Modelling in the Mediterranean Sea

by the group at HCMR (Hellenic Centre for Marine Research) in Greece

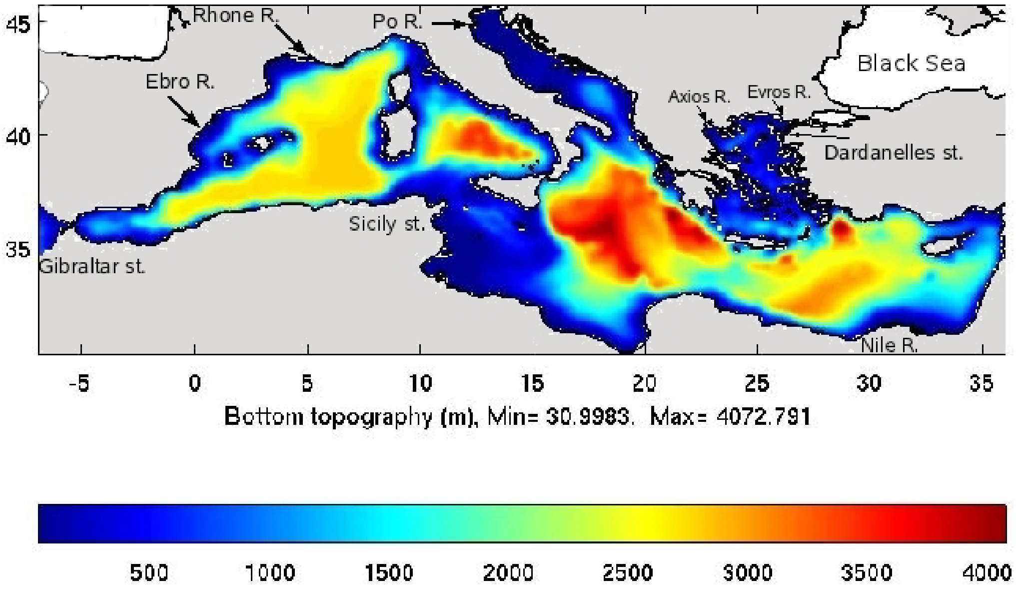
Contents

Data provider

HMCR is a highly active centre for marine research, created in 2003 from the merger of the National Centre for Marine Research with the Institute of Marine Biology of Crete. The modelling team is led by Dr George Triantafyllou.

Regional summary

The Mediterranean is a semi-enclosed sea, connected through the Strait of Gibraltar to the Atlantic Ocean in the west and through the Dardanelles to the Sea of Marmara and the Black Sea in the northeast. About 92% of the estimated natural riverine input of 15,000 m^3/s is from the northern shores. However the management of these inputs has significantly reduced their discharge influencing large areas of the basin. In order to balance the approximately 3,250 km^3/yr water loss (Evaporation – Precipitation – Rivers – Black Sea) there is an influx of Atlantic waters through the straits of Gibraltar (Bryden et al., 1994).



Mediterranean model domain and bathymetry. Major rivers and straits are indicated.

There are two distinct basins in the Mediterranean separated by the shallow Sicily Strait (~500m), which limits exchange, thus decoupling hydrodynamic and ecological conditions (Crise et al., 1999). The eastern basin, due to the anti-estuarine circulation and the relatively low terrestrial inputs, since the construction of Aswan dam in Egypt in 1965, is one of the most oligotrophic areas of the world (Azov, 1991), supporting very low primary productivity and characterised by a deep chlorophyll maximum (DCM) deeper than 100m.

Phosphorous is thought to be the limiting nutrient for phytoplankton and bacterial growth with decreasing concentrations from west to east (Krom et al., 2004).

The Mediterranean Sea is a region with significant atmospheric inputs, mostly composed by Saharan dusts and anthropogenic inputs. In the Eastern basin, atmospheric inputs of nitrogen (mainly as nitrate, NO_3^-, and ammonium, NH_4^+) and phosphorus (as phosphate, PO_4^{-3}) are believed to be an important source of nutrients in the euphotic zone of the open sea, other than the vertical mixing of water during winter (Mara et al., 2009; Christodoulaki et al., 2012).

The primary production is mainly controlled by vertical mixing processes that supply the euphotic zone with deep water nutrients, showing a maximum from December to March and a minimum from June to September. The seasonal cycle is stronger in areas characterized by deep water formation as the northwestern basin that is one of the most productive areas [Morel et André, 1991; Bosc et al., 2004; Marty et al., 2002]. The stratified period is characterized by a deep chlorophyll maximum that follows the evolution of the nutricline depth [Siokou-Frangou et al., 2010].

The concentrations of anthropogenic CO_2 are much higher than those found in the Atlantic Ocean (the minimum concentration at the DYFAMED site is 50 mmol.kg^{-1}), and the temporal trend for anthropogenic CO_2 (carbon accumulates in the atmosphere since the beginning of the industrial era) is decreasing, especially in the intermediate water (LIW) in the Ligurian Sea [Touratier and Goyet, 2009].

Fishing is a traditional human activity all over the Mediterranean basin and nowadays is an important economic activity for several regions. Given the high biodiversity of the Mediterranean, which is inhabited by more than 650 fish species, the number of commercial fish species exceeds 100. Mediterranean fisheries are mostly multi-species and the fleets are composed by vessels that are usually having length less than 20-25m, being considered small in comparison to the vessel exploiting the nearby Atlantic area. Numerous fishing gears are employed but most of the catches are made by demersal trawlers, purse-seiners and artisanal vessels using various types of gillnets and longlines. In the latest years, Mediterranean and Black Sea capture fisheries production is around to 1.5 million tonnes corresponding to less than 2% of the world's fisheries production. Although, as already mentioned, the number of commercial species exceeds one hundred, few species such as tunas, red shrimps, red mullet, hake, anchovy and sardine compose more than 70% of the total landings. It should be noticed that only small pelagics (mainly sardine and anchovy) compose around 40% of the total Mediterranean catch.

Justification of model selection

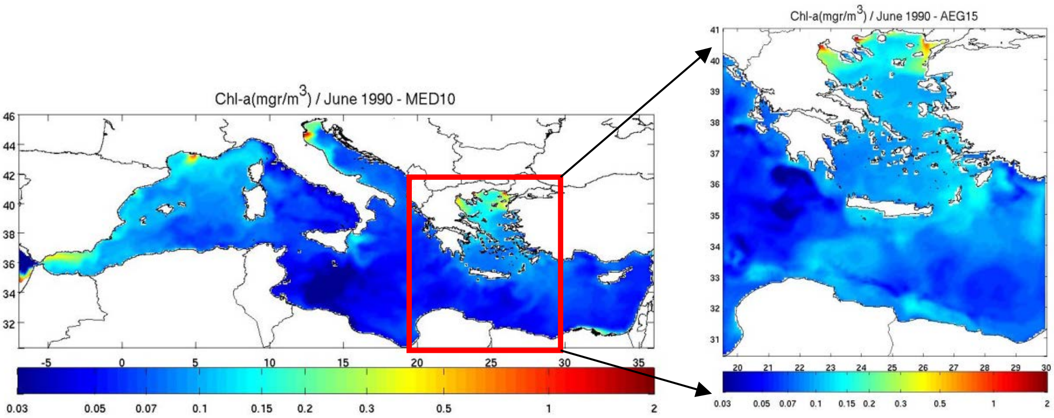
The Mediterranean Sea ecosystem is highly complex and as such it cannot be studied with short-term campaigns. Considering the vast number of parameters and processes dynamically inter-connected, it becomes rather evident that models are perfect tools to acquire new knowledge on the structure and functioning of the ecosystem. As has been generally acknowledged models with all trophic levels fully described by differential equations seem to be the only option in reproducing major qualitative aspects of the experimental system (Thingstad et al., 1999). To achieve this, a model is required which can consider the offshore gradients in vertical-mixing regimes, light and nutrient availability, and grazing pressure on primary and bacterial production. The accurate simulation of the spatial and temporal variability of the physical and biogeochemical characteristics of the Mediterranean marine ecosystem is a fully coupled coastal-open ocean problem requiring the solution of a fully three-dimensional density driven general circulation problem, together with the appropriate description of ecological and biogeochemical processes. ERSEM is a comprehensive model, describing with the necessary complexity the Mediterranean planktonic food web and biogeochemical processes.

Small pelagic fish play a key role in the ecosystem, being the primary consumers of plankton as well as the main prey for fish higher trophic levels. Anchovy is the most important commercial fish in the Aegean in terms of catch and biomass. Understanding the growth, mortality, reproduction and transport patterns of small pelagic fish requires their coupling to hydrodynamics and lower trophic level dynamics. The anchovy-IBM, being on-line coupled to the biophysical model provides an integrated modelling framework to address issues related to the spatial and temporal dynamics of fish stocks by taking into account the circulation patterns, as well as temperature and plankton fields within a marine ecosystem.

Technical overview of models used in this region

Hydrodynamic model

A coupled hydrodynamic/biogeochemical model is implemented in the Mediterranean with 1/10 x 1/10 (~10Km) resolution. A higher resolution (1/15^o x 1/15^o) model is downscaled in the Aegean Sea (see figure), using open boundary conditions from the basin-scale model. A high-trophic-level (HTL) model (anchovy-IBM) is implemented in the Aegean.

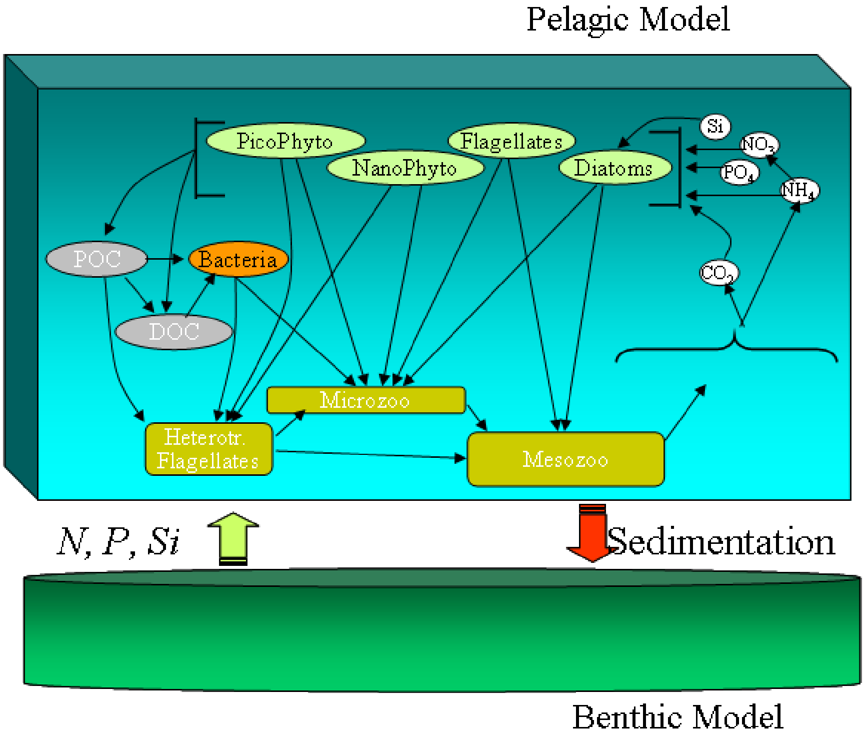


Mediterranean basin-scale (left) and Aegean Sea (right) model areas.

The hydrodynamic model is based on the Princeton Ocean Model (POM, (Blumberg and Mellor, 1983)), which is a 3-dimensional, primitive equation, free surface and sigma-coordinate circulation model. POM is a widely spread community model that has been extensively described in the literature (e.g. Blumberg and Mellor, 1987; Galperin and Mellor, 1990; Mellor and Ezer, 1991) and has been used in numerous applications (a comprehensive user's guide and an extensive list of applications can be found at the POM home page: http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom).

Lower Trophic level model

The biogeochemical model is based on the European Regional Seas Ecosystem Model (ERSEM), (Baretta et al., 1995; Petihakis et al. 2002), a generic comprehensive model that has been successfully implemented across a wide range of coastal and open ocean ecosystems, such as the North Sea continental shelf (Pätsch and Radach, 1997), the oligotrophic Mediterranean (Petihakis et al., 2002; Allen et al., 2002) and the Arabian Sea (Blackford and Burkill, 2002), among others. A basin-scale Mediterranean coupled model of 10Km resolution is currently operational as part of the "POSEIDON" forecasting system (www.poseidon.hcmr.gr). ERSEM uses a "functional" group approach, where biotic groups are distinguished not by species but by their functional role in the ecosystem using size as the major characteristic.



Schematic diagram of the ERSEM pelagic model

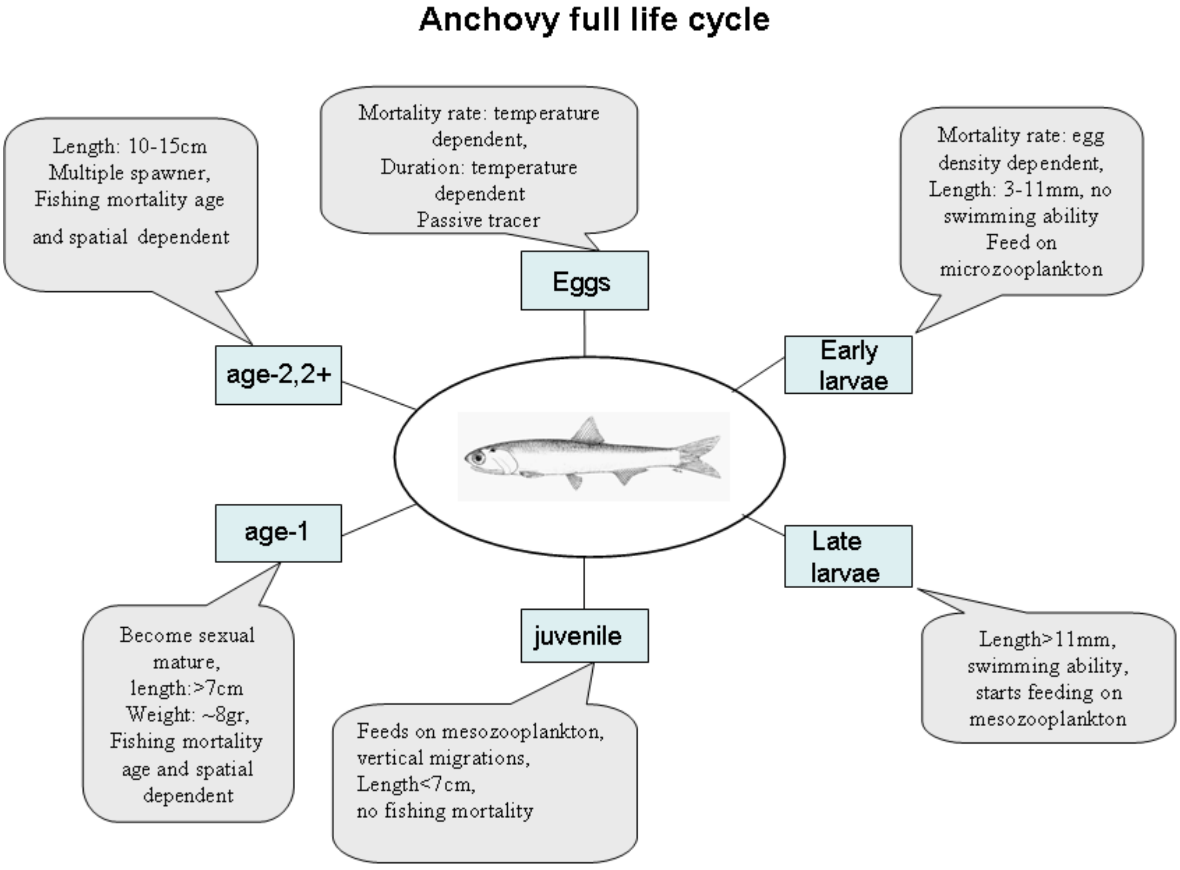
The pelagic model food web that has been slightly modified from the standard configuration in order to better represent the Eastern Mediterranean system, consists of 4 phytoplankton groups: diatoms (20-200µm, silicate consumers), nanoplankton (2-20µm), picoplankton(<2µm) and dinoflagellates (20-200µm), bacteria and 3 zooplankton groups: heterotrophic nanoflagellates (feeding on bacteria, picophytoplankton and nanophytoplankton), microzooplankton (feeding on nanophytoplankton, heterotrophic nanoflagellates, diatoms and dinoflagellates) and mesozooplankton(feeding on diatoms, dinoflagellates and microzooplankton) The pelagic model variables include also particulate and dissolved organic matter (produced by the mortality, excretion and lysis of primary and secondary producers and utilised by bacteria), along with dissolved inorganic nutrients (nitrate, ammonia, phosphate, silicate). Carbon dynamics are coupled to chemical dynamics of nitrogen and phosphate, as each group has dynamically varying C/N/P ratios. The uptake of dissolved inorganic nitrogen and phosphorus by phytoplankton is regulated based on the difference between internal and external nutrient pools, following a Droop kinetics formulation (Droop, 1974) to describe nutrient limitation, allowing for luxury uptake. Since there is no internal storage of silicate, the diatoms growth is further regulated by a Michaelis-Menten function of the external availability of dissolved silica. As a closure term for mesozooplankton, a sigmoid density-dependent loss function (Edwards and Yool, 2000) is adopted, parameterising top-predator mortality. Finally the benthic-pelagic coupling is described by a simple first order benthic return module, which includes the settling of organic detritus into the benthos and diffusional nutrient fluxes into and out of the sediment.

Higher trophic level models

The High Trophic Level (HTL) model that is implemented in the Aegean Sea is a full life cycle (including all life stages from eggs to adults) individual-based (IBM) model for small pelagic species (anchovy). The anchovy-IBM is on-line coupled to the Aegean LTL biogeochemical/hydrodynamic model ($1/15^o$ x $1/15^o$) that provides the ocean currents, temperature and zooplankton as input. For the representation of the entire fish population, the notion of the super-individuals (Scheffer et al., 1995) is used. Each SI refers to a fish population or a "fish school" that shares the same attributes in terms of growth, mortality, movement, reproduction etc.

A bioenergetics model (Politikos et al., 2011; Rose et al., 2007) is used to describe the anchovy growth, taking account of the most important processes (consumption, respiration, excretion, egestion, specific dynamic action, egg production), while the anchovy population dynamics are controlled by natural, starvation and fishing mortality.

A Lagrangian model is used to simulate the anchovy SIs horizontal position based on movement rules that take into account of several factors such as the ocean currents, food availability, bathymetry and fish swimming speed. Since anchovy full life cycle is characterized by significant ontogenetic differences and behaviours, the SI is categorized into the following stages: embryonic, early larval stage, late larval stage, juvenile stage (age-0), adult stage (age-1), adult stage (age-2) and adult stage (age-3). SIs that belong at the same life stage have identical characteristics in terms of feeding preferences, mortalities and movement strategies.



Main behavioural, feeding and population characteristics of the anchovy full life cycle.

Data Assimilation

The data assimilation biogeochemical data, will be based on the SEEK (Singular evolutive Extended Kalman) filter approach. The models described here consider the SEEK filter and two of its variants, the Singular Fixed Extended Kalman (SFEK) filter, assuming persistence of the error sub-space with time, and its Ensemble version, the Singular Extended Interpolated Kalman (SEIK) filter, in which the linearization used in the SEEK filter is replaced by linear interpolation (Triantafyllou et al., 2003). Here, we briefly present the SEEK filter, adopting a notation proposed by (Ide et al., 1997). Full details

Forcing and Boundary Conditions

Atmospheric Forcing

The atmospheric forcing for the hindcast simulation of the HCMR Mediterranean coupled hydrodynamic/biogeochemical model was obtained from the regional climate model HIRHAM5 simulation (further details). The atmospheric forcing has been compared against ERA40 re-analysis forcing over 1990-1999 period and net heat/fresh water budget estimates in the Mediterranean.

Boundary conditions

The Dardanelles water exchange is parameterized through a two-layer open boundary condition (Nittis et al., 2006) with prescribed water inflow/outflow and salinity, adopting climatological data of seasonally varying water inflow and dissolved inorganic nutrients (Tugrul et al., 2002) and annual mean organic matter and ammonium concentrations (Polat et al., 1996; 1997). Average alkalinity and dissolved inorganic carbon concentration of the inflowing BSW was adopted from Copin-Montegut (1993).

Along the western open boundary near Gibraltar strait, the following boundary conditions are used:

- Flather (1976) boundary condition, for the integrated (barotropic) velocity.
- Sommerfeld radiation condition, for Baroclinic velocities.
- Zero-gradient condition for free-surface elevation.
- Upstream advection scheme for tracers (Temperature, Salinity, biogeochemical variables), during outflow. During inflow, temperature and salinity are prescribed from MODB seasonal climatology. Inorganic nutrients (phosphate, nitrate, silicate) are obtained from MEDATLAS climatology, while total alkalinity and dissolved inorganic carbon are obtained from GLODAP annual climatology.

For full details on models used in this region please refer to http://marine-opec.eu/downloads/OPEC_D2.4.pdf

References

Allen, J.I., Somerfield, P.J., Siddorn, J., 2002. Primary and bacterial production in the Mediterranean Sea: a modelling study. Journal of Marine Systems 33–34, 473– 495.

Anderson T.R. and P. Pondaven, 2003. Non-redfield carbon and nitrogen cycling in the Sargasso Sea: pelagic imbalances and export flux, Deep-Sea Research I, 50, 573-591.

Azov, Y., 1991. Desert? Marine Pollution Bulletin 23, 225-232.

Baretta, J.W., Ebenhoh, W. and Ruardij, P., 1995. The European regional seas ecosystem model, a complex marine ecosystem model. Netherlands Journal of Sea Research, 33, 233-246.

Becacos-Kontos, T., 1977. Primary production and environmental factors in an oligotrophic biome in the Aegean Sea. Marine Biology 42, 93-98.

Berland, B., Bonin, D., Maestrini, S., 1980. Azote ou phosphore ? Considerations sur le "paradoxe nutrionnel" de la Mer Mediterranee. Oceaonologica Acta 3, 135-142.

Blackford, J.C. and F.J. Gilbert, 2007. pH variability and CO2 induced acidification in the North Sea, J Mar Sys. 64, 229-242.

Blackford, C.J., Allen, J.I. and Gilbert, J.F., 2004. Ecosystem dynamics at six contrasting sites: a generic modelling study. Journal of Marine Systems, 52: 191-215.

Blackford, J.C., Burkill, P.H., 2002. Planktonic community structure and carbon cycling in the Arabian Sea as a result of monsoonalforcing: The application of a generic model. Journal of Marine Systems 36 (3–4), 239–267.

Blumberg, A.F., Mellor, G.L., 1983. Diagnostic and prognostic numerical circulation studies of the South Atlantic Bight. J. Geophys. Res., 88(C8), 4579-459.

Bosc, E., Bricaud, A. et Antoine, D., 2004. Seasonal and interannual variability in algal biomass and primary production in the Mediterranean Sea, as derived from 4 years of SeaWiFS observations, Global Biogeochem Cycles, 18 (GB1005).

Bryden, H.L., Candela, J., Kinder, T.H., 1994. Exchange through the Strait of Gibraltar. Prog. Oceanog. 33, 201-248.

Castellari S., N. Pinardi and K. Leaman, 1998. A model study of air-sea interactions in the Mediterranean Sea, Journal of Marine Systems, 18, 890114.

Christodoulaki, S., Petihakis, G., Kanakidou, M., Mihalopoulos, N., Tsiaras, K., Triantafyllou, G., 2013. Atmospheric deposition in the Eastern Mediterranean. A driving force for ecosystem dynamics. Journal of Marine Systems (in press).

Crise, A., Allen, J.I., Baretta, J., Crispi, G., Mosetti, R., Solidoro, C., 1999. The Mediterranean pelagic ecosystem response to physical forcing. Progress in Oceanography 44, 219-243.

Copin-Montegut, C., 1993. Alkaninity and carbon budgets in the Mediterranean, Global Biogeochemical Cycles, 7(4), 915-925.

D'Ortenzio et Ribera d'Alcala, 2009

Drakopoulos, P.G. and Lascaratos, A., 1997. Modelling the Mediterranean Sea: climatological forcing. Journal of Marine Systems, 20: 157-173.

Edwards AM, Yool A (2000) The role of higher predation in plankton population models Journal of Plankton Research 22:1085-1112.

Hoteit, I., Pham, D.-T., Blum, J., 2002. A simplified reduced order kalman filtering and application to altimetric data assimilation in tropical pacific. J. Mar. Sys. 36, 101-127.

Galperin, B. and Mellor, G.L., 1990. A time-dependent, three-dimensional model of the Delaware Bay and River. Part I: Description of the model and tidal analysis. Estuarine Coastal and Shelf Science, 31: 231-253.

Giannoulaki M., Somarakis S., Machias A., Kalianiotis A., Tserpes G., Petrakis G., Papaconstantinou C. (2007). Preliminary Results from stock assessment of the Aegean Sea anchovy stock by integrated Catch at age analysis. GENERAL FISHERIES COMMISSION FOR THE MEDITERRANEAN SCIENTIFIC ADVISORY COMMITTEE Sub-Committee for Stock Assessment Working Group on Small Pelagic Species FAO, Athens.

Giannoulaki M, Valavanis VD, Palialexis A, Tsagarakis K, Machias A, Somarakis S, Papaconstantinou C. (2008). Modelling the presence of anchovy Engraulis encrasicolus in the Aegean sea during early summer, based on satellite environmental data. Hydrobiologia, 612, 225-240.

Horton, C., Clifford, M., Schmitz, J. and Kantha, L.H., 1997. A real-time oceanographic nowcast/forecast system for the Mediterranean Sea. J. Geophys. Res., 102(C11): 25123-25156.

Ide, K., Bennett, A.F., Courtier, P., Ghil, M., Lorenc, A.C., 1997. Unified notation for data assimilation: operational, sequential and variational. Journal of Meteorological Society of Japan 75, 181-189.

Ingri, N., W. Kakolowicz, L.G. Sillen and B. Warnqvist, 1967. Highspeed computere as a supplement to graphical methods: V. HALTAFALL, a general program for calculating the composition of equilibrium mixtures. Talanta 14, 1261.

Korres, G. and Lascaratos, A., 2003. An eddy resolving model of the Aegean and Levantine basins for the Mediterranean Forecasting System Pilot Project (MFSPP): Implementation and climatological runs. Analles Geophysicae, 21: 205-220.

Korres, G., Nittis, K., Hoteit, I. and Triantafyllou, G., 2009. A high resolution data assimilation system for the Aegean Sea hydrodynamics. Journal of Marine Systems, 77(3): 325-340

Kourafalou, V.H. and Barbopoulos, K., 2003. High resolution simulations on the North Aegean Sea seasonal circulation. Annales Geophysicae, 21: 251-265.

Krom, M., Herut, B., Mantoura, C.F.R., 2004. Nutrient budget for the Eastern Mediterranean: Implications for phosphorus limitation. Limnol. Oceanogr., 1582-1592.

Krom, M.D., Brenner, S., Kress, N., Neori, A., Gordon, L.I., 1992. Nutrient dynamics and new production in a warm-core eddy from the Eastern Mediterranean Sea. Deep-Sea Research 39, 467-480.

Krom, M., Kress, N., Brenner, L., Gordon, I., 1991. Phosphorus limitation and primary productivity in the Eastern Mediterrranenan Sea. Limnology & Oceanography 36, 424-432.

Kress, N., Herut, B., 2001. Spatial and seasonal evolution of dissolved oxygen and nutrients in the Southern Levantine Basin (Eastern Mediterranean Sea): chemical characterization of the water masses and inferences on the N: P ratios. Deep-Sea Research I 48, 2347–2372.

Kress, N., Manca, B. B., Klein, B., Deponte, D., 2003. Continuing influence of the changing thermohaline circulation in the Eastern Mediterranean on the distribution of dissolved oxygen and nutrients: Physical and chemical characterization of the water masses. J. Geophys. Res., 108: 9-1-9-20.

Lascaratos, A. and Nittis, K., 1998. A high-resolution three-dimensional study of intermediate water formation in the Levantine Sea. Journal of Geophysical Research, 103(C9): 18497-18511.

Lin, H.J., Nixon, S.W., Taylor, D.I., Granger, S.L. and Buckley, B.A., 1996. Responses of epiphytes on eelgrass, Zostera marina L., to separate and combined nitrogen and phosphorus enrichment. Aquatic Botany, 52: 243-258.

Mara, P., Mihalopoulos, N., Gogou, A., Daehnke, K., Schlarbaum, T., Emeis, K.C., Krom, M., 2009. Isotopic composition of nitrate in wet and dry atmospheric deposition on Crete in the eastern Mediterranean Sea. Global Biogeochemical Cycles, 23, doi:10.1029/2008GB003395.

Marty, J.-C., Chiaverini, J., Pizay, M.-D., Avril, B., 2002. Seasonal and interannual dynamics of nutrients and phytoplankton pigments in the western Mediterranean Sea at the DYFAMED time-series station (1991–1999). Deep-Sea Research II 49, 1965–1985.McGill, 1965;

Mellor, G.L. and Blumberg, A.F., 1985. Modeling vertical and horizontal diffusivities with the sigma coordinate system. Monthly Weather Review, 113: 1379-1383.

Mellor, G.L. and Ezer, T., 1991. A Gulf Stream model and an altimetry assimilation scheme. Journal of Geophysical Research, 96: 8779-8795.

Mellor, G.L. and Yamada, T., 1982. Development of a Turbulence Closure Model for Geophysical Fluid Problems. Review Geophysics and Space Physics, 20: 851-875.

Mihailov, A.A., Denisenko, V.V., 1985. The zooplankton communities of the Eastern Mediterranean Levantine Basin, Aegean Sea influence of the man made factors, in: V, M.-A.M., Kiortsis (Eds.), In Mediterranean Marine Ecosystems. Plenum Press, New York, pp. 303-331.

Morel A. and J.-M. André, 1991. Pigment distribution and primary production in the western Mediterranean as derived and modeled from coastal zone color scanner observations, Journal of Geophysical Research, 96, 12685-12698.

Moutin, T., Raimbault, P., 2002. Primary production, carbon export and nutrients availability in western and eastern Mediterranean Sea in early summer 1996 (MINOS cruise). Journal of Marine Systems 33-34, 273-288.

Nerger, L., Danilov, S., Hiller, W., Schroter, J., 2006. Using sea-level data to constrain a finite-element primitive-equation ocean model with a local SEIK filter. Ocean Dynam 56, 634-649.

Nittis, K., Perivoliotis, L., Korres, G., Tziavos, C. and Thanos, I., 2006. Operational monitoring and forecasting for marine environmental applications in the Aegean Sea. Environmental Modelling and Software, 21: 243-257.

Pa¨tsch, J., Radach, G., 1997. Long term simulation of the eutrophication of the North Sea: temporal development of nutrients, chlorophyll and primary production in comparison to observations. Journal of Sea Research 38, 275– 310.

Petihakis, G., Triantafyllou, G., Allen, I.J., Hoteit, I., Dounas, C., 2002. Modelling the spatial and temporal variability of the Cretan Sea ecosystem, J. Mar. Syst. 36 (3-4), 173-196.

Pham, D.T., Verron, J., Gourdeau, L., 1998. Singular evolutive Kalman filters for data assimilation in oceanography. C. R. Acad. sci. Paris 326, 255-260.

Pham, D.T., Verron, J., Roubaud, M.C., 1997. Singular evolutive Kalman filter with EOF initialization for data assimilation in oceanography. Journal of Marine Systems 16, 323-340.

Pham, D.T., 1996. A singular evolutive interpolated kalman filter for data assimilation in oceanography, Tec. Rep. 163.

Pinardi, N., Masetti, E., 2000. Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review. Palaeogeography, Palaeoclimatology, Palaeoecology 158, 153-174.

Politikos DV, Triantafyllou GN, Petihakis G, Tsiaras K, Somarakis S, Ito S-I, Megrey BA. (2011). Application of a bioenergetics growth model for European anchovy (*Engraulis Encrasicolus*) linked with a lower trophic level ecosystem model. Hydrobiologia 670, 141-163.

Rose, K.A., F.E. Werner, B.A. Megrey, M.N. Aita, Y. Yamanaka, D.E. Hay, J.F. Schweigert, Foster M.B. (2007). Simulated herring growth responses in the Northeastern Pacific to historic temperature and zooplankton conditions generated by the 3Dimensional NEMURO nutrient-phytoplankton-zooplankton model. Ecol. Model. 202(1-2): 184-195.

Scheffer M., J.M. Baveco, D.L. DeAngelis, Rose K.A. (1995). Super-individuals: a simple solution for modelling large populations on an individual basis, *Ecological Modelling* 80: 161–170.

Schneider, A., Douglas W.R. Wallace and A. Kortzinger, 2007. Alkalinity of the Mediterraean Sea, Geophysical research letters, vol.24, L15608, doi:10.1029/2006GL028842.

Siokou-Frangou I., Christaki, U., Mazzocchi, M.G., Montresor, M., Ribera d’Alcala, M., Vaque, D., Zingone, A., 2010. Plankton in the open Mediterranean Sea: a review. Biogeosciences, 7: 1543–1586.

Smagorinsky, J., 1963. General circulation experiments with the primitive equations, I, The basic experiment. Mon. Weather Rev., 91: 99-164.

Somarakis, S., Nikolioudakis N. (2007a). Oceanographic habitat, growth and mortality of larval anchovy (*Engraulis encrasicolus*) in the northern Aegean Sea (eastern Mediterranean) Mar. Biol. 152, 1143-1158.

Somarakis S, Schismenou E, Siapatis A, Giannoulaki M, Kallianiotis A, Machias A, 2010 .Variability in the Daily Egg Production Method parameters of the N. Aegean Sea anchovy stock (eastern Mediterranean): Evidence for density dependent daily specific fecundity.

Theocharis, A., Georgopoulos, D., Lascaratos, A., Nittis, K., 1993. Water masses and circulation in the central region of the Eastern Mediterranean: Eastern Ionian, South Aegean and Northwest Levantine. Deep-Sea Research II 40, 1121-1142.

Thingstad, T.F., Rassoulzadegan, F., 1995. Nutrient limitations, microbial food webs, and 'biological C-pumps': suggested interactions in a P-limited Mediterranean. Marine Ecology Progress Series, 117: 299-306.

Touratier F. and C. Goyet (2009). Decadal evolution of anthropogenic CO2 in the north western Mediterranean Sea (at the Dyfamed site) from the mid-1990’s to the mid-2000’s. Deep Sea Research Part I, 56, 1708–1716

Triantafyllou, G., Hoteit, I., Petihakis, G., 2003. A singular evolutive interpolated Kalman filter for efficient data assimilation in a 3D complex physical-biogeochemical model of the Cretan Sea. Journal of Marine Systems 40-41, 213-231.

Zavatarelli, M. and Mellor, G.L., 1995. A numerical study of the Mediterranean sea circulation. Journal of Physical Oceanography, 25(6): 1384-1414.

Zavatarelli, M. and Pinardi, N., 1995. The Adriatic Sea general circulation: modeling with the Princeton Ocean Model. Annales Geophysicae, 13(Supplement 2).