the marine systems is one of the most important research topics that oceanographers are facing. The improvement in observational and modelling skills of the physical dynamics, are revealing temporal and spatial scales of variability above and below the seasonal and the “large-scale” ones, that are deeply influencing, and significantly driving, the biogeochemical and ecological dynamics of the system.

A modelling system for the Mediterranean and Black Sea Basins should be able to provide reliable information on the physical dynamics of the region under analysis, in order to provide the correct physical framework to be connected with models of ecosystem dynamics.

At the same time the model simulating the biogeochemical and ecological dynamics of the system should be able to describe the various trophic structures that can be encountered in the system as well as the spatial and temporal shifts from a structure to another one in response to the seasonal and interannual variability of the physical and biogeochemical forcing functions. The Mediterranean and the Black Sea have remarkably different biogeochemical characteristics; moreover, in both basins observational and modelling evidences indicate that the spatial and temporal variability in the marine ecosystem structure and functioning can be large (Pinardi *et al.*, 2004, Oguz *et. al* 2002). This implies that the Ecological model should be designed with strong elements of genericity (should not be site-specific. Blackford *et al*., 2004).

Such model should connect with socio economical models of sustainable development and management of marine resources (Pinardi *et al.* 2002a). Since the major impact of the exploitation activities on the marine system occur in the coastal zone, it is therefore extremely important that the model resolves correctly coastal physical and ecological processes, including those relevant to environmentally sustainable exploitation/management, such as coastal eutrophication, harmful algal blooms and the development of invasive/opportunistic species. The state variables considered by the model should allow the direct and/or indirect (e.g. trough synthetic indexes) connection with socio-economical studies of the marine ecosystem use and sustainable management.

Therefore, the objectives that should be pursued in designing a coupled physical ecological model for the Mediterranean and Black Sea basins should be the following:

- Resolve the physical biological coupling of the system at the relevant spatial and temporal physical scales.

- Envisage a marine ecosystem description allowing for spatial and temporal trophic structure shift in dependence of the variability of the forcing functions acting on the system.
- Provide adequate description of the coastal zone ecosystem dynamics.
- Provide relevant information for socio-economical studies focusing on the integrated coastal zone management.

3. Characteristics

3.1. Coastal and open sea physical processes.

As stated above, the correct simulation of coastal processes is an issue of primary importance if the model has to produce information relevant for socio economic management and policy planning. However, a complete focus on coastal physical and ecological processes, reducing the influence of the large-scale open-sea dynamics to a sort of “open boundary condition definition”, might not be a viable one for both The Mediterranean and the Black Seas.

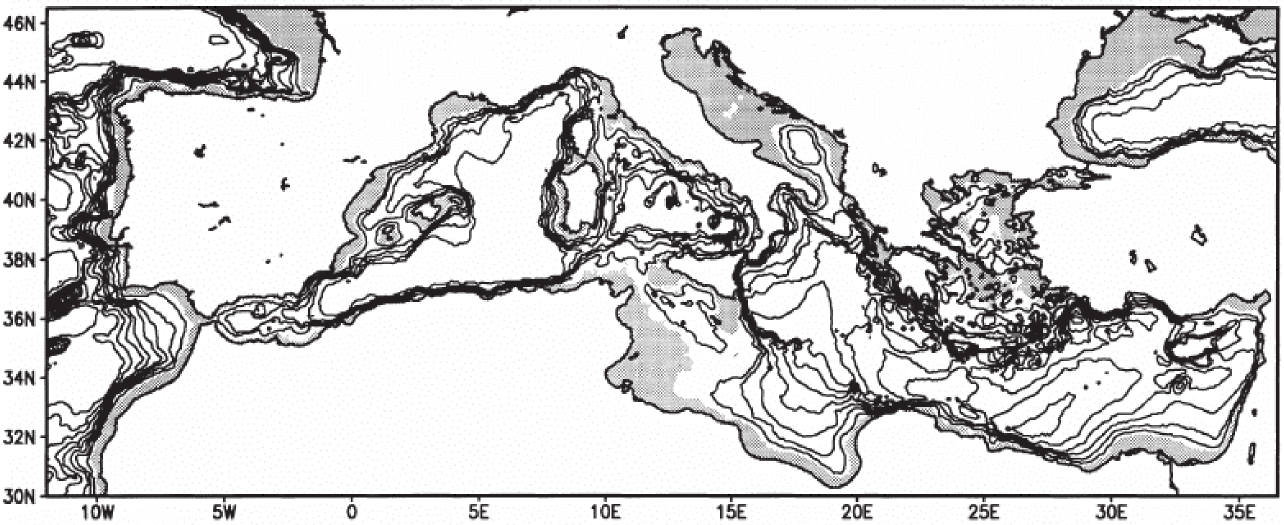


Figure 1a. Mediterranean Sea bathymetry. The shading indicates the extension of the continental shelf, defined as the area having bottom depth less than 200 m. From Pinardi et al. (1997). Modified.

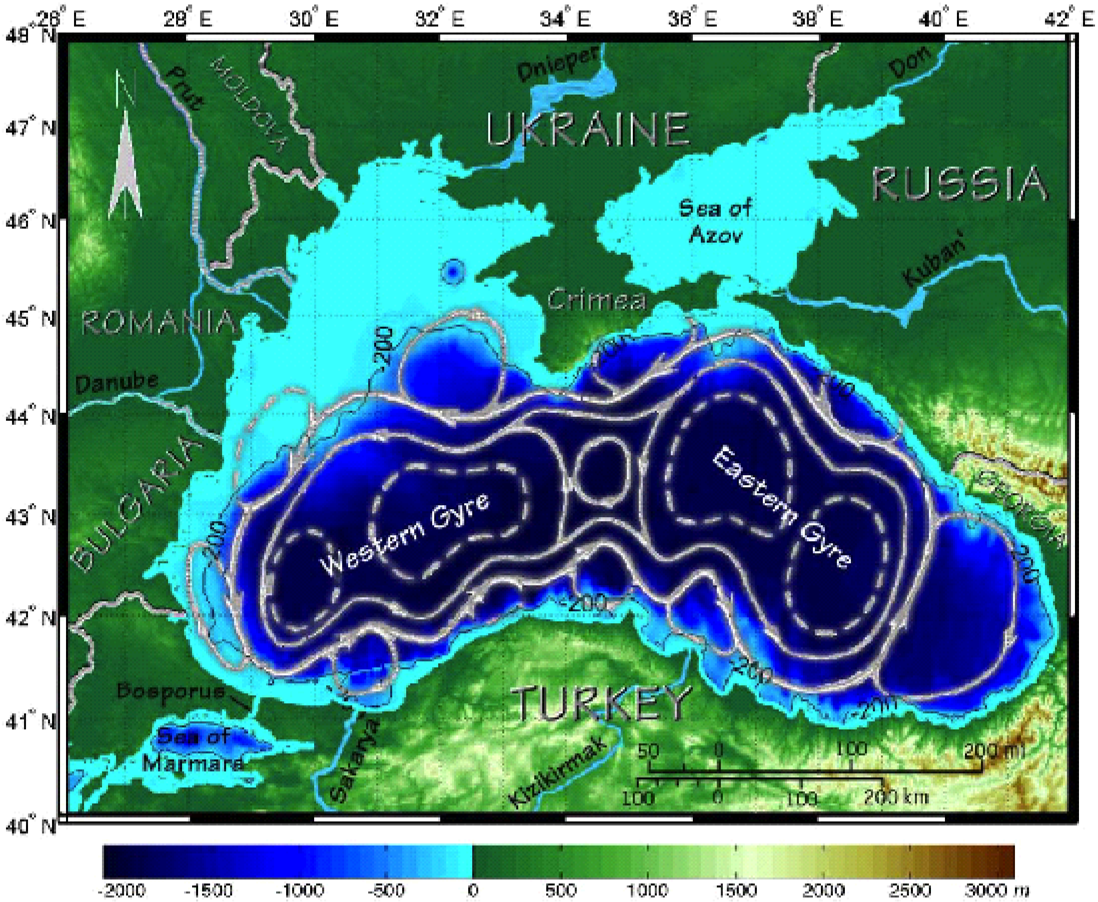


Figure 1b. Black Sea bathymetry. The light blue areas indicate the extension of the continental shelf, defined as the area having bottom depth less than 200 m. From Chu et al. (2005). The superimposed circulation scheme is taken from Oguz et al. (1993).

Despite the well known physical and ecological differences characterising the two basins, some common elements (with different relative importance) can be identified at the morphological level. Both basins (Fig 1a for the Mediterranean Sea and 1b for the Black Sea) in fact show two kind of coastal areas: Areas with an extended continental shelf (the northern Adriatic, the Gulf of Lions in the Mediterranean Sea and the whole northern coast of the Black Sea) and areas with a narrow continental shelves and steep slopes.

Areas characterised by extended continental shelf are also strongly affected by river runoff, whose fresh water discharge contribute to force the thermohaline circulation of the two basins. Such areas are episodically but significantly influenced by the open Sea circulation in the form of current meanders or intrusions over the shelf (Pinardi *et al*., 2004).

On the other hand, as pointed out by Pinardi *et al.* (1997) for the Mediterranean Sea areas with narrow continental shelf (but the concept equally applies to the Black Sea), the open Sea, general circulation processes strongly influence the coastal circulation by advecting into the coastal domain water masses formed in the open Sea and transporting offshore water that has been subject to land-sea interactions (See also Pinardi *et al.*, 2004 and Stanev *et al.*, 2002.)

In both cases the general circulation (Fig. 2 for the Mediterranean Sea and 1b for the Black Sea) is composed also by features that are directly impinging on the coastal domain (such as the Mediterranean Liguro-Provençal current or the Algerian current in the Mediterranean and the Black Sea “Rim Current”) or directly connecting the coastal with the open sea domain (such as the Mediterranean Western Adriatic Coastal current)

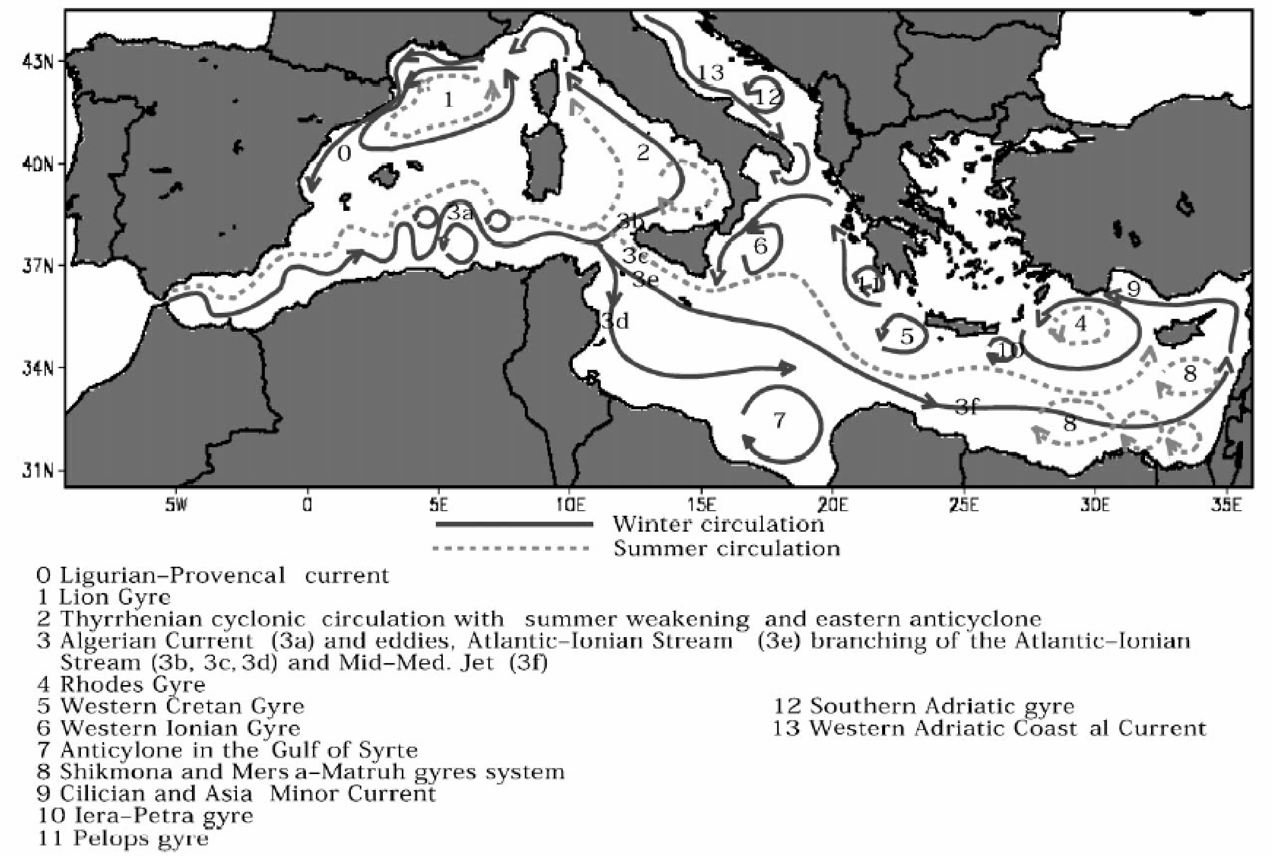


Figure 2. Schematic of the Mediterranean Sea major basin current and gyres and their seasonal variability. From Pinardi and Masetti (2000).

Therefore, given the significant, and two ways, exchanges between the coastal and open Sea domains in the two basins, a distinctive characteristic in the design of the coupled physical ecological model should be the explicit consideration of the general circulation in order to provide the essential connection of the shelf transport to basin scale features and to account for the lateral heat, salt, nutrients and biomass transport at the coastal/open sea interface.

3.2 Ecosystem functioning.

The herbivorous and the microbial food-web

It is needless to say that the Mediterranean and the Black Sea have profound differences in their biogeochemical characteristics (Fig. 3a and b respectively) linked to the antiestuarine (Mediterranean Sea) and estuarine (Black Sea) regime of their thermohaline circulation. The Mediterranean Sea is regarded essentially as an oligotrophic basin (Estrada, 1996), while the Black Sea is known to have moderate to high primary production (Sur et al., 1996). Coastal areas of both basins, with an extended continental shelf and affected by significant river runoff, however, show meso to eutrophic conditions (Fig. 3) often enhanced by anthropogenic nutrient load. A striking example of this is given by the western coastal areas of the Black Sea (Moncheva *et al.*, 2001) and (to a lesser but still significant extent) by the northern Adriatic (Sangiorgi and Donders, 2004).

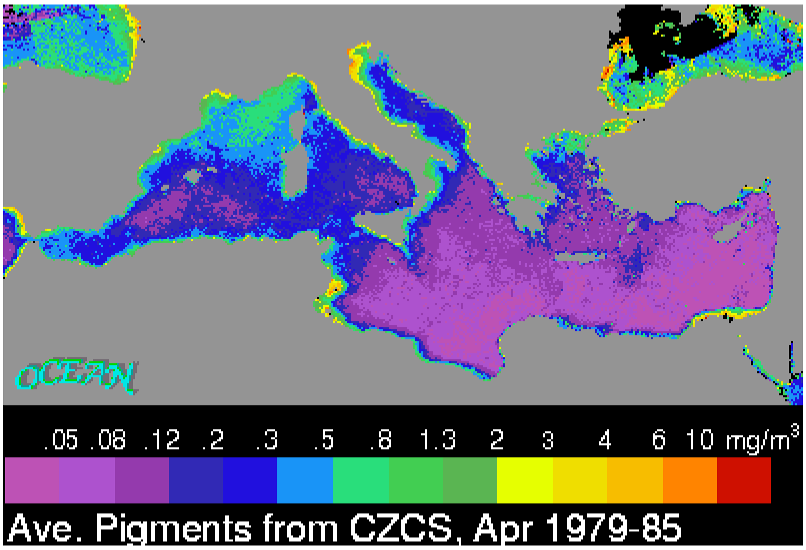


Fig 3a. Distribution of Mediterranean Sea surface pigments from the 1979-1985 CZCS remote observations relative to April.

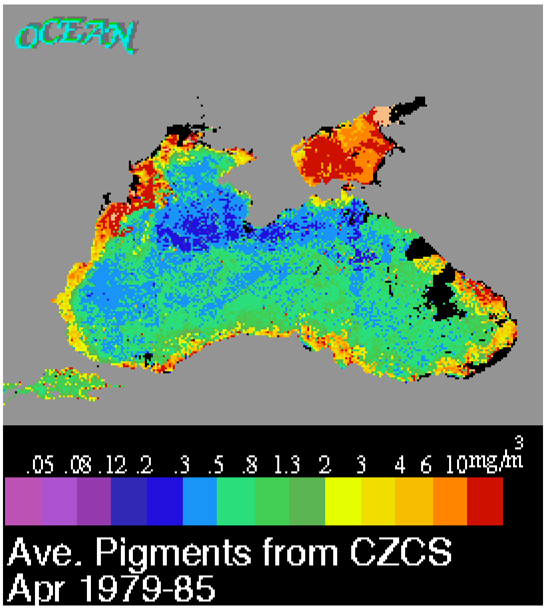


Fig 3b. Distribution of Black Sea surface pigments from the 1979-1985 CZCS remote observations relative to April.

Therefore the Mediterranean-Black Sea system hosts an extremely wide range of ecosystem trophic structures, whose extremes ends are the so called “herbivorous” food web (Cushing, 1989), dominated by microphytoplankton (more specifically diatoms) and mesozooplankton, and the microbial food web, where that a large part of the carbon fluxes to go through the small phytoplankton, protozoa and bacteria (Thingstad and Rassoulzadegan, 1999).

Fig. 4 gives a schematic representation of the conditions leading to the development of the coastal and oceanic marine ecosystems. In dependence of the physical structure of the water column and of the prevailing limiting factor, the ecosystem structure is “rigidly” shaped into a coastal or open sea structure characterized respectively by the herbivorous and the microbial loop food chains. However, Legendre and Rassoulzadegan (1995) argue that the marine ecosystem might be shaped in a much wider spectrum of conditions (in dependence of changing environmental conditions) along a trophic continuum of which the two ecosystem structures mentioned above represent the two opposite extremes.

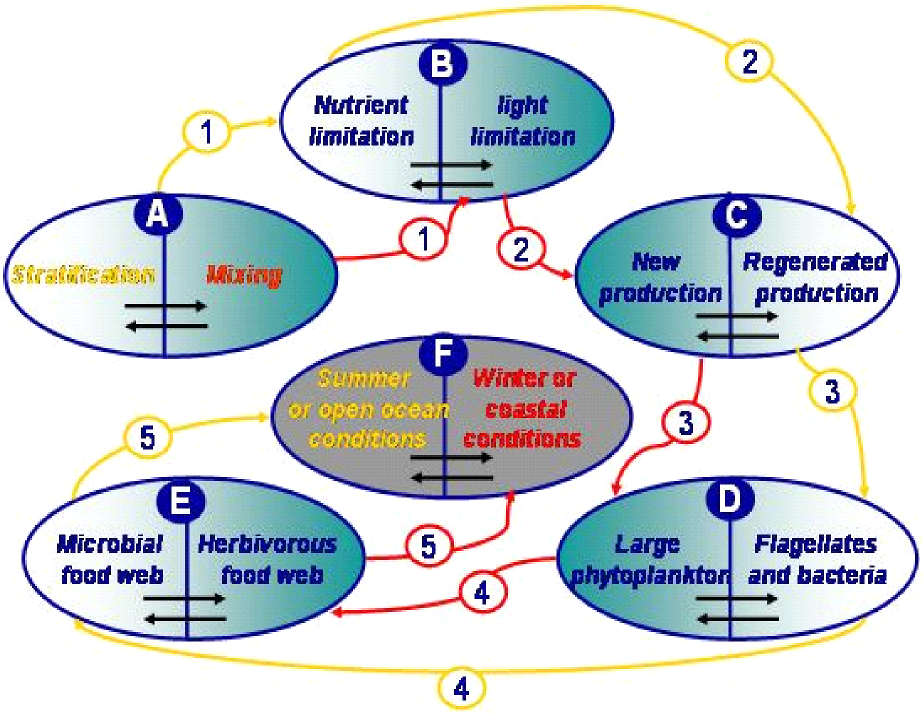


Fig 4. Representation of conditions leading to the establishment of a coastal or oceanic pelagic ecosystem. The sequence is a: the water column vertical structure; b: the factors limiting growth; c: the type of primary production; d: the type of organisms; e: the resulting food web; f: the type of ecosystem. Redrawn with modifications from Legendre and Rassoulzadegan (1995).

The transition along this trophic continuum determines the observed spatial and temporal variability of the Marine ecosystem in response to the physical dynamics and to the boundary conditions, and the coupled physical ecological model of both basins should be designed in a way to reproduce this spatio temporal variability.

The benthic-pelagic coupling.

The considerations stated above about the ecosystem functioning at the lower trophic levels applies to the pelagic (water column) domain. Given the presence in both basins of areas with an extended continental shelf, the role of the benthic domain in biogeochemical cycling can hardly be disregarded. For the Northern Adriatic Sea Giordani *et al.* (1992) estimated that the nutrient recycling due to mineralization of organic matter in the sediment is a significant source of nutrient for the water column. Even more important is the Black Sea Benthic pelagic coupling in the north western areas of the basins, where Friedrich *et al.* (2002) estimated the magnitude of the benthic phosphate and silica recycling being approximately 50 and 35 % (respectively) of the Danube load in summer.

Such an important process of nutrient cycling should not go unnoticed in the design of a coupled physical ecological model for coastal areas and basins having regions with significantly wide continental shelf areas.

Anoxia

Due to its strong vertical stratification conditions, the Black Sea is one of the world's largest stable anoxic basins. Such a feature strongly influences the Biogeochemical cycling processes (Galimov *et al.,* 2002).

The Mediterranean Sea is, on the contrary a well ventilated basin. However, anoxic phenomena in coastal water (as in the northern Adriatic Sea) do occur episodically, are related to eutrophication processes (Justic *et al.*, 1987) and can have serious consequences on marine biological resources exploitation.

The biogeochemical processes occurring in the transition from oxic to anoxic conditions and in the permanently anoxic zone (Black Sea) should be explicitly modelled. This implies the inclusion of the anaerobic bacteria (Galimov *et al.*, 2002) and the sulfides (Gregoire and Lacroix, 2001) as model state variables. Moreover, the episodically onset of anoxic condition in coastal waters and/or the limited ventilation of the Black sea permanently anoxic zone are processes entirely depending on the physical dynamics (Stanev *et al.* 2004) and call once more for a detailed representation of the coupling between physical and biogeochemical processes.

Harmful Algal Blooms

Harmful effects of microalgae in coastal water are often referred as Harmful Algal Blooms (HAB's). These episodes includes discoloration of waters and blooms of toxin producing species that accumulate in the food web, that may lead to economical losses and/or health problems for humans. Such effects are obviously undesirable as they:

- Can poison (or kill) commercially important   shellfish and fish species
- Damage recreational coastal areas

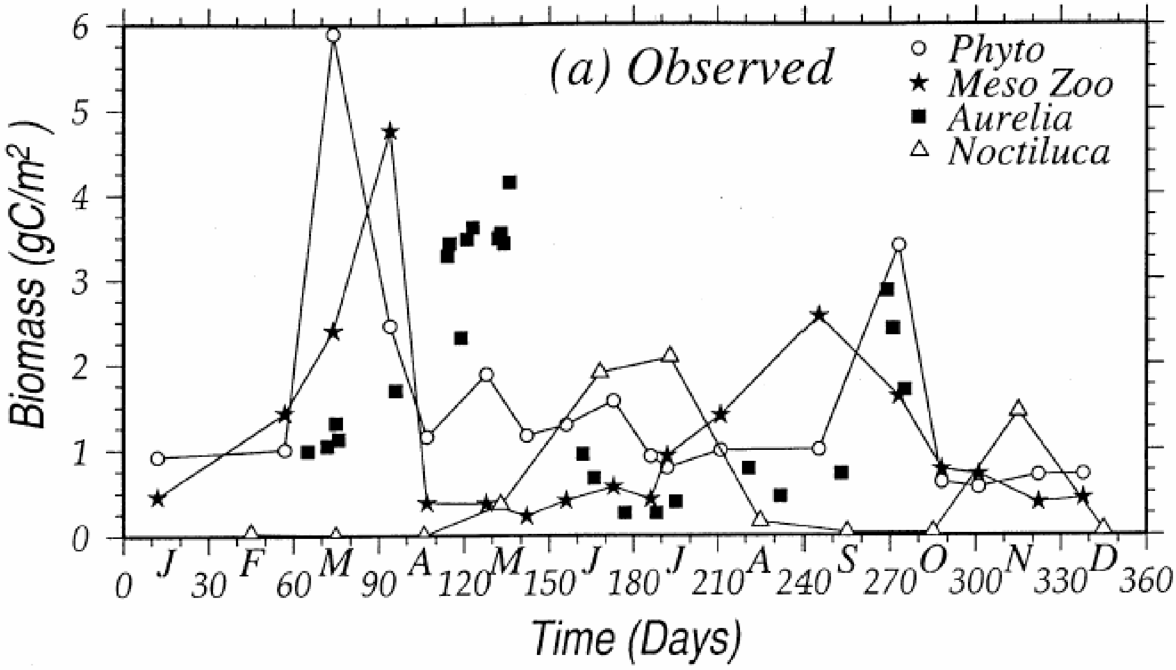
Although HaB's can occur naturally, the anthropogenic forcing (eutrophication, disruption of the marine food chain by overfishing, intensive aquaculture etc.) is recognized as a possible factor in determining them (Granèli et al. 1998).

The HaB's impact on environmental sustainability of coastal areas cannot therefore be disregarded and an ecological model aiming to interact efficiently with procedures of environmental management and policy planning of the coastal zone should explicitly consider this phenomena. This implies the inclusion in the ecological model of a specific functional group representing "Harmful Algae" with allelopathic characteristics and subjected to a reduced (with respect to the non-harmful functional groups) grazing pressure (Sole et al., 2005)

Gelatinous Zooplankton

Gelatinous zooplankton blooms affected mainly (*Aurelia Aurita sp. and Mnemiopsis Leidy)* the black Sea in the past two decades (Kideys *et al.*, 2000). The appearance of such blooms was related to the changed trophic characteristics of the basin determined by the strongly increase nutrient loading (Mee, 1992) and caused a strong reshaping of the trophic web structure (Moncheva and Krastev, 1997)by exerting a strong top down control (Oguz *et al*., 2001).

Modelling efforts of gelatinous Zooplankton in the Black Sea were already undertaken (see fig. 5) and given the strong importance of these predators in defining the state of the Black Sea they should be strongly encouraged.



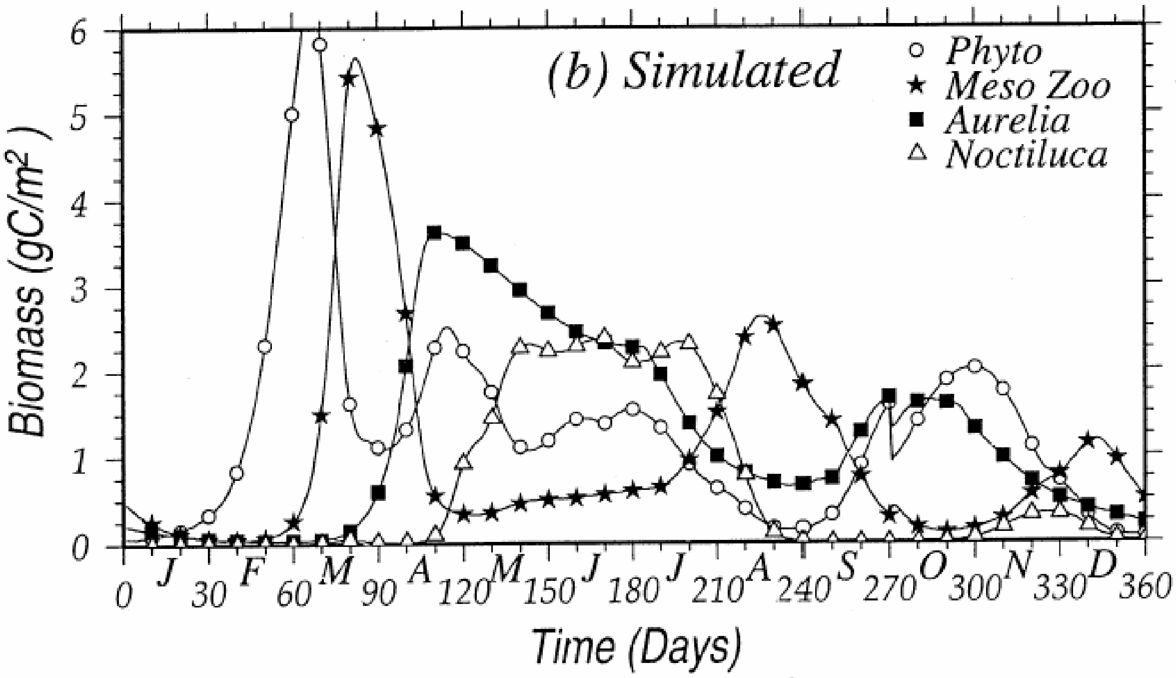


Fig 5. Observed (a) and simulated (b) annual distribution of total phytoplankton, zooplankton, Noctiluca and Aurelia Biomass in the Black Sea. From Oguz et. al. (2001).

Although gelatinous zooplankton does not affect the Mediterranean Sea so heavily as the Black Sea, episodic intense blooms of Jelly fish occurred in the past (Boero, 1991). Modelling investigations on the Mediterranean Sea should also be sought.

4. Structure

4.1 A nested physical models hierarchy

The need to include explicitly the simulation of the large scale open sea dynamics in an effort to provide reliable simulation/forecasting of the coastal physical dynamics, calls for the implementation of a modelling component of the modelling/forecasting system constituted by a hierarchy of numerical models, considering the diverse temporal and spatial scales characterizing the open-sea, regional and coastal marine circulation and for the use of one way "nesting" techniques to provide connection between the models and downscaling of the information from the models dealing with the larger scale to the one dealing with the smaller ones. The nesting should reduce the unpredictability scale of the system by reducing the uncertainties related to the definition of open boundary conditions for limited area modelling domains.

Here, by "nesting" is meant a numerical technique based on finite differences aimed to simulate (with high resolution) a limited area domain embedded into a larger (and coarsely resolved) model domain, so that the simulated "nested" model circulation is influenced (trough proper specification of open boundary conditions) by the larger scale circulation simulated by the coarser resolution "nesting" model. Time varying specification of temperature, salinity, free surface elevation, velocity and biogeochemical fields, arising from the "nesting" model simulations, on the open boundaries of the "nested" model are designed in a way to allow disturbances, arising from possible dynamical inconsistencies between the two models solutions, to move out of the domain in order not to affect the "nested" model simulation. Nesting techniques have been largely used in numerical weather prediction and their use in numerical oceanography is expanding in view of the increased use of numerical ocean models to simulate and forecast limited coastal areas (Pullen and Allen, 2000; 2001). The use of nesting techniques has been already adopted in a Mediterranean Sea context in the framework of the ended EU Project "Mediterranean Forecasting System Pilot Project, MFSPP" (Pinardi *et al.,* 2003) and in the ongoing EU Project "Mediterranean Forecasting System: Toward Environmental Predictions, MFSTEP" (Pinardi *et al.* 2002b), where the nesting approach is being extended to ecological models, to implement a basin wide modelling/forecasting system with information downscaling from the basin to the shelf scale. As an example of such a structure Fig. 6 reproduces the MFSPP/MFSTEP modelling/forecasting system structure implemented for the Adriatic Sea (Zavatarelli and Pinardi, 2003). The System is constituted by two state of the art numerical models: The Modular Ocean Model, MOM and the Princeton Ocean Model, POM.

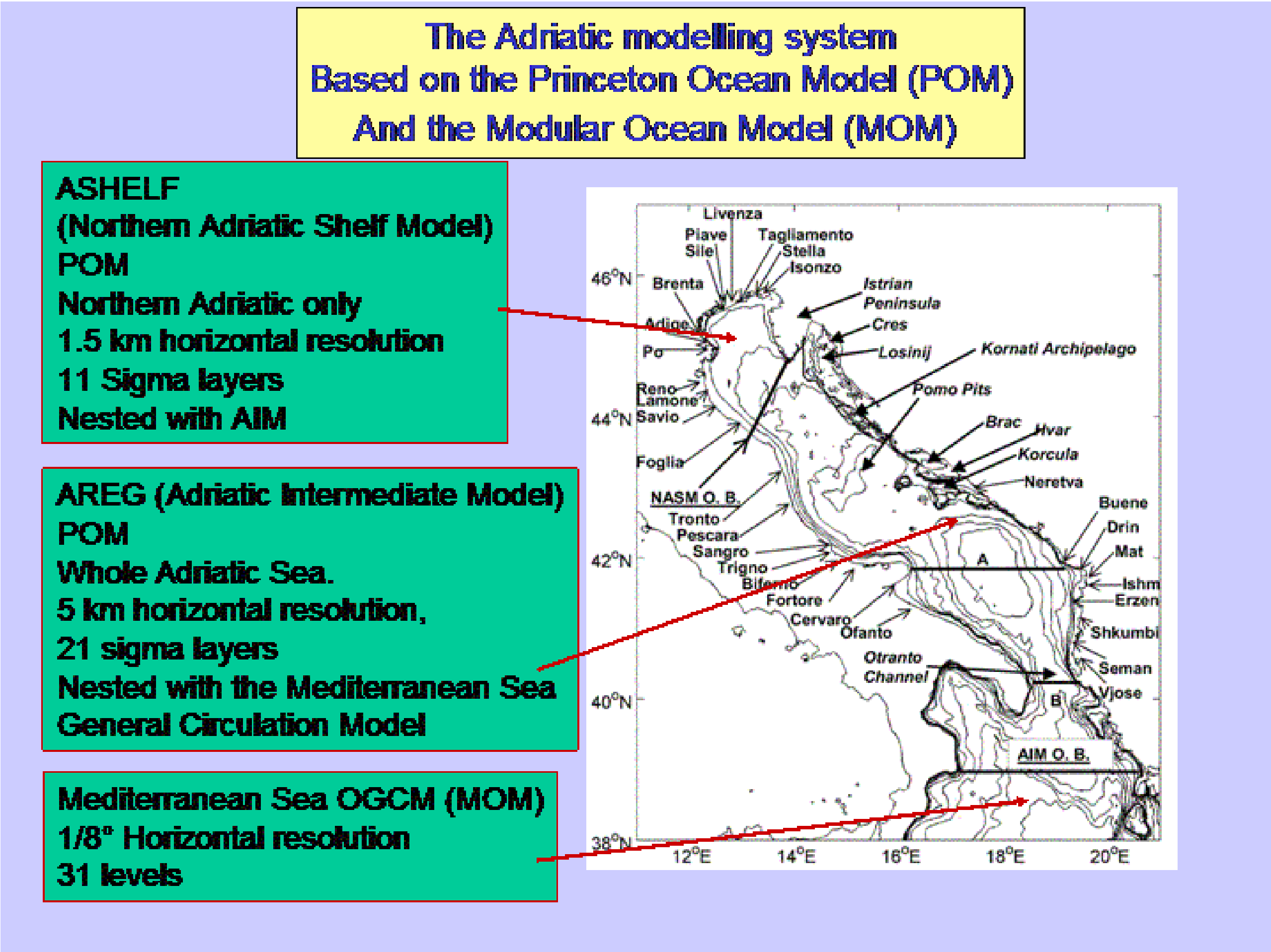


Figure 6: Schematic of the MFSPP/MFSTEP Adriatic Sea modelling system. The Figure summarizes the implementation characteristics of the three models hierarchy and the Location of the AREG and ASHELF models open boundaries (AREG O.B. and ASHELF O.B. respectively). The Approximate location of the mouth of the many rivers discharging in the Adriatic Sea is also shown. Modified from Zavatarelli and Pinardi (2003).

The Model hierarchy is constituted by:

1. A whole Mediterranean Sea general circulation Model (MOM based), OGCM, at approximately 12.5 km horizontal resolution and with 31 vertical levels.
2. A whole Adriatic Sea model (POM based), AREG, at approximately 5 km horizontal resolution and with 21 “sigma” (bottom following) layers.
3. A northern Adriatic Sea model (POM based), ASHELF, at approximately 1.5 km horizontal resolution and with 11 “sigma” layers.

The adoption of free surface “sigma” layers models (such as POM) for the modelling of the regional/shelf area is dictated by the need to potentially include the tidal forcing and to achieve a good vertical resolution also in shallow areas.

The nesting involves data interpolation on the “nested” model open boundary. Inaccuracies arising from the interpolation might generate errors leading to violation of mass conservation. The technique adopted and is designed in a way to satisfy the volume conservation constraint (the volume transport across the open boundary of the “nested” model matches the volume transport across the corresponding section of the “nesting” model. See Pinardi et al., 2003 and Zavatarelli and Pinardi, 2003).

4.2 The Ecological model.

The nested physical modelling systems summarised above should be coupled (in an on-line or off line mode) with ecological models enabling to represent the trophic structures described in section 3.2. The structure of the coupling is shown in fig. 7.

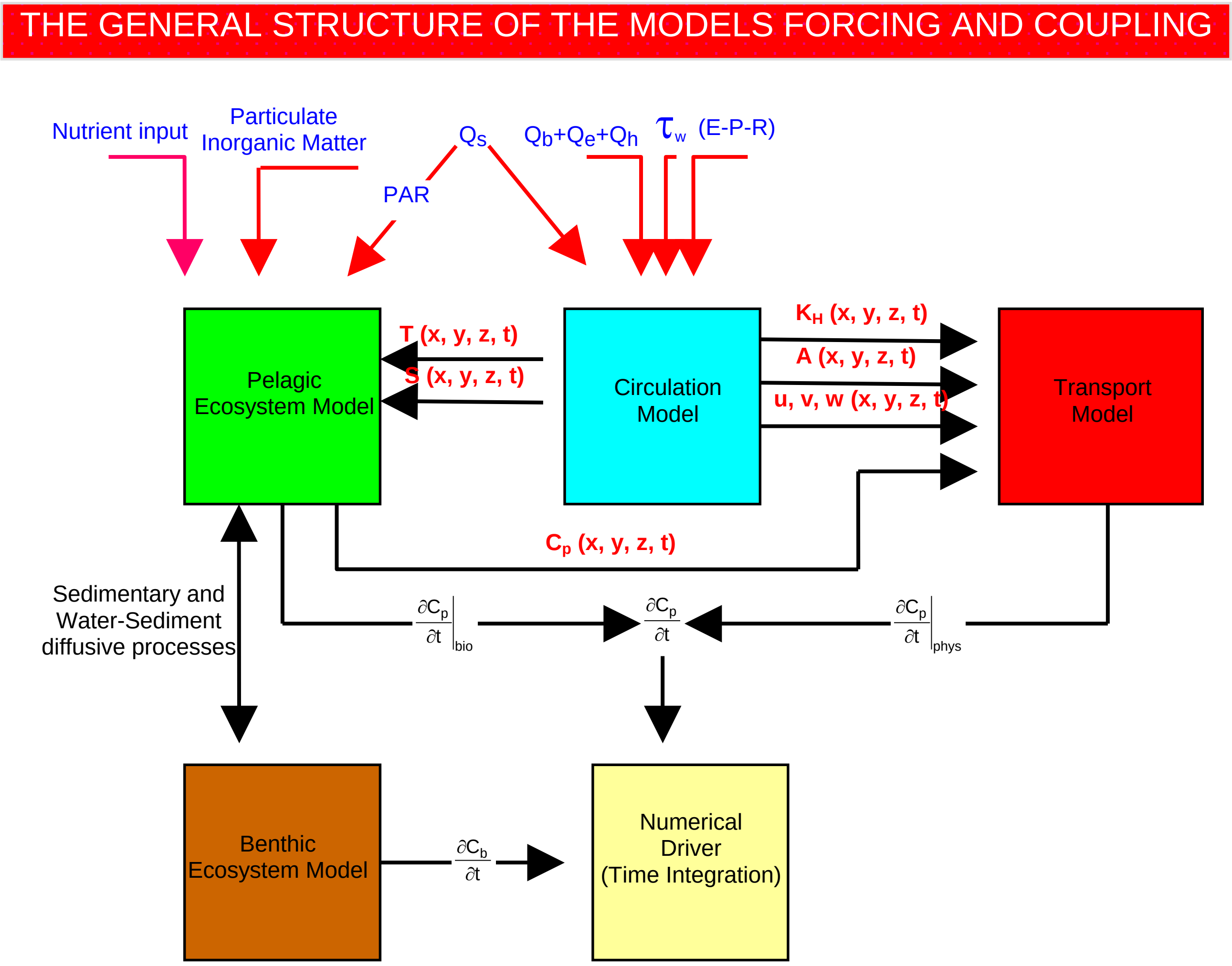


Figure 7: Schematic of the model coupling.

At each model time step, the coupling involves:

- The transfer of the Temperature and Salinity fields from the circulation model to the ecological model. Temperature is used to compute the metabolic response of the different biota. Salinity enters the formula for the computation of the oxygen saturation.
- The transfer of the velocity (u, v, w), horizontal (A) and vertical (KH) diffusion coefficient fields (from the circulation model) and of the pelagic state variables (from the ecological model) to the transport model in order to compute the advective/diffusive rate of change of Cp ($\left.\frac{\partial C_p}{\partial t}\right|_{Phys}$).

- $\left.\frac{\partial C_p}{\partial t}\right|_{Phys}$ is added to the rate of change (computed by the ecological model) of the pelagic state variables $\left.\frac{\partial C_p}{\partial t}\right|_{Bio}$ dependent on the various biogeochemical processes, to form the total rate of change $\frac{\partial C_p}{\partial t}$ that is transferred to the numerical driver that operates the time integration of the state variables.
- The benthic state variables of the ecological model are affected by sedimentary processes (sinking), transferring particulate organic matter from the pelagic to the benthic domain, and by diffusion of dissolved nutrients and organic matter from the sediment pore water to/from the water column, so that is in fact decoupled from the circulation model. Therefore, their rate of change $\frac{\partial C_b}{\partial t}$ is directly transferred to the numerical driver.

The ecological models most currently implemented in the Mediterranean and the Black Sea are biomass based and utilize the functional groups approach. The dynamics of biological functional groups are described by population processes (growth, migration, mortality) and physiological (ingestion, respiration, excretion, egestion). The biota is subdivided in three main functional groups types: producers (phytoplankton), decomposers (pelagic and benthic bacteria) and consumers (zooplankton and zoobenthos). These broad functional classifications are the subdivided, by grouping biota according to size classes or feeding method, to create a food web (Fig 8).

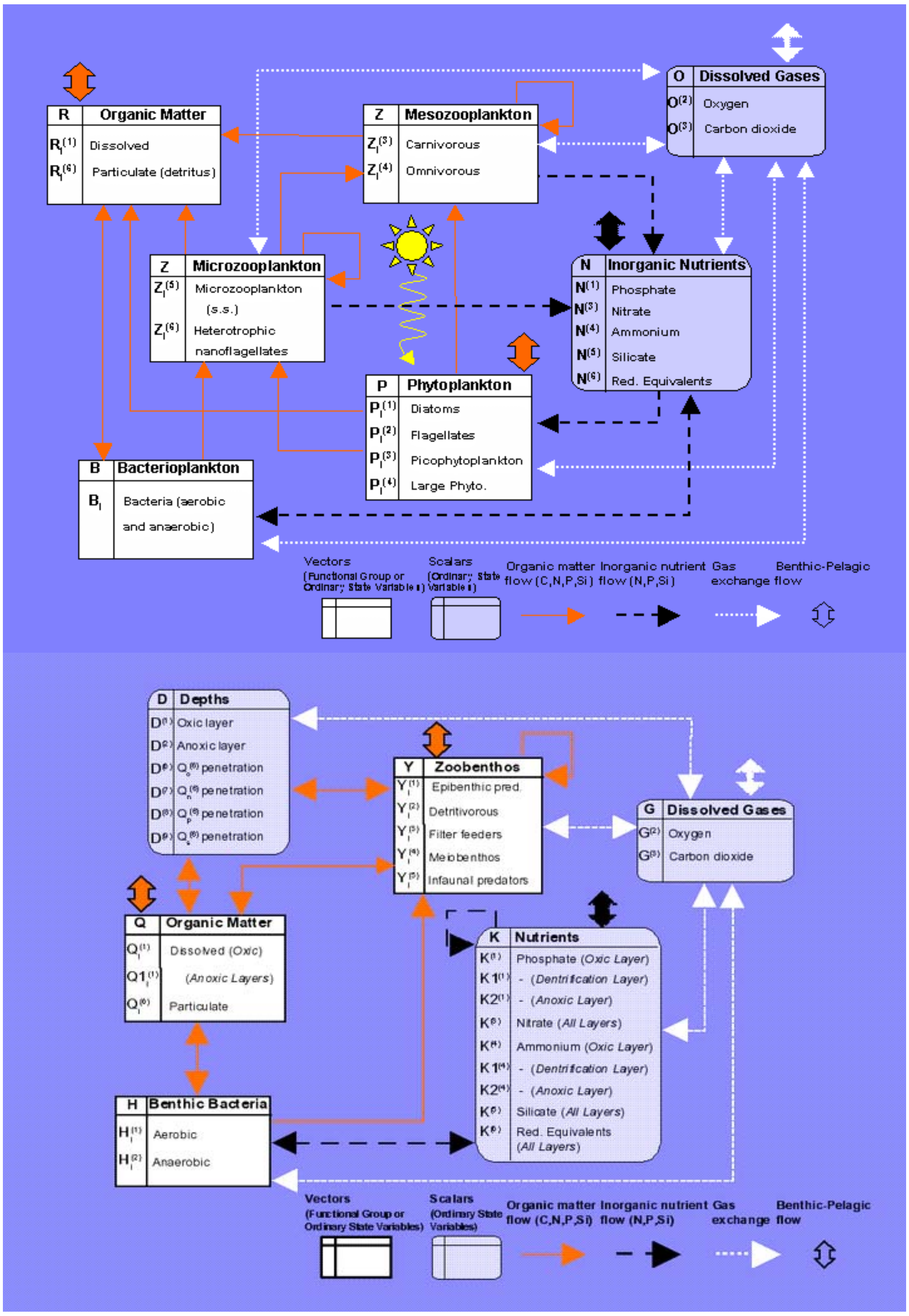


Figure 8: Example of a biomass based ecosystem model utilising the Functional group approach: The ERSEM model (Baretta et. al. 1995). Both the pelagic and the benthic domain are represented.

A model structure like the one depicted in the figure above explicitly resolve the two main trophic chains (as well as the intermediate structures. Vichi *et al*. 2003). The use of the full set of inorganic nutrients appears, moreover, particularly suited for the implementation in both the coastal and the open sea domains, as well as in basins having strongly different biogeochemical characteristics such as the Mediterranean and the Black Seas.

The state variables represented in Figure 7 are, obviously only indicative and the model configuration is left open to the state variables required to represent the process/ecosystem characteristics summarised in Section 3.

The above approach has been proven to satisfactory represent the basic ecosystem dynamics, however, the representation of the secondary producers processes (Meso and Mega Zooplankton) might require effort towards the coupling of a biomass based model for the lower trophic level, with more sophisticated models for secondary producers such as individual based model (Miller *et al.* 1998). Such a coupling effort would surely improve the models performance and would also facilitate the further inclusion in the model of the fishes population.

5. Recommendations

On the basis of the points discussed above, the development of a Mediterranean and Black Seas coupled physical-ecological model should adhere to the Following characteristics:

1. The regional/coastal system should be coupled with a large scale system in order to provide an effective and explicit simulation of the influence of the large-scale circulation on the coastal dynamics.
2. The nesting between the regional coastal system and the large scale one should be based on established nesting techniques complying with the volume (circulation model) and mass (ecological model) conservation constraint.
3. The coupling between the physical and the ecological model should be carried out in the on or off-line mode. For the off-line mode, however, the frequency of the update of the physical fields should be carefully established.
4. The ecological model should explicitly resolve for the time-space variability of the trophic web structure.
5. The ecological model should be a multinutrient one and (for the lower trophic levels) a biomass based one making use of the functional group approach.
6. Attempt to couple the biomass based approach for the lower trophic levels with individual based models for the secondary producers should be encouraged.
7. In order to have the coupled models providing relevant information's to the environmental policy makers and environmental managers, it is recommended a modelling effort toward the simulations of anoxia processes, HaB's and gelatinous zooplankton dynamics.

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