A NUMERICAL ESSAY OF THE INTERANNUAL VARIABILITY OF THE ECOSYSTEM IN THE IONIAN SEA

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INTRODUCTION

 Mediterranean Sea and its subbasins have a prominent year-to-year variability that deeply modifies both upper ocean and deep circulation. Satellite thermal images show the recurrent onset of the Eastern Alboran Gyre, long lasting geostrophic eddies generated by Algerian Current instabilities (LeVourch et al, 1993) while the formation and the evolution of the anticyclonic Mersa Matruh and Shikmona gyre were monitored during experimental surveys on a multiannual basis (Robinson et. al., 1991). The East Mediterranean seems to be in a transient state because of the modification of the deep and intermediate circulation (Roether et al., 1995) driven by density changes in Cretan Deep Water. Deep water formation rate exhibits an evident variability in the years both in Southern Adriatic Sea and in Gulf of Lions (Béthoux and Taillez, 1994). Similar considerations on the year-to-year variability can be applied to straits transports (Candela et al., 1989,Astraldi et al., 1994, Viezzoli and Gacic, 1998) where the interannual signal is a significant fraction of the seasonal one. For what concerns model studies, a numerical exercise on the interannual variability of the Mediterranean upper ocean circulation was carried out by Pinardi et al. (1997).

Much less experimental evidence and literature is available on the Mediterranean pelagic ecosystem interannual variability. Béthoux et al. (1992) shows a long-term increase of nitrate and phosphate concentration in Mediterranean deep waters while ten years-long monitoring activity puts in evidence the relative eutrophication of the Cretan Sea benthic ecosystem (Danovaro et al., 1998). Long-term variability in the eastern Mediterannean biochemical processes is also hypothesised by Ribera d'Alcalà et al. (1997) on the basis of the unbalance of nutrients budgets.

According with the widely accepted Sverdrup paradigm for mid-latitudes, the seasonal cycle is generally explained in terms of vertical processes where mixed layer dynamics and concomitant nutrient entrainment/detrainment in the euphotic zone play a major role in controlling the production as shown also for the Ionian Sea (Civitarese et al., 1996). Conversely the interannual signal cannot be simply explained in terms of a specific physical process.

The present paper is aimed to present a preliminary analysis of the results obtained by MOM-NPD, a coupled three-dimensional eco-hydrodynamical model (Crise et al., 1998 henceforth CCM1, Crispi et al., 1999, henceforth CCM2) forced in this case with NMC 1980-1988 monthly mean winds. This analysis puts in evidence as the role of wind regime determines fluctuations in the ecosystem variability in a sample station located in the Ionian Sea (36N,19E).

MODEL DESIGN

One of the most important mechanisms which shows relevant interannual variability is the mixed layer dynamics: in principle, the stronger the mixing, the higher the primary production. The interaction between subbasin-scales processes with general circulation also can play a major role in interannual variability. This means that subbasin scale processes can carry a significant contribution of physical and biogeochemical properties when interact with the mean flow. This interaction is potentially more important in Ionian Sea than in the ocean. A simple scale analysis shows that spatial scales of the Ionian Sea are smaller if scaled by r_i, the internal Rossby radius of deformation compared with the similar dimensionless scales in the Ocean:a climatological calculation of r_i in the four seasons for Mediterranean Sea shows that the averaged length is about 11 km and never exceeds 15 km.(Grilli and Pinardi, 1998). In the North Atlantic at Mediterranean latitudes (30N-45N) r_i varies from 12.2 to 37.9 km and the corresponding Pacific values are slightly larger (Emery et al., 1984).

$$\frac{L}{r_i} \equiv \frac{[10^6]}{[10^4]} (Mediterranean) < \frac{L}{r_i} \equiv \frac{[10^7]}{[2\ 10^4]} (Ocean)$$

where L is the typical length of the basin (1000 km for Mediterranean Sea ten times larger for the Ocean).This adimensional length analysis shows that the properties carried by mesoscale structures are relativaly more important that in the ocean and potentially they can more effectively modify the mean flows physical and biogeochemical properties.

The importance of mesoscale can be a problem in models that are eddy-permitting but not eddy-resolving, being eddy diffusivity and viscosity a coarse parametrizations of subgrid processes and this shortcoming should be considered in analysing model results.

The basic physical formulation is a GFDL MOM1 scheme, with a resolution of ¼ x ¼ of degree, with realistic biogeochemical exchanges though Gibraltar Strait and interactive heat fluxes while the aggregated ecological formulation is a nitrogen-based nutrient (N) plankton (P) and detritus (D) food chain. For all the details regarding model implementation, initial and boundary conditions, parametrisation and verification against data the interested reader can refer to CCM1 and CCM2.

Here we briefly recall some background needed in the model interpretation . The ecosystem evolution is governed by the generic advection-diffusion-reaction equation:

$$\dot{B} + (\vec{u} \cdot \nabla)B \; = \; -K_h \nabla^4 B + K_v \frac{\partial^2 B}{\partial t^2} + w_s \frac{\partial B}{\partial z} + source(B, T, I, \ldots) - sink(B, T, \ldots)$$

where B is the generic biological state variable, w_s the sinking velocity (if any) , T and I are respectively the sea temperature and the incoming Photosynthetic Active Radiation (PAR) and *source* and *sink* are the two generic terms that group positive and negative contribution to the time rate of change of B. The variability in the environmental parameters is sensed locally by the modification of temperature and PAR while the transport terms act as a exogenous source/sink in the evolution of the ecosystem described in a eulerian reference frame.

The run analysed here has been obtained after eight year of 'perpetual year' forcing to obtain the dynamical spin-up. No clouds shading on PAR is allowed, leaving the wind stress as the only variant forcing. The Gibraltar boundary conditions (BC) are those presented in CCM1 and are kept as constant throughout the whole simulation. Model outputs are delivered as bimonthly averages of both physical and biological variables

DISCUSSION OF THE RESULTS

In this preliminary study, we will examine a time series located in the Ionian Sea. The station can be representative of the gross behaviour of the entire basin but exhibits also its own peculiarities.

In Fig. 1 (lower graph) is summarised the evolution of nutrients and phytoplankton both expressed in mgAt N/m**3 in a time/depth (Hovmoller) diagram for the period 1980-1987. Nutrients concentration is shaded (the darker, the higher concentration) while planktonic concentration is contoured. We observe that. there are some recurrent seasonal patterns, namely (a) the winter mixing that destroys vertical structure and (b) the stratification period where upper layer is quickly nutrient depleted because of the energetic activity of primary producers. A recurrent subsurface (light controlled) biomass maximum (SBM) is generally found at 70m depth during summer. This general picture is clearly subjected to large interannual variability both in nutrients and in plankton concentrations.

In 1981, after the biological spin-up, a strong, a long lasting mixing event creates an unusually high nutrient concentration untill surface. This turbulent regime prevents the expected producers bloom until April, when stratification appears. As usually, the SBM starts near the surface and progressively deepens maintainig its characteristics till the Autumn. Below the euphotic zone there is an accumulation of inorganic nutrients which partly derive from the upper layer export production and though remineralization are again put at disposal for successive mixing events.
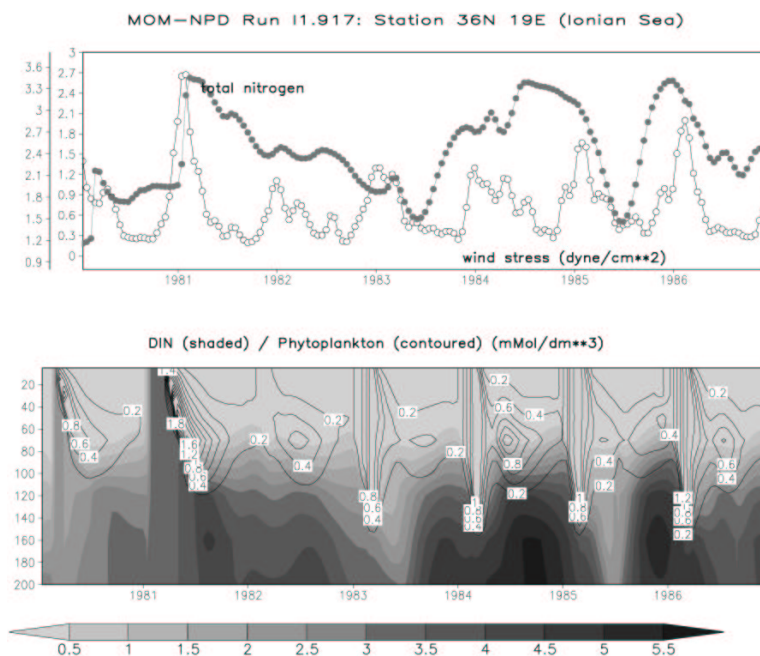
Fig. 1 *Upper graph* Time evolution of the total biologically available Nitrogen (DIN+ phytoplankton+detritus expressed in mgAtN/m**3) as obtained by MOM-NPD interannual run (black dots) in the sample station 35N 19E located in central Ionian Sea.NMC wind stress , used to force the model, is also plotted (white dots) as estimeted in the same location. *Lower graph* Nutrients concentration (shaded) and phytoplankton concentration (contoured) evolution as predicted by the interannual MOM-NPD run in the Ionian Station.

Winter conditions can vary from year to year: in 1980 and 1982 for example the mixed layer depth does not reach deep nutrients-rich layers below nutricline and the vertical nutrient gradient is increased because of the detrital fallout that transports biogenic material outside the productive layer weakly counterbalanced by diapycnal mixing.

In 1984-86 winters the mixing is stronger and is able to sustain a well developed new production giving way to higher standing crops even in the stratification season. A pretty straightforward explanation of such variability can be obtained from the inspection of the wind stress variability as applied as BC to the model. (Fig.1 upper graph). The white dots plot represents the monthly mean wind stress: the 1981 severe winter is strictly connected with exceptional strong mixing found in model results in the same period while the intensity of planktonic maxima are related with the peak events of wind stress (with two exception in correspondence of 1983 and 1985 which will be discussed later). Conversely, the presence of secondary wind stress maxima in Autumn does not affect the ecosystem response, owing the fact that

the high buoyancy content in the upper layer prevents a deepening of the mixed layer depth below the nutricline.

Wind stress dynamics induces also variability at longer time scales: the total biologically available nitrogen (TBAN) defined as the sum of nutrient, plankton and detritus contained in the first 200m (shown with black dots in the Fig.1 upper graph) shows a prominent variability and has its maximum (2.7 mgAtN/m**3) as expected in correspondence of 1981 event, while in the two following years a constant decrease is evidenced. It is worth noting that the cause of the variations in TBAN can be ascribed only to three-dimensional transport terms, since the formulation of the ecological submodel is strictly conservative,.

TBAN higher values are found during 1984-1986 with the noticeable minima in summer 1983 and 1985 and ,to less extent, in summer 1986. This minima derive from the minimum values of nutrients found below the euphotic zone, and this signal is clearly evident in Hovmoller diagram of Fig.1: the origin of this anomalous minima cannot be related to biological activity (the nutrient depletions takes place below the euphotic zone) but it is related to the presence of an anticyclonic eddy which variability in strength and position. Anticyclonic areas are known to enhance oligotrophy because of surface nutrient impoverished convergence and dynamical trapping, and also in this case the nutrients distribution closely follows the dynamical constraint.

To corroborate this explanation, May averaged streamfunction in 1983-1986 period are shown in Fig.2 Even if a wind driven anticyclone is strictly baroclinic, the signal in its essence is also captured by the barotropic component. In May 1983 the Ionian station (marked with a black dot in Fig.2) in influenced by an anticyclone (darker areas in Fig.2), whose centre is located about one degree northward and eastward, while in 1984 a cyclonic structure influences the same area. In the successive year, an intensified anticyclone is present in the same position found in '83, thus affecting the trophic regime of the Ionian station and 1986 we find again a similar situation, except for a reduced intensity of the anticyclone. Another interesting effect connected with the onset of anticyclonic circulation near the Ionian station is shown by SBM: in 1983 and 1985 there is a breaking of the continuity in the SBM during the anticyclonic episodes giving way to a secondary maximum after the anticyclone disappearance.

The pigments concentration as obtained from CZCS images processed by JRC Ocean Project can be assumed as an estimate of the primary produces evolution in the first optical length. Averaged surface values were collected in the same position of the Ionian station and represented in the bar graph showed in Fig.3. Maximum values are found in early winter (January) but values higher than 0.1 mgChl/m*3 can be found also in early spring (1980, 1981, 1983). In summer period the chlorophyll values attain the lowest values close to the instrumental sensitivity (0.03 mgChl/m*3).

The evolution of the surface chlorophyll is also diagnostically estimated by model, using a standard Nitrogen:Carbon ratio (14:12) and transforming the planktonic concentration Carbon equivalent in chlorophyll adopting a variable functional C:Chl relation which depends on nutrient concentration, temperature and irradiance (Cloern et al., 1995). The model estimate is superposed in Fig.3 as a dotted

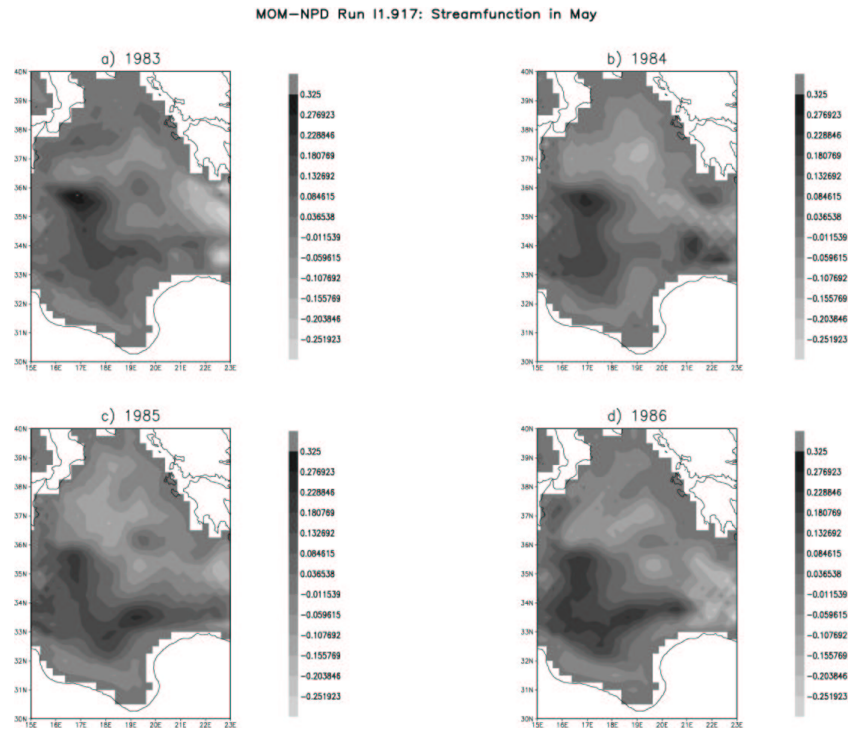MOM—NPD Run I1.917: Streamfunction in May

Fig. 2   MOM-NPD Stream function averages for 4 May months in the period 1983-1986. The recurrent appearance and the variable strength of an anticyclonic area (darker of the surroundings) in the vicinity of the station position, marked with a black dot, modifies nutricline depth and breaks the continuity of the subsurface biomass maximum.

plot. The interannual variability of the CZCS (when data are available) and model results seem to be confined during winter season while both show permanent low values during stratification. CZCS maxima in December and January should be considered with care, since aereosol correction in these cases is even more critical than in the other seasons, because of the slanted optical path during winter and the reduced number of images available. In the period 1980-1983 where CZCS data are more abundant, a good correlation between model and remotely sensed data appears in particular in 1980 and 1983 while in the winter 1981 the existence of the double peak with a maximum in April is neither confirmed nor excluded. In 1982 a general underestimation of values is given by model possibly because of the reduced intensity of the wind estimates (the ECMWF analysis in the same period shows a more energetic wind stress). In the 1984-1985 period the data are too scattered and are missing during winter so nothing can be argued on the seasonal cycle amplitude, suggesting instead a possible anticipation of the maximum. The absence of an explicit grazing pressure would explain relatively slow disappearance of the bloom.
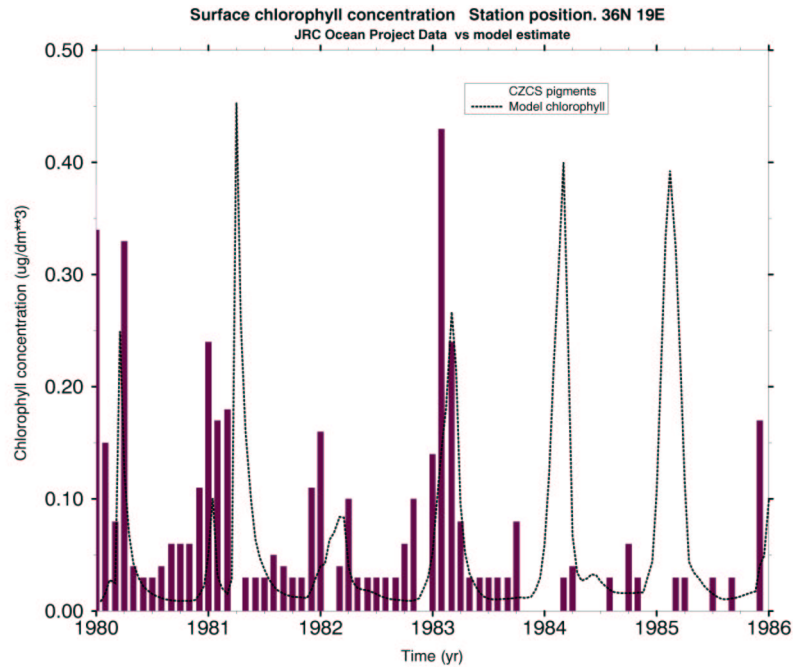
FIG. 3   Comparison of CZCS surface pigments estimated as derived by JRC Ocean Project (bar graph) and the model estimate as diagnostically calculated chlorophyll from bimonthly averages of biological state variables.

CONCLUSION

Wind stress seasonal and interannual signal accounts for the variability in the upper ocean, directly impacting on the mixed layer dynamics and vertically modifying temperature and stratification through the induced heat and buoyancy fluxes. On the other hand large scale transports have similar scales of sinking and redistribute below the euphotic zone nutrients and sinking biogenic material, acting as a preconditioning phase for the winter mixing events. Winter wind stress imparts momentum and buoyancy fluxes that enhance a fast vertical response of the upper ocean. The long-term memory as shown by TBAN contained in the upper ocean and nutricline position are influenced by general circulation processes. Since synoptic eddies in the atmosphere are about two order of magnitude larger than in the sea, energetic perturbations of atmospheric origin affect almost homogeneously open ocean determining a common, basin-wide response of the ecosystem. The 'memory' of the (eco)system differentiates the response on spatial basis, being contained in the nutrients content below the euphotic zone and the in the buoyancy content in the upper layer. As a paradigmatic example, the 1981 severe winter induces an increment

in TBAN which last for more than one seasonal cycle. The modification of this nutritive potential concentration is index of the efficiency of the export processes in this area. Below the euphotic zone we can assume that the variability in nutrient distribution is largely due to advection and diffusion instead to biological degradation of organic matter and the nutrients act as passive tracers. This assumption partially explains the extreme parsimony in the choice of the ecosystem representation while the intrinsic three-dimensional dynamic processes which are involved at long time scale justify a three-dimensional coupled formulation of the eco-hydrodynamical model.

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