MENOR: A HIGH-RESOLUTION (1.2 KM) MODELING OF THE NORTH-WESTERN MEDITERRANEAN SEA ROUTINELY RUN BY THE PREVIMER OPERATIONAL FORECAST SYSTEM

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Abstract

IFREMER has encouraged for over 15 years the oceanographic modeling of sea waters all around the metropolitan French coasts in order to facilitate environmental coastal studies. In that context, the North-Western Mediterranean Sea configuration (MENOR: 1.2 km – 60 vertical levels) has been introduced in the framework of Previmer operational forecasting system (http://www.previmer.org/en). This article gives an insight into the operational applications and scientific research using this MENOR configuration.

Introduction

Previmer aimed at producing short term forecasts and long term hindcasts of the marine environment all along the French coasts. The Model for Applications at Regional Scale (MARS), used within this context, has been developed by the French Research Institute for Exploitation of the Sea (IFREMER). It is dedicated to simulating environmental coastal dynamics and has been implemented in the area of North-Western Mediterranean Sea at high resolution. The domain extends from 39.5°N to 44.5°N and from Spain to Italy. Such a spatial extension allows simulating the full cyclonic gyre on the abyssal plain in the open of the Gulf of Lions. The realistic simulation of the Northern Current, main component of the general circulation, is also improved. Moreover, the 1.2 km resolution allows the meso-(submeso)scale activity to be fully developed over the plain, along the shelf break, and over the Gulf of Lions (figure 1).

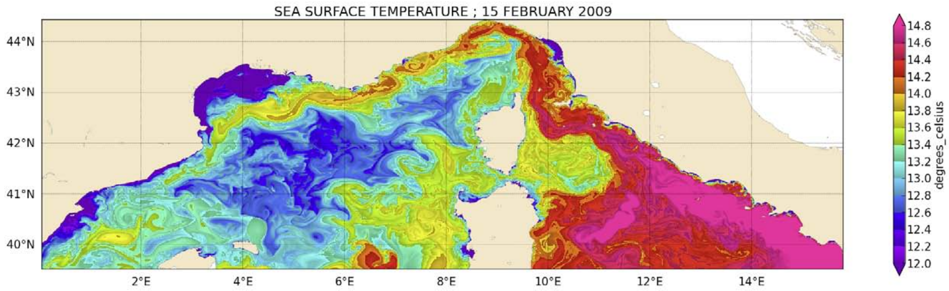

Figure 1: Snapshot of the sea surface temperature on February 15, 2009, simulated by MARS.

Modeling description

MARS solves the system of incompressible Navier-Stokes equations in the classical Boussinesq approximation with the hydrostatic approximation [Blumberg and Mellor, 1987). It uses a generalized vertical, terrain-following, coordinate system and has the particularity of resolving the barotropic and baroclinic modes with a common time step, thanks to the alternating direction implicit scheme. The simulation characteristics are summarized in table 1.

area	*0-16°E ; 39.5°N-44.5°N*
grid	*1.2 km resolution* *generalized vertical, terrain-following, layers* *(1101x463x60)*
forcing	*Rivers: 14. The Rhone, Var, Tet, Herault, Aude, Gapeau, Argens, Tech, Lez, Orb river discharges are the observations of the day before.* *Initial and open boundary oceanic conditions: Mediterranean Oceanography Network for the Global Ocean Observing System (daily fields)* *Atmospheric forcing: French Met-Office model Arpege (10 km, 3h)* *No tide*
scheme	*Bulk turbulent flux: Fairall et al. 2003* *Momentum: QUICK (3rd order)* *Viscosity: Smagorinsky (1963)* *Tracers: horiz. 5th order, Upwind Compact and Conservative (UCC 5th order),3D MACHO method (Duhaut and Debreu, 2008, Debreu et al. 2011)* *Diffusion: centered scheme (1m^2.s^{-1})* *Pressure gradient: density jacobian cubic spline (Shchepetkin and Mc Williams, 2003)* *Turbulence: GLS (k-epsilon)*

Table 1: Characteristics of the MENOR configuration

MENOR simulations benefit from progress on numerical schemes following the work of L. Debreu and his colleagues. The remodeled time scheme and barotropic/baroclinic splitting techniques in MARS [Duhaut et al., 2008] allows the dissipation of numerical noise and the simulation of small long-lived coherent eddies. The development of high order schemes for the momentum and advection schemes (3^{rd} and 5^{th} order respectively) and the 3D extension of the MACHO method (to take into account the crossing terms while solving advection) [Debreu and Duhaut, 2011] have strongly reduced the diapycnal mixing. Lastly, the introduction of a two equation turbulence scheme [Umlauf and Burchard, 2003], used with a suitable rate of dissipation of the turbulent kinetic energy, has improved the conservation of the intermediate and deep water masses hydrological characteristics. In order to improve the simulated sea surface temperature, the radiative atmospheric fluxes penetrate the surface layers according to two different wave lengths. This adjustment improves the correct representation of the sea surface temperature seasonal cycle.

Every day, Previmer operational forecasting system imports analyses and forecasts from the French Met-Office model Arpege (10 km, 3h), river discharge observations, daily OGCM fields from Mediterranean Oceanography Network for the Global Ocean Observing System (MONGOOS) and runs the MENOR configuration. Each run produces an analysis for the day before (J-1 at 0 am) and a four day forecast up to J+4 0 am. It saves all the hydrodynamic variables every 3 hours over the global domain and makes result files available to users. Up to January 2013, the atmospheric forcing was provided by ACRI-ST which was running MM5 model (9 km, 3h) as a zoom of the NCEP model.

Operational applications

MENOR outputs (222 Go a year) are downloaded by File Transfer Protocol (FTP) or openDAP (Open-source Project for a Network Data Access Protocol) by a third of the users interested by hydrodynamic results (which represent 46% of Previmer products users) [Pineau-Guillou 2013, Pineau-Guillou et al., 2014, this issue]. The MENOR configuration itself is mainly used in scientific institutes for research applications (58%) while 42% of the requests for access to simulation results come from private companies. Model outputs are used as open boundary and initial fields to force coastal models or for direct analyses. The main domains of applications are flora and underwater fauna (26%), marine water quality (22%), hydro(-sedimento) dynamics (20%), environmental pollution (16%), shipping route optimization (8%), Renewable Marine Energy (6%), and meteorology (2%). Statistics from MENOR output requests suggest that 44% of the user applications have real time objectives.

From feedbacks from Previmer users, the MENOR analyses are the most used fields. For instance, they allow investigations on bacteria dispersion due to sewage releases or on drifts of micro-plastics, they provide information to evaluate potential installation of wind mill farms... Real time applications remain relatively marginal but a few can be noticed. A private company used real time forecasts as boundary conditions for an embedded model of the Provençal area, aimed at monitoring Oil Spill drifts during summer. People from LAMA (Tuscany, Italy) used MENOR results for a real time modeling of the Tuscany shelf. Previmer team participated to an antipollution exercise managed by the REMPEC (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea). And lastly Previmer provides currents, temperature and salinity for a Mediterranean integrated Oil Spill System in the framework of MEDESS4MS project. Of course, scientists examine the MENOR configuration just before or during a field experiment as a support to manage the data sample strategy.

In 2013, IFREMER participated in HYMEX (Hydrological cycle in Mediterranean Experiment) second Special Observation Period (Feb.-March 2013) effort dedicated to the documentation of dense water formation in the North-Western Mediterranean area. Along with the Laboratory of Aerology (SYMPHONIE-NWMED-111 configuration) and Mercator Ocean (PSY2V4R2 [Lellouche et al., 2013] and IBI36V2R1 [Maraldi et al., 2013] configurations), IFREMER used MENOR operational outputs in order to provide quicklooks describing the hydrological situation of the area and the development of deep convection and dense water formation. Analyses were sent in real time to help the Operational Center of the SOP2 experiment to adjust the deployment of the in-situ measurements. There are available on the http://sop.hymex.org website.

Research applications

MENOR simulates the general circulation, its seasonal and interannual variability, as well as mesoscale processes such as intermittent upwellings, coherent eddies on the shelf itself [Schaeffer et al., 2011] or off Toulon [André et al., 2009] and the Rhone plume dynamics. Over the global domain, IFREMER research studies focus on the hydrodynamics itself and on biogeochemical, benthic and fisheries applications.

Mesoscale hydrodynamic interpretation

The understanding of the mesoscale structures dynamics is an essential step to consider their contribution to primary production, recruitment of larvae and transfer of contaminants. Numerous hydrodynamical studies have therefore focused on mesoscale eddies, which are observed from satellite, in-situ measurements and lagrangian drifters, and well reproduced in MENOR simulations. Thanks to the simultaneous modeling of both the Gulf of Lions and the abyssal plain, Garreau et al. [2011] explained the dynamics linking the “LATEX” and “CATALAN” eddies. The LATEX eddy is a large anticyclonic structure, fully developed in summer in the southwestern corner of the Gulf of Lions. It was first documented by Millot [1982] and monitored by the Lagrangian Transport Experiment. The “CATALAN” eddies are large anticyclonic gyres of 40-50 km in diameter. They exhibit sub-surface current velocities up to 0.5 m s-1 and their vertical extension may reach down to 100 m water depth [Rubio et al., 2005]. They occur once to three times a year during summer and autumn in the Catalan Sea. Careful analyses of a particular event in autumn 2007, monitored both by drifting buoys and Jason1’s tracks and simulated within MENOR configuration, have allowed Garreau et al. [2011] to conclude (figure 2) that: 1 - the LATEX anticyclonic eddy is a warm and less dense water body, isolated and partially fed by a coastal current carrying warm water from the Catalan Sea during long Tramontane summer events, 2 – that a burst of southeasterlies and/or northerlies appeared to trigger the “LATEX” eddy detachment, which then flowed out of the Gulf of Lions, migrating along the Catalan continental slope before reaching the Balearic Sea where it is known as the “CATALAN” eddy.

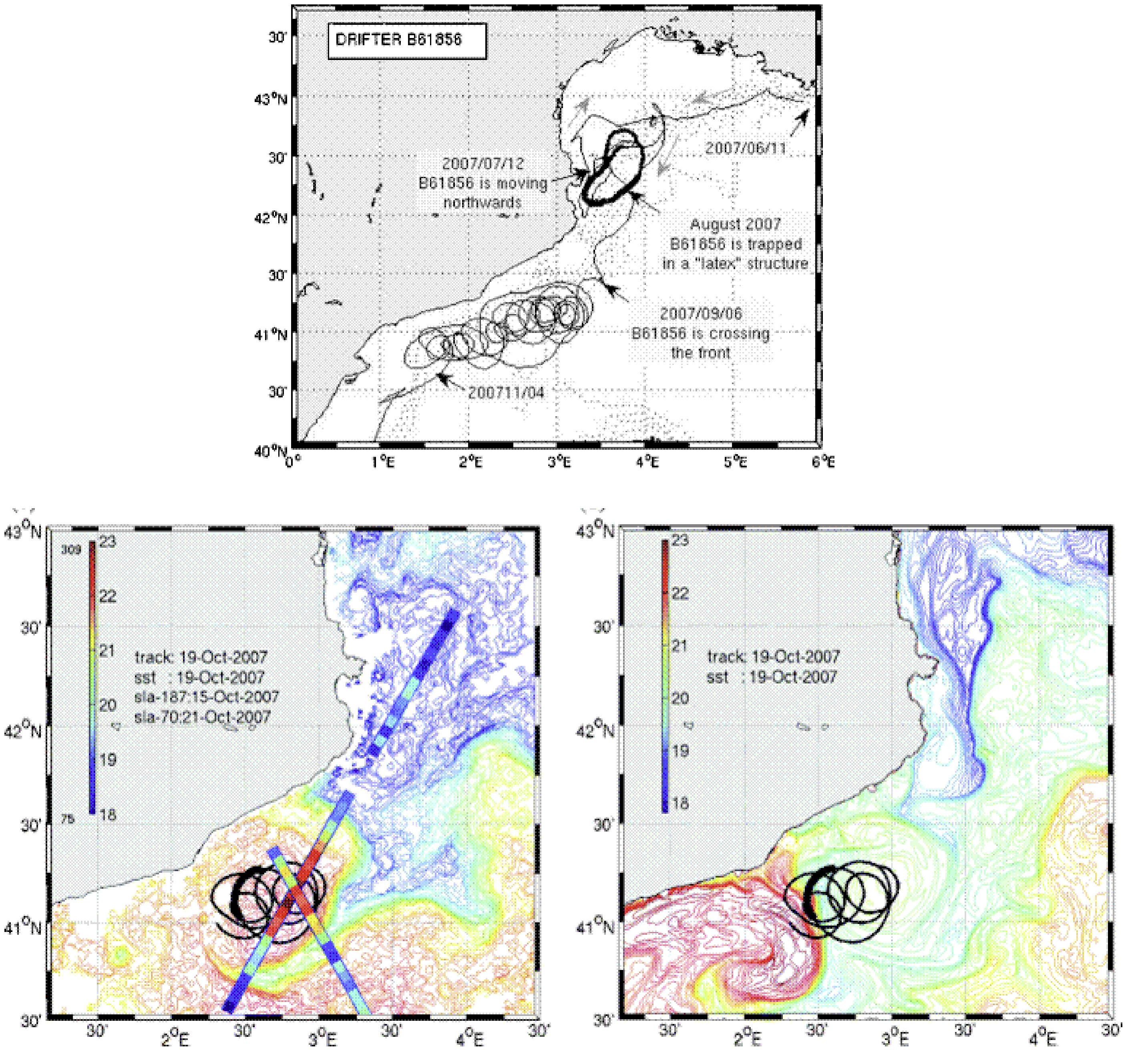

Figure 2: Trajectory of the drifters B61856 dropped on 11 June 2007 off Toulon with a holey sock at 50 m depth: from late July to late August, B61856 is trapped in the southwestern corner of the Gulf of Lions (LATEX area) before being caught by a CATALAN eddy. Sea surface temperature (remote sensed (middle) and modeled (bottom)) and sea level anomaly (sla) along Jason1's tracks on October 19. The left hand side of the color legend represents the scales of the sla (millimeters). The right hand side represents the scale of SST (degrees Celsius). The black line represents the track of the drifter for 10 days centered on the picture time. [Extracted from figures 2 and 6, Garreau et al., 2011]

Towards applications to climate change impacts

At a decadal-scale, long-term hydrological hindcasts issued from MENOR results also provide an interesting tool to investigate the potential impacts of temperature anomalies induced by climate change on marine benthic biodiversity. Along the rocky coasts of the North-Western Mediterranean Sea, the red gorgonian **P**aramuricea-**clavata** species (among others) suffered mass mortality events in 1999, 2003 and 2006, while abnormal warming events were reported at the same time. Analyses of the high-resolution T-MedNet temperature time series measured in the Mediterranean coastal waters (0–40 m) have highlighted relationships between the thermal stress and the degree of mass mortality [Bensoussan et al., *2010,* Crisci et al., 2011]. A review of available data from aquarium experiments on thermo-tolerance for the red gorgonian **P. clavata** allowed to quantify a thermo-tolerance function linking the exposure to different temperatures (number of days exposed to temperatures ranging from 23 to 28 °C) and the degree of population necrosis. A comparison between MENOR modeled temperature statistics and T-MedNed observations over 2001-2010 confirmed the model's ability to reproduce temperature variations during the stratified periods (with a tendency to underestimate the temperature in subsurface layers). Model temperature hindcasts have then been combined with the thermo-tolerance function and the spatial red gorgonian

P. clavata distribution in order to produce maps of mortality risk along the North Western Mediterranean coastline within the 60-m isobath [Pairaud et al., 2014]. Results pointed out that Marseilles and the Gulf of Genoa could be areas the most impacted, while mortality risks were lower along the Catalan coast, especially in the northern part (figure 3). This pattern is in agreement with observed impacts on population carried out during the large mass mortality events in different areas of the northwestern Mediterranean [Crisci et al., 2011]. The methodological approach is therefore validated, although improvements need to be made in the process of mapping the risk of mortality.

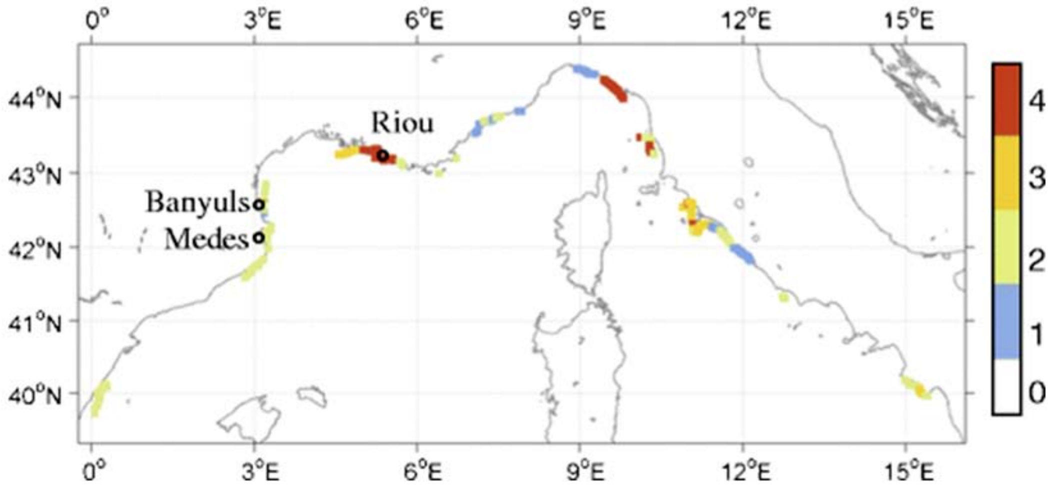

Figure 3: Map of risk for the red gorgonian P. clavata based on integrating the thermo-tolerance thresholds and species geographical and vertical distribution information and using model temperature hindcasts over the period 2001–2010. Scores between 0 and 4 correspond to the risk of mortality: sub lethal (population remains healthy), medium (first signs of necrosis are observed), high (the mortality is important) and extreme (the population is decimated) lethal impact. [Extracted from figure 6, Pairaud et al. 2014]

Application to small-scale pelagic recruitment

In the Gulf of Lions and the Catalan Sea, Anchovy (Engraulis encrasicolus) is an important commercial species and one of the most abundant pelagic fish. Its recruitment largely depends on hydrodynamics which determines whether the organisms can reach areas favorable to recruitment or are dispersed. MENOR simulated currents and salinity fields have been used as inputs for a lagrangian tool over the 2001-2008 period (ICHTYOP) in order to investigate the transport and fate of anchovy eggs and larvae (hereinafter called “particles”) into the North-Western Mediterranean Sea.

According to anchovy spawning observations, 100,000 particles are homogeneously distributed over the Gulf of Lions at 15 m depth. Spawning (release) takes place every week from May 15 to August 15. Recruitment of each cohort is evaluated after 30 days of lagrangian transport because one-month old anchovy larvae have real autonomous swimming movement. Two types of experiments are carried out to take into account the living evolution of anchovy larvae: the passive transport (PT) at 15 m depth corresponds to the behavior of the youngest larvae, while the introduction of a diel vertical migration (DVM) simulates 7-day-old larvae, which moves down to 50 m deep (maximum of chlorophyll) in the daytime (7 a.m.) and move up to the surface at night (7 p.m.).

Surprisingly, although circulation in the Gulf of Lions is strongly influenced by the wind, particles retention in the Gulf of Lions appears to be independent of atmospheric forcing. Actually, the maximum of particles concentration coincides with areas of low salinity and the diel vertical migration intensifies this trend (figure 4). This positive effect complies with observations: located in fresher waters (with more nutrients), larvae have more possibility to survive. Even though the diurnal vertical migration allows more particles to escape the gulf of Lions and reach low salinity areas in the Catalan Sea, the residence time remains relatively high (40 days, an estimate coherent to buoy observations and salt balance) and one can conclude, from a simple method with no real interactions between physical and biological processes, that the Gulf of Lions is a potentially favorable area for anchovy recruitment.

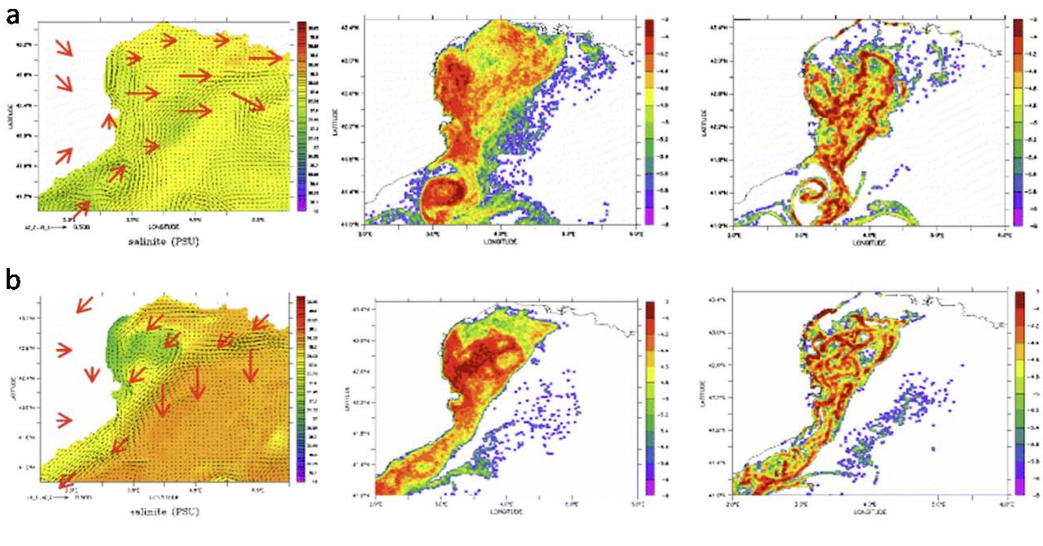

Figure 4: Currents and salinity at 15 m depth averaged between 16 and 23 June with wind direction (red arrow; left column). Particle concentration (logarithmic scale) after 30 days for passive transport (central column). Particle concentration after 30 days for diel vertical migration (right column). The spawning date is May 22 for a 2003, b 2006. [Extracted from figure 5, Nicolle et al., 2009]

Biogeochemical coupling

As the hydrodynamic processes and patterns are simulated with a sufficient accuracy in the MENOR configuration, MARS has been coupled on-line with a 3D bio-geo-chemical model embedded in the Eco3M modular numerical tool [Baklouti et al., 2006a, b]. Eco3M model is a food-web model containing different plankton functional types with a flexible plankton stoichiometry. Such a model is particularly suitable for studies in the Mediterranean Sea since, depending on the season and the geographical position, Nitrogen (N) and/or Phosphorus (P) can limit primary production, and because of the specificity of this sea in terms of N:P stoichiometry [Pujo-Pay et al., 2011].

The hydrodynamic and biogeochemical processes have been simulated from September 1, 2009 to January 31, 2011 [Alekseenko et al., 2014]. Comparisons with two field trips conducted in the Gulf of Lions (ANR COSTAS Project) illustrated a good agreement between modeled and observed patterns of nutrients and Chl-a in spring (Costeau-4: April 27 – May 2, 2010), especially in the eastern half of the Gulf of Lions where the Rhone River has the largest influence, while results were less successful in winter (Costeau-6 : January 23 – January 27, 2011). Comparisons of sea surface chlorophyll with MODIS data showed an accurate phytoplankton productivity in spring, not only on the eutrophic continental shelf of the Gulf of Lions, but also in the open sea area which is separated from the shelf by the low Chl-a waters of the Northern Current. Lastly, a 1-year quantitative comparison of the surface chlorophyll spatially averaged over the global domain (figure 5) concluded to a satisfactory reproduction of the phytoplankton bloom, while modeled Chl-a is slightly underestimated partly due to the general underestimation of small phytoplankton biomass.

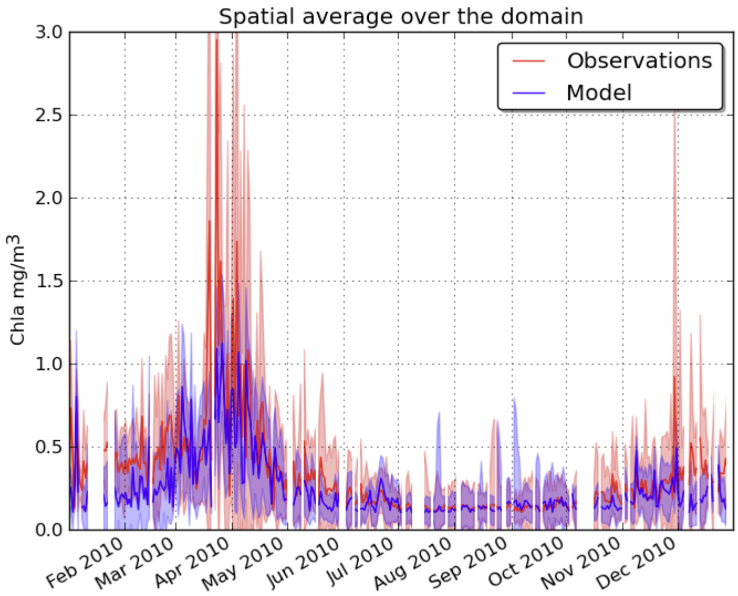

Figure 5: Time variations of averaged chlorophyll over the NW Mediterranean Sea (red line: satellite observations (MODIS), blue line: model results; color shift from lines indicate the minimum and maximum values for the study area; empty spaces correspond to insufficient satellite data for the comparison at these periods) [figure 12 Alekseenko et al., 2014]

Alekseenko et al. [2014] focused on the temporal and spatial variability of intracellular contents of living and non-living compartments (figure 6). From simulated relative intracellular quotas in phosphorus (P), nitrogen (N), carbon (C), they concluded that each one of the three elements is limiting at some periods of the year [Alekseenko et al., 2014]. In large phytoplankton cells, P is the most limiting element but during winter mixing, C (which depends on light availability) can become more limiting than N. Bacteria are limited by C throughout the year but at the end of the stratified period, P can become more limiting than N.

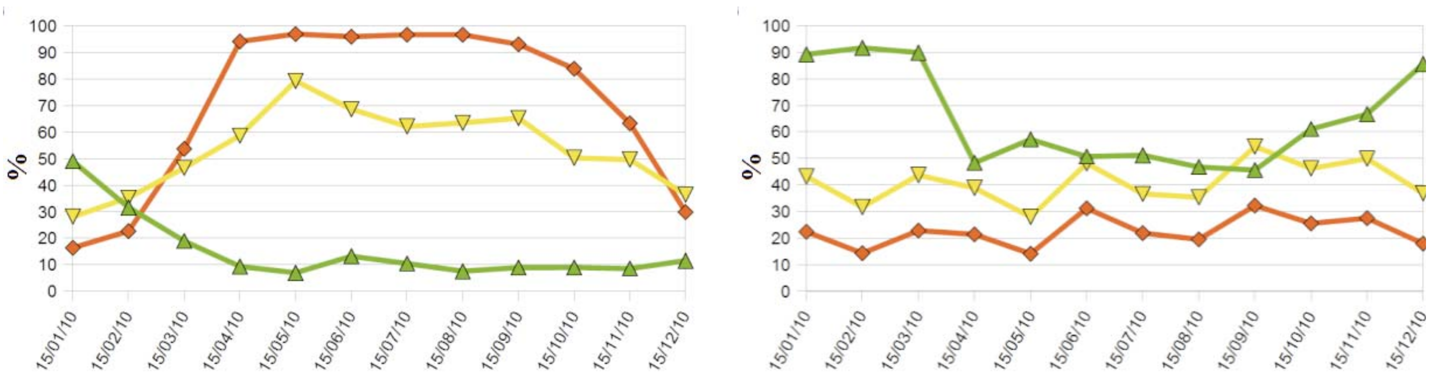

Figure 6: Relative intracellular quotas (in %) of C (red line), N (yellow line), and P (green line), averaged over the surface layer of the domain of whole NW Mediterranean: - a for large phytoplankton (> 10 µm) - b for bacteria [extracted from figure 18 Alekseenko et al., 2014]

Although these preliminary results need to be validated by measurements, they illustrate some potentialities offered by the MARS-ECO3M model to explain the functioning of the Mediterranean ecosystem. This model has been further coupled with a contaminant module in order to study PCBs dispersion (Polychlorinated biphenyls) in the Gulf of Lions and their transfer from water to mesozooplankton via biogeochemical processes.

Conclusion

After sensitivity studies and validation, numerical modeling provides a 4D representation of the environment that complements satellite and in-situ observations. With its large extended domain (0-16°E – 39.5-44.5°N) and its high resolution (1.2 km 60 layers), the MENOR configuration provides powerful results to interpret and study the processes at play in the North-Western Mediterranean sea. The operational Previmer system routinely runs the configuration to provide users - research institutes, universities or private companies - with daily analyses and 4-day forecasts of the area. Operational forecasts will be improved in 2014 thanks to the introduction of the spectral nudging method [Herbert et al., 2014, this issue]. Long-term hindcasts are also published, and this article has briefly reviewed some of the research applications lead by IFREMER and based on MENOR hindcasts. Research applications have confirmed that MENOR is realistic enough to elucidate dynamical behaviors [Garreau et al., 2011], to propose methodologies in order to investigate the potential impact of climate changes [Pairaud et al., 2014], to be coupled with ECO3M model to investigate key biogeochemical processes [Alekseenko et al., 2014] and to interest pelagic fish recruitment [Nicolle et al., 2009].

MENOR main flaw is its incapacity to reproduce the development of deep convection and dense water formation, which are strongly constrained by the initial hydrological conditions in deep water. A new and improved coherent long-term hindcast correcting this bias is therefore needed; it would moreover take advantage of MARS latest significant evolutions and of the experiences shared by all French teams involved in modeling the North-Western Mediterranean sea (within SIMED project). The future hindcast will be forced by CNRM (Centre National de Recherches Météorologiques) ALADIN-climate model (12 km downscaling of ERA-INTERIM [Colin et al., 2010]) and by NEMOMED12 [Beuvier et al., 2012], a NEMO regional simulation at 6-7 km resolution forced by the same atmospherical fields and devoted to the inter-annual variability of the Mediterranean sea. This hindcast will be qualified in 2014 to pursue scientific studies planned within the HYMEX and MedCORDEX programs as well as PPR-GMMC SIMED projects.

Acknowledgements

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