



Quarterly Newsletter

Editorial – October 2009



The Tara Oceans expedition has started last September 2009 and will travel the seas of the entire globe, exploring the oceans studying the plankton, in order to deepen knowledge on marine biodiversity. This expedition will last three years. Credits: (Left) Plankton is recovered © S.Bollet/Fonds Tara; (Right) Copepod © C Sardet CNRS/Tara Oceans, Sacha Bollet Fonds Tara.

Greetings all,

This month's newsletter is devoted to Oceanic biogeochemistry.

Le Traon is introducing this newsletter telling us about Argo- the single most important in-situ observing system for operational oceanography- and Euro-Argo which is aiming at maintaining the array's size and global coverage in the coming decades in order to develop and progressively consolidate the European component of the global network.

Scientific articles about Oceanic biogeochemistry are then displayed as follows: D'Ortenzio et al. are writing about the PABIM project (Biogeochemical Autonomous Platforms: Instrumentation and Measures) which aims at developing and exploiting biogeochemical observations obtained from autonomous platforms (gliders, profiling floats, animals). Lévy et al. are then telling us about the remote impacts of sub-mesoscale dynamics on new production with a net new production that decreases by 10% at higher resolution, with regional differences reaching +/- 30%. Lefèvre et al. are then explaining about autonomous CO₂ measurements in the tropical Atlantic Ocean with an observational CO₂ network that has been set up to better document the variability of the fugacity of CO₂ (fCO₂) in the Atlantic ocean, to determine its long term trend, and to provide accurate estimates of the air-sea CO₂ flux. Finally, Lehodey et al. with the "Mercator-Vert" project are working on a prototype of coupled physical/ biogeochemical model with the objective to routinely estimate and forecast the biogeochemical variables of the global ocean. Such operational models should provide in a near future the necessary inputs for ecosystem models of the upper trophic levels, allowing the development of new tools and products for a real-time management and monitoring of marine ecosystems and resources.

The next January 2010 newsletter will review the current work on Data Assimilation and its application for Ocean reanalyses. We wish you a pleasant reading.

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Euro-Argo News

By Pierre-Yves Le Traon

Ifremer. Centre de Brest. Plouzané, France

Argo is the single most important in-situ observing system for operational oceanography. It delivers critical data (especially over the vertical dimension of the oceans) for assimilation in ocean forecasting models, climate monitoring and seasonal to decadal forecasting. Maintaining the array's size and global coverage in the coming decades is the next challenge for Argo, climate research and operational oceanography. Euro-Argo will develop and progressively consolidate the European component of the global network. As a new European research infrastructure, Euro-Argo (www.euro-argo.eu) started a preparatory phase funded through the EU 7th Framework Research Programme in January 2008. Euro-Argo preparatory phase includes all European member states involved in Argo and several potential new actors. The main objective of the Euro-Argo preparatory phase is to undertake the work needed to ensure that Europe will be able to deploy and operate on the long term an array of 800 floats (i.e. deploying 250 floats/year) and to provide a world-class service to the research (climate) and environment monitoring (e.g. GMES) communities.

Euro-Argo already allowed us to develop and consolidate long term national plans for Argo and attract new countries. Analyses have been carried out to detail the infrastructure costs and to review float technology, deployment and data processing issues. The impact of Argo data for research and operational oceanography in Europe has also been reviewed. Float technology tests have been or are being performed. In order to strengthen the user community in Europe and analyze/consolidate user requirements, user and training meetings are held every year. Euro-Argo has also been developing strong links with GMES Marine Core Service and its MyOcean project (www.myocean.eu.org) since its start. It is now clearly recognized as the major in-situ data required by GMES and there are good prospects for long term funding from GMES to complement funding from member states.

One of the main objectives of the preparatory phase is to define and agree on a long term organization for Euro-Argo. The future long-term structure for Euro-Argo is currently being defined and will be agreed by the end of 2009. It should allow us:

- To supervise operation of the infrastructure and ensure that it evolves in accordance with the requirements set forth by the research and operational communities.
- To coordinate and supervise float deployment to ensure that Argo and Euro-Argo objectives are fulfilled.
- To decide on the evolution of the Euro-Argo infrastructure.
- To share expertise on all scientific/technological developments and use of Argo.
- To monitor the operation of the infrastructure and to maintain/develop the links with research and operational (GMES) user communities.
- To organize float procurement at European level.
- To link with, and integrate into, international structure.

The structure will include a central facility (Central RI) and distributed national facilities. The C-RI will play a coordination role and will participate actively in the program. The central RI should have a European legal structure (such as the ERIC¹ model that was recently agreed by the European Commission) to receive European and national funding, to procure floats (this includes logistics and test facilities) and to provide funding to the international structure. A governance model for the structure has been defined (council, board, scientific and technical advisory group) and its main characteristics have been agreed by all partners.

An important issue for Argo and Euro-Argo is to define and agree on the long-term evolution of the core Argo mission (global T & S monitoring in ice free regions on a 3° x 3° resolution). The first short term priority should be to sustain Argo as it is now. This is needed to consolidate the different components of Argo (float technology, float deployment, real time and delayed mode data systems). There are strong user requirements in Europe (e.g. GMES Marine Core Service) to extend the array to European marginal seas and high latitude ice covered regions. On the longer run, there is also a need to move towards biogeochemical measurements. Dissolved oxygen and Chl-a would be very useful for validation of (and assimilation in) coupled physical-biological models. Chl-a measurements would also be very useful to complement measurements from ocean color satellites. While there are technical/feasibility and legal issues that need to be carefully analyzed, operational oceanography systems developed as part of GMES will likely require an extension towards biogeochemical parameters. This is the main topic of this newsletter. The subject also has been actively discussed at the Oceanobs09 Venice conference.

¹ The Community legal framework for a European Research Infrastructure Consortium (ERIC) is a new legal form designed to facilitate the joint establishment and operation of research facilities of European interest.

Biogeochemical Autonomous Platforms: Instrumentation and Measures (PABIM Project)

By **Fabrizio D'Ortenzio¹** and the **PABIM group**

¹ *Laboratoire d'océanographie de Villefranche, CNRS and UPMC, Villefranche sur Mer, France*

Abstract

In this paper a summary of the GMMC PABIM project ("Plateformes Autonomes en Biogéochimie: Instrumentation et Mesure", PI. F. D'Ortenzio) is presented. The PABIM consortium is composed by eight French laboratories² involved in the development and exploitation of biogeochemical observations obtained from autonomous platforms (gliders, profiling floats, animals). Main motivation of the PABIM project is to provide biogeochemical oceanographers with a "user's manual" on the autonomous platforms, with the declared aim of sharing the experiences of the authors towards an enlarged community. A quality control of the biogeochemical data obtained by autonomous platforms is also proposed.

Introduction

The modelling of the marine ecosystems has strongly improved in the recent years (LeQuéré et al. 2005, Sarmiento et al. 2004). Coupled physical and biogeochemical marine models are actively developed, providing high-quality estimations of the ocean ecosystems from regional to global and from short to decadal scales (i.e. Bopp et al. 2002; Boyd and Doney, 2002; Pierce, 2004). The real-time operational application of these models is also rapidly developing, and prototypes of near real-time systems are presently implemented (see Brasseur et al. 2009 for a recent review).

Definitely, models cannot be unconnected from observations. Data are essential to characterise processes and to formulate parameterizations, and, in the model based operational systems, data contribute to a model's performance, permanently refining simulation outputs at the different stages of the modelling process (i.e. initialization, assimilation, validation). More complex and realistic models demand, then, more accurate and abundant observations.

The observation of marine ecosystems has always been a challenge. Conversely to physical oceanography, which benefits, since the 1970's, from a set of accurate, non-invasive and remote controlled sensors for temperature and salinity (i.e. the key parameters to determine the physical state of water column), the measure of the biogeochemical parameters of the sea was much more complicated, as it was almost exclusively based on the collection and analysis of water samples. In the 1980's, the availability of low-cost and easy-to-use bio-optical (i.e. fluorescence) and chemical (i.e. optode) sensors marked the first turning point. The new sensors, based on non-intrusive methods and which easily interfaced on the standard CTD probe, allowed regular and routine measures of biological (i.e. chlorophyll concentration) or chemical (i.e. dissolved oxygen concentration) proxies. Ocean colour satellite remote sensing represented a second revolution, allowing, for the first time, a synoptic and global view of a biologically relevant parameter, the surface chlorophyll concentration (McClain et al. 2004). Although recognised to have several and often relevant limitations, these experimental approaches spectacularly increased the quantity of data available. As a consequence, the scientific advancements and findings related to the increased available information induced an amelioration of the ecosystem models devoted to the simulation of the observed processes and to the prevision on the medium and long terms.

Now, another revolution approaches.

A new series of recent technological improvements have led to the fabrication of miniaturized and very low energy demanding biogeochemical sensors. Simultaneously, more efficient and low-cost satellite transmission systems have become available. Mounted on autonomous platforms, they allow the measurement and transmission of a set of biogeochemical variables in an automatic, low-cost and real time way. Profiling floats, gliders and animals, originally devoted to purely temperature and salinity monitoring, are now successfully equipped of biogeochemical scientific packs. Scientific applications and results have followed naturally (i.e. Niewiadomska et al. 2008; Boss et al. 2007; Perry et al. 2009). Initially implemented on a punctual basis, exclusively related to specific, process-oriented studies, the biogeochemical autonomous platforms (BAP) are now entering into a new phase. Following the pathway indicated by the physical oceanographers, networks of BAP are under construction, with the specific and

² The Laboratoire d'Océanographie de Villefranche (H. Claustre, K. Niewiadomska, A. Poteau, L. Prieur, D. Antoine), The Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (G. Eldin, V. Garçon, Danièle Thouon), The Laboratoire d'Océanographie Physique (Virginie Thierry, Pascal Lherminier), the Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (P. Testor, L. Mortier), the Centres d'Etudes Biologiques de Chizé (C. Guinet), the Laboratoire de Microbiologie, Géochimie et Ecologie Marines (M. Tedetti, D. Lefevre), the Écosystèmes Littoraux et Côtiers (H. Loisiel), the CORIOLIS data center (C. Coatanoan, T. Carval, C. de Boyer Montegut).

declared aim to provide the involved scientific community with a continuous, real-time, and automatic flux of accurate biogeochemical observations (Claustre et al., 2010). BAP networks will assure, in the future, the necessary data flow to initialise, constrain and validate operational real-time ecosystem models.

BAP are, however, not free from scientific and technical challenges. As every remote and automatic experimental system, they require a particular effort to assure data accuracy. Lasting on sea for periods of 1-2 months (gliders) up to 2-3 years (profiling floats), BAP derived observations should be controlled and accurately checked, before their scientific use can be envisaged. Long term sensor calibration and data coherence are additional issues that require consideration.

In this context, the working group PABIM (PI F. D'Ortenzio) was created in 2007, under the supervision of the GMMC. Strongly involved in the development and exploitation of autonomous platform based observations, the GMMC encouraged BAP activities, supporting pioneering projects on this topic over the last 5 years. The PABIM working group is composed of six French laboratories that have developed BAP activity in the framework of GMMC. The project has a two-fold objective:

- To write a "White Book" on the present day status of the biogeochemical oceanic observations performed with autonomous platforms.
- To implement a set of automatic quality control tests for data collected with autonomous platforms.

The rationale of the PABIM White Book was to provide interested scientists with a "user's manual" on the BAP, with the declared aim of sharing the experiences of the authors towards an enlarged community. The PABIM White Book was mainly based on the know-how acquired on the field by the authors and represents about 5 years of efforts of the French oceanographic community involved. The authors tried to be as exhaustive as possible, however, the topic is continuously evolving and it cannot be a priori excluded that some issue is missing or partially treated.

The present paper has been then composed extracting parts from the PABIM white book (available on the GMMC web site), though some sections are specifically composed.

The Core parameters

For the BAPs, the choice of the measured variables was initially guided by the available technology. Technology is, however, continuously evolving and now the miniaturized instruments commercially available make possible the measurement of a vast set of biogeochemical parameters (i.e. chlorophyll concentration, dissolved oxygen concentration, backscattering, CDOM concentration, underwater light transmittance and nitrate concentrations etc.). In the near future, technological advancements in the fields of the miniaturization, energetic power and transmission will certainly allow a wider list of available parameters.

It is obvious that every parameter is (or should be) considered scientifically relevant, as its evaluation always adds an important piece of information to the knowledge of the marine ecosystem functioning. However, practical, economical, and logistic reasons happen to reduce the number of the instruments mounted on an autonomous platform, with a consequent impact on the quantity of acquired parameters. Additionally, scientific reasons could determine the decision to include or not a specific measure for an autonomous platform based experiment. Finally, the type of the experiment could also influence the selection of the sampled parameters, as a basin-scale/long-term experiment of monitoring has different constraints than that of a specific, more process focused sea operation. In conclusion, the field of application of BAP is so vast that a first set of parameters (the "core parameters") need to be defined.

For the PABIM project, we decided to fix four criteria to define a core parameter. They are necessarily arbitrary, as they are specifically defined for the purpose of the project. Moreover, they derive directly from the author's experiences (which are obviously limited) and, as such, need to be considered as a starting point for further discussions.

The 4 requirements proposed here are:

- A core parameter should be a robust proxy of a biogeochemical oceanic process or variable.
- The measurement of a core parameter with an autonomous platform should be cost effective and low energy consuming.
- A core parameter should have already been measured extensively and for a long time with referenced methods.
- A core parameter obtained from autonomous platforms should be easily comparable with observations collected with classical methods (i.e. ships, satellites, moorings). If climatologies are produced from previous observations, data from autonomous floats should be easily incorporated.

Presently, only the Chlorophyll-a concentration and the Dissolved Oxygen concentration meet all the four requirements, with points 3 and 4 being the most limiting requirements.

Among the present day possibilities (i.e. sensors commercially available), we have selected 3 other parameters, which, in our opinion, will meet the full set of requirements in the near future: the Particulate Organic Carbon (POC), the Coloured Dissolved Organic Matter (CDOM) and the Nutrients concentrations. They are not discussed here, though the reader can refer to the PABIM White Book document for further details.

Chlorophyll-a Concentration and Dissolved Oxygen Concentration: Scientific Rationale and Measuring Methods

Dissolved Oxygen Concentration (O_2 hereafter) is a key parameter to understand both dynamics and biogeochemistry of the world oceans: it has been used for a long time as a tracer to follow water mass pathways and quantify mixing rates. In addition, O_2 variability is associated with many biological processes, such as primary production, respiration and remineralization. Historically, O_2 was first measured through a chemical titration method (Winkler, 1888), which cannot be practically used on an autonomous platform. Nowadays, sensors are based on two techniques; an electrochemical method and an optical method. The first, which is based on the principle of the reduction of molecular oxygen at a cathode (Clark et al. 1953), has been used in shipboard CTD systems since the 1970s, and requires simultaneous measurements of temperature, salinity and pressure to compute O_2 values from the partial pressure measurement. The second method, more recently developed, operates on the principle of fluorescence quenching (Tengberg et al., 2006). Blue light excites molecules of a fluorescent dye that are included in a foil on the sensor optical surface. When oxygen molecules diffuse into the film, they collide with excited dye molecules before they emit their photons, and energy is transferred to O_2 rather than being lost by fluorescence emission. The O_2 sensor operates by detecting the decrease in fluorescence lifetime that is produced by the interaction of the dye molecules with oxygen, which is proportional to the concentration of O_2 .

Chlorophyll-a (Chl-a hereafter) is a pigment found in most plants, algae and cyanobacteria. It serves the primary function to absorb and transfer solar energy to chemical energy, allowing plants to obtain energy from sun radiation (Kirk, 1994). Because it is coloured, specific to, and shared amongst all primary producers, Chl-a concentration is considered the best proxy for oceanic biomass (Huot et al, 2007) and is then a key parameter of biological oceanography. Despite this widely acknowledged importance (or maybe as a consequence), several methods exist to determine the oceanic Chl-a concentration: radiometric (in-situ and from space), chemical (HPLC on discrete samples) or using specifically calibrated sensors based on fluorescence or light absorption. Only two of the available methods could be presently implemented on autonomous platforms: the fluorescence-based methods and the radiometric inversion of light measurements (HPLC, which is considered the most accurate method, needs collecting in situ samples, while instruments based on absorption are still far to be miniaturised). The first method is based on the fluorescence process: part of the photons absorbed by a Chl-a molecule in the blue part of the spectrum is re-emitted as less energetic photons in the red part. The sensor provides estimate of Chl-a concentration by exciting the water sample with a blue light and measuring the photons flux emitted in the red, which is directly proportional to concentration of Chl-a molecules present in the sample. Fluorometers are widely used on the CTD systems, and data obtained with this method represents the largest portion of Chl-a profiles presently available.

The second method is based on the proportionality (Morel and Maritorena, 2001) between the Chl-a concentration and the diffuse attenuation coefficient ($K_d(\lambda)$). K_d is estimated by measuring the downwards planar irradiance (i.e. the quantity of light radiation integrated over the upper hemisphere) with irradiance meters (i.e. submersible light sensors, which use spherical devices to diffuse the light, to have an integrated observation on the upper hemisphere). The Chl-a concentration could be then evaluated, by inverting the K_d /Chl-a relationship.

Present status of available biogeochemical autonomous platforms

Instruments to measure the O_2 and the Chl-a concentration are presently available on profiling floats and gliders. On the animal based platforms, only Chl-a concentration is currently measured. In the next section, a brief description of the 3 different platforms is given.

Biogeochemical profiling floats

Profiling floats are passive and automatic buoys, which drift at fixed depths, following oceanic currents. They can be programmed to change their buoyancy using a hydraulic pump, which, by modifying the total volume of the device, allows for vertical displacements within the water column. Equipped with scientific instruments, profiling floats can autonomously acquire vertical profiles of oceanographic parameters. The collected data are transmitted on land in real-time, through satellite communications. The most important, and the best known, profiling floats network is organised in the international Argo project (<http://www.argo.ucsd.edu/>), which has disseminated more than 3000 buoys (collecting temperature and salinity profiles) in the global ocean.

In recent years, profiling floats equipped with biogeochemical sensors (in addition to temperature and salinity sensors) have been developed and successfully deployed. Biogeochemical sensors demanded an increased amount of available energy, which lead to the generalised use of more performing batteries (i.e. Lithium). The enhanced quantity of collected data required the use of more efficient data transmission systems (i.e. IRIIDIUM), which, in addition, allowed a two-way communication (i.e. commands could be sent to the float). This technical solution impacted also on the scientific potentialities of the profiling buoys, giving the possibility to change, in real time, the sampling strategy. Presently, the most developed biogeochemical floats network (in terms of number of buoys) concerns profiling floats equipped with oxygen sensors (Gruber et al., 2007). Additionally, a float with a chlorophyll calibrated fluorometer acquired more than 2 years of observations (Boss et al., 2008) in the North Atlantic. In 2008, 12 PROVIO floats with fluorometers (Chl and CDOM), irradiance sensors, transmittance and backscattering meters (LeReste et al, 2009) were deployed in 3 different oceanic regions (Mediterranean, North Atlantic, North Pacific, South Pacific) by the LOV (PI H. Claustre). See Figure 1 for the positions of the present day operational profiling floats.

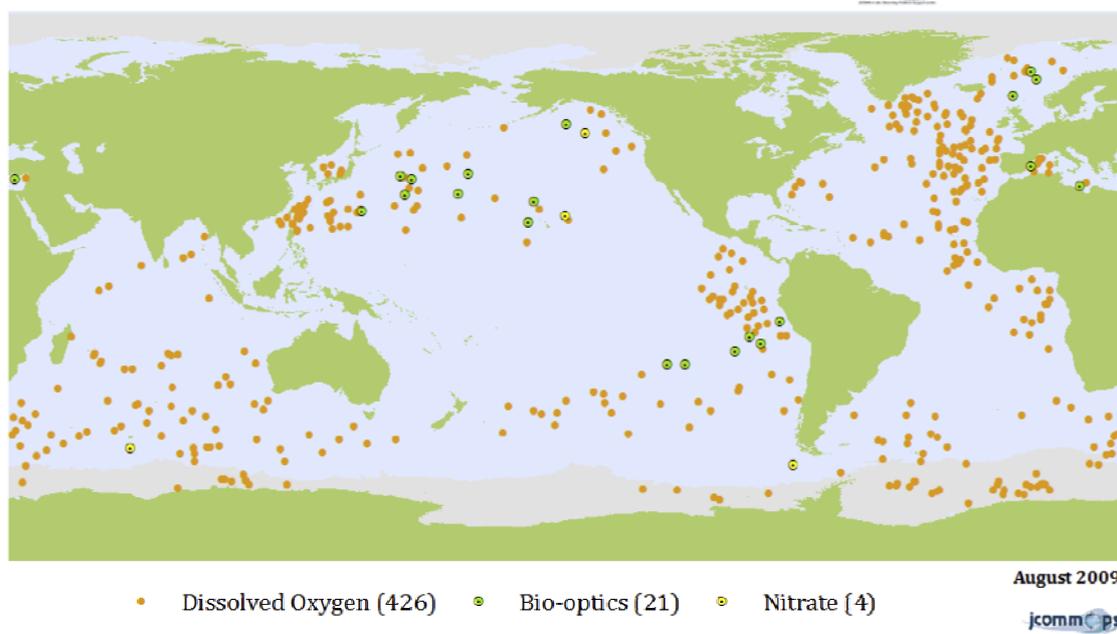


Figure 1

Positions of the operational biogeochemical profiling floats (August 2009; courtesy JCOMMOPS web site)

Biogeochemical gliders

Gliders can "fly" underwater along slightly inclined paths. No propeller is required. A change in volume (generated by filling an external oil bladder) creates positive and negative buoyancy. Because of the fixed wings, the buoyancy force results in forward velocity as well as vertical motion. So gliders move in a switchback pattern, gliding downward when denser than surrounding water and upward when buoyant. Pitch and roll are controlled (by modifying the internal mass distribution) to achieve the desired angle of ascent/descent and heading. The high efficiency of the propulsion system enables gliders to be operated for several months during which they cover thousands of kilometres. During each surfacing, a two-way communication system via satellite allows us to download data in near real-time and to send commands to the glider in order to change the mission parameters (heading, angle of ascent/dive, max depth etc.). In this way gliders can be steered remotely. Gliders equipped with the same bio-optical and chemical sensors are already successfully used to characterise physical biological interactions at very short spatial and temporal scales (Niewiadomska et al. 2008, Perry et al. 2008).

Biogeochemical animals

Specially developed data relayed satellite tags were developed by the Sea Mammal Research unit and deployed on a number of seal species foraging in high latitude waters. While diving (up to 2000 meters) these animals are collecting accurate (1/100) temperature and salinity data which are transferred near real-time by the Argos systems along the foraging track of these animals. Data collected by elephant seals represent 95 % of the CTD data provided to the Coriolis data centre in the region south of 60°S and 98 % of the data collected within sea-ice.

In recent years, as part of a program lead by the CEBC-CNRS, Argos CTD tags equipped with a fluorometer (additionally to temperature and salinity sensors) have been developed and successfully deployed on southern elephant seals at Kerguelen Island. With respect to the biogeochemical profiling floats, the potential for the animals to cross water masses and fronts give an

additional capability to the animal tags. In this sense, they could be seen as an “intermediate” platform between the purely passive lagrangian floats and the more active gliders. With respect to the gliders, however, they have a longer lifetime, allowing missions in very difficult regions. However, due to the short period of time spent at the surface to breathe between dives, there is a strong constraint on data transmission. To save energy and data transmission, only three temperature, salinity and fluorescence profiles are sampled per day. Moreover, data are undersampled and compressed, again to save energy and transmission costs.

A tentative QC automatic system for Oxygen and Chlorophyll Concentrations

Potentially, BAP derived data could strongly increase the relevance and the ability of the integrated systems to operationally predict oceanic ecosystem dynamics. To be efficiently exploited, however, the quality of the BAP derived data needs to be rapidly controlled and made available in a short time lag after the collection. An operational Quality Control (QC) system is then mandatory. In the framework of the PABIM project a tentative data flow and QC protocol are proposed, in strong interaction with the Coriolis data centre, which already manage the data of the Argo network. A synopsis of the PABIM biogeochemical QC is explained in the following section.

For the BAP-QC proposed by the PABIM group, the provenance of the data is not considered. The only hypothesis for the QC process is that the incoming data must have a “profile-like” format: the observations should be vertically organised from surface to the maximum depth reached during the sampling. In this context, “vertical” means the direction orthogonal to the sea surface. Gliders and animal data therefore require a pre-processing step, as they are collected along trajectories, which could deviate from the strict profile-like data structure. The pre-processing of gliders and animals data is independent of the QC, and is generally performed before the QC.

The suggested BAP-QC protocol follows the same strategy of the Argo QC for temperature and salinity. It is performed using a three level approach: “Real time” (RT), “Adjusted” (AM) and “Delayed” modes (DM).

The RT QC only checks the presence of anomalous values and then assumes implicitly that BAP transmitted data are well calibrated. Although in a first approximation this assumption could be considered realistic, it cannot always be exact and needs to be verified. Two main situations can be defined:

- Bad data derived from an erroneous calibration of the instrument
- Bad data derived from a temporary or permanent degradation of the sensor performance

In the first case, data are affected by a calibration problem, which concerns all the data of a specific instrument, and which could be, at least in theory, corrected by a re-calibration of the observations, when and if, the error is detected. In the second case, the error could affect only a limited portion of the data obtained by a specific instrument, even if the initial calibration is correct. This should be the case, for example, for profiles affected by biofouling or for O₂ profiles in regions with strong vertical gradients. Again, following the strategy of the Argo QC system, the PABIM group proposes to address the issue of the calibration in the “Adjusted” mode and the issue of stability of the estimations in the “Delayed” mode.

Real Time Mode

Most of the Argo QC RT tests are performed to identify problems related to bad geo-localisation, erroneous timing, wrong platform identification, pressure errors etc. For these tests, the Argo procedure is strictly adopted for the biogeochemical parameters. Another set of Argo RT tests cannot be applied to biogeochemical parameters (i.e. Density inversion).

Only three tests of the Argo RT QC are parameter dependent: “global range”, “spike test” and “gradient test”. For the application of these tests to the Chl-a and O₂ parameters, the algorithms are kept the same as those of Argo QC, although the required threshold values are calculated on the basis of the available data. A complete description of the PABIM RT-QC tests is presented in the PABIM white book. An example of the PABIM QC on a PROVIO derived Chl-a profile is presented in Figure 2.

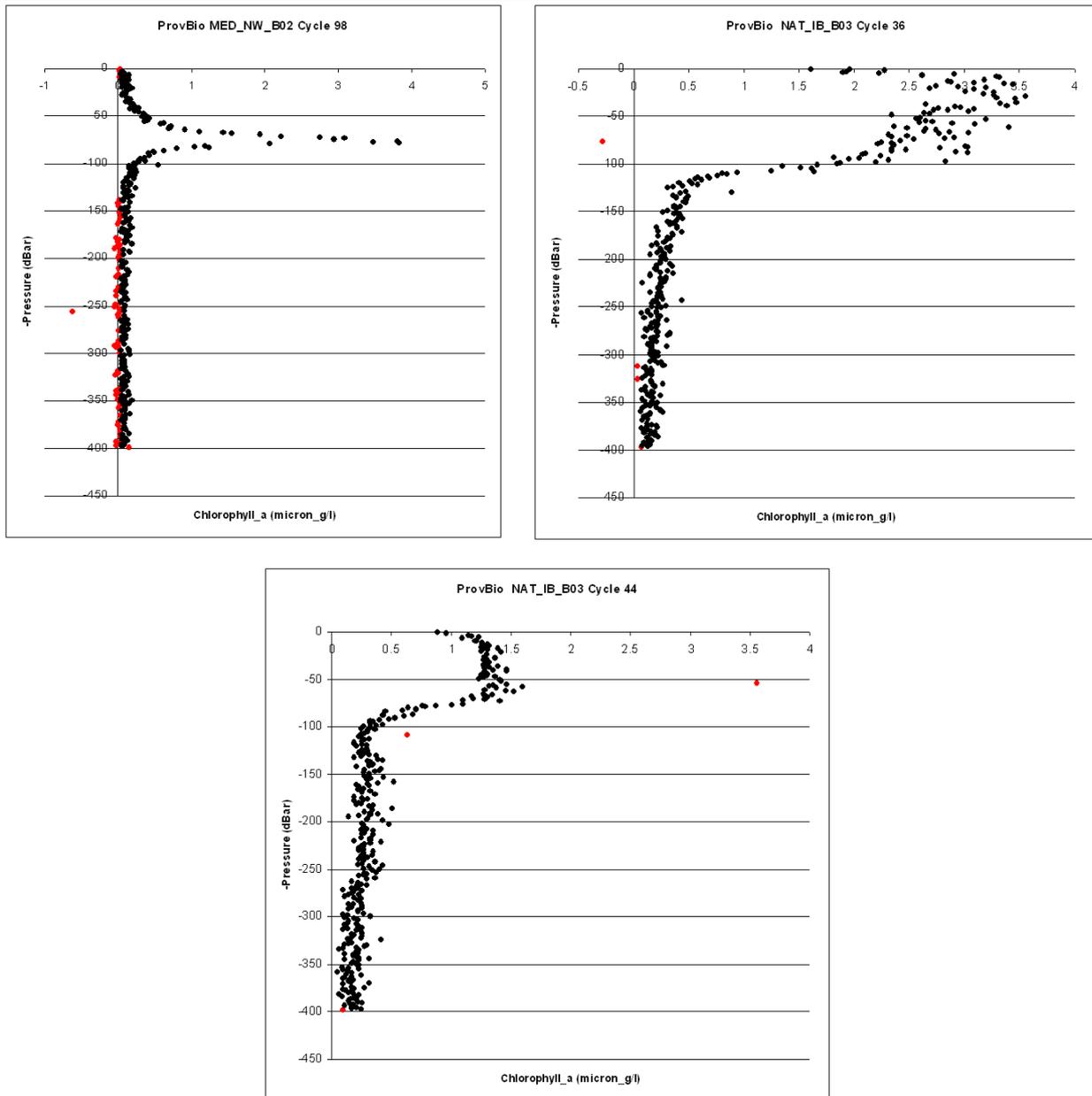


Figure 2

Chlorophyll-a profiles obtained by PROVIO floats. Red points indicate observations flagged by PABIM QC

Adjusted Mode

The best way to check the initial calibration of a sensor is to compare BAP data to concurrent Chl-a or O₂ estimations obtained with standard methods, such as HPLC or Titration. Water samples to evaluate with standard methods (HPLC or Titration) the water column O₂ or Chl-a concentration (a “reference” profile) should be considered mandatory every time an autonomous mission starts. Samples should be collected as close as possible in time and in space to the deployment of the autonomous platform. In the case of recoverable platforms (i.e. gliders and, in some case, animals), a reference profile should be also performed at the end of the mission, when the platform is recovered.

Reference profiles should be stored in the meta-data of the missions and a re-calibration of the RT data should be performed if biases are detected. The corrected data, when existing, should be stored as “Adjusted” data (see Figure 3 for an example of comparison between O₂ concentration profiles derived by a profiling float and by a concurrent CTD-O₂ cast used as reference profile).

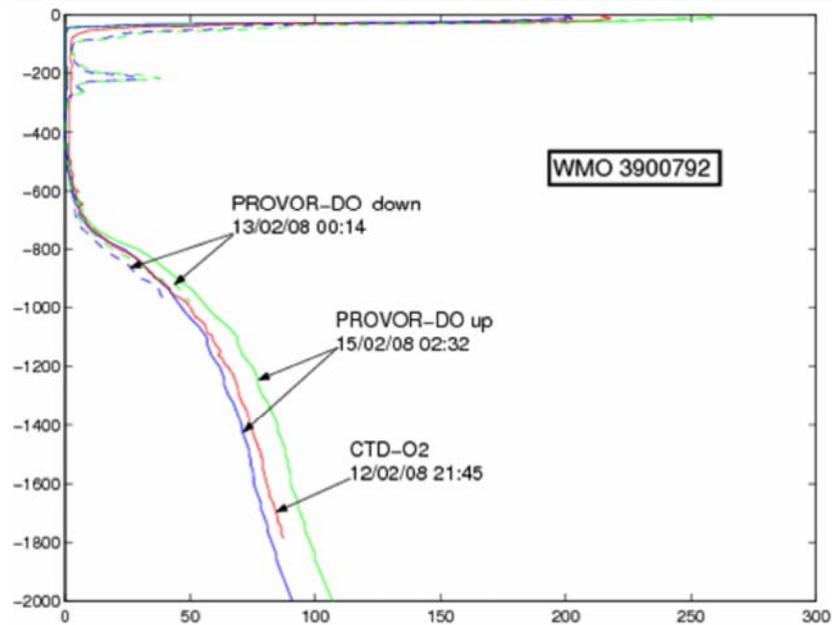


Figure 3

Comparison between O_2 observations obtained in South Pacific from a PROVOR-DO profiling float (blue and green lines) and a concurrent CTD- O_2 cast (red line)

Delayed Mode

The delayed mode allows for a more precise assessment of the data set accuracy, as statistics and tests can be applied to a long-term series. During the delayed mode process (usually occurring 4-6 months after data acquisition), visual inspection of the profiles is required, and generally performed by the scientists involved in the scientific exploitation of the data (and, then, not by the data centre). This approach allows the identification of data problems that passed all of the automatic tests. Presently, no semi-automatic delayed mode tests are proposed for Chl-a and O_2 . Two different approaches are, however, under examination by the PABIM group.

The first method concerns the use of climatological data to verify depth values of the O_2 parameter, similarly to the Argo method for checking salinity consistency. At depth, O_2 concentration typically varies very slowly, and the climatological data could provide an insight into the performance of the BAP derived data. In this way, an important drift or malfunctioning of the O_2 sensor could be detected, comparing BAP and climatological deep time series.

For the Chl-a parameter, the available global climatologies (i.e. Levitus) are derived by strongly interpolating very sparse data sets of in situ profiles. Consequently, they cannot be adopted to verify BAP data. More importantly, Chl-a is strongly variable, with typical values spanning seasonally, and sometimes weekly, between 2-3 orders of magnitude. Finally, the whole dynamic is concentrated in the first 150-200 meters (no chlorophyll at depth), preventing any check based on the temporal evolution of deepest values, similarly to salinity or O_2 . To check the BAP Chl-a sensor stability, the PABIM group proposes a routine comparison of the BAP-derived surface values with concurrent observations obtained from ocean colour satellites. Although remote sensing Chl-a estimations are affected by important errors (McClain et al., 2004), they are, however, very stable with time and they depend only weakly on the absolute values of the Chl-a concentration. Satellite observations could be then efficiently used to verify the surface BAP derived data, in particular to identify episodic drift or permanent bias in the time series.

Conclusion

Biogeochemical autonomous platforms have an enormous potential and will likely become one of the key components of an integrated system devoted to evaluating, characterising and predicting the state of the oceanic ecosystems. In this context, they will represent a milestone for the future oceanographic studies and for the derived applications. A huge effort is, however, required to adapt the "historical" strategies and philosophies of the biogeochemical studies to the novel concepts that autonomous platforms are introducing. Often used to work solitarily, with very specific (and non-exportable) protocols and with a very small amount of data, biogeochemical oceanographers are now confronted with a revolutionary approach to address their key questions. The atmospheric sciences and physical oceanography have already demonstrated the value of a real-time operational approach. Biogeochemical ocean scientists have to learn the same lesson and contribute to the present-day effort to develop and design an integrated, operational and real time system for ecosystem forecasts. Their contribution is definitively invaluable, mainly

in the definition of the observational components of the future system. On the other hand, the biogeochemical community will obtain tremendous benefits from an integrated, real time, operational system.

The PABIM group has worked, and still works, in this direction. The definition of the protocols for autonomously measuring two key oceanic ecosystem parameters, the effort to harmonise and produce a unique set of data, indifferently to the platform source, and the proposition of a first, tentative, QC protocol are the three main results of the PABIM group in the last two years.

The future perspectives of PABIM are really exciting. In parallel, with the validation of the proposed Real Time protocols, the Adjusted and Delayed Modes will be better defined. The strong collaboration with the Coriolis data centre will allow a rapid implementation of the proposed QC tests in the established data management system. BAP data, which are already managed by Coriolis, will be delivered within the next few months to users with an evaluation of the parameters errors (at least for Chl-a and O₂). Three other parameters (POC, CDOM and NO₃ concentrations) will be discussed by the PABIM group over the coming months and, again, a specific QC protocol will be proposed.

Finally, the participation and/or animation of the PABIM members to several extra-France projects (the "EURO-Argo" project, F. D'Ortenzio; the European Glider Observatory, P. Testor; the "BIO-Argo" IOCCG group, H. Claustre, the "South Elephant Seals as Oceanographic Samplers", C. Guinet) will give an international dimension to the PABIM project, allowing a wider distribution of the results and an increased collaboration with similar actions developed in others countries.

References

- Bopp, L., Le Quere, C., Heimann, M., Manning, A.C., Monfray, P., 2002: Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget. *Global Biogeochemical Cycles* 16 (2).
- Boyd, P.W., Doney, S.C., 2002. Modelling regional responses by marine pelagic ecosystems to global climate change. *Geophysical Research Letters* 29 (16).
- Boss, E., Swift, D., Taylor, L., Brickley, P., Zaneveld, R., Riser, S., Perry, M.J., P.G, S., 2008. Observations of pigment and particle distributions in the western North Atlantic from an autonomous float and ocean color satellite. . *Limnology and Oceanography* 52 (2), 112-122.
- Brasseur, P., Gruber, N., Barciela, R., Brander, K., Doron, M., El Moussaoui, A., Hobday, A.J., Huret, M., Kremer, A., Lehodey, P., Matear, R., Moulin, C., Murtugudde, R., Senina, I., Svendsen, M., 2009 : Integrating Biogeochemistry and Ecology into Ocean Data Assimilation Systems, *Oceanography* 22 (3), 26-30.
- Clark L. C., R. Wolf, D. Granger and Z. Taylor (1953), Continuous recording of blood oxygen tensions by polarography, *J Appl Physiol.* ,6, 189-193.
- Claustre et al. , 2010: "Bio-optical profiling floats as new observational tools for biogeochemical and ecosystem studies". Proceedings of the OceanObs09 : Sustained Ocean Observations and Information for Society » Conference, Venice, Italy, 21-25 September, Hall, J., Harrison D.E., Stammer, D., Eds, ESA Publication WPP-306,2010.
- Gruber, N., Doney, S., Emerson, S., Gilbert, D., Kobayashi, T., Koertzing, A., Johnson, G., Johnson, K., Riser, S., O., U., 2007. The Argo-oxygen program: A white paper to promote the addition of oxygen sensors to the international Argo float program. . Available online at: http://www.imber.info/C_WG_SubGroup2.html.
- Huot, Y., M. Babin, F. Bruyant, C. Grob, M. S. Twardowski and H. Claustre, 2007: Does chlorophyll a provide the best index of phytoplankton biomass for primary productivity studies? *Biogeosciences*, 4, 853-868
- Kirk, J.T., 1994: *Light and Photosynthesis in Aquatic Ecosystems*. University Press, Cambridge
- Le Quéré, C., Harrison, S.P., Prentice, I.C., Buitenhuis, E.T., Aumont, O., Bopp, L., Claustre, H., da Cunha, L.C., Geider, R., Giraud, X., Klaas, C., Kohfeld, K.E., Legendre, L., Manizza, M., Platt, T., Rivkin, R.B., Sathyendranath, S., Uitz, J., Watson, A.J., and Wolf-Gladrow, D. 2005: Ecosystem dynamics based on plankton functional types for global ocean biogeochemistry models. *Global Change Biology*, 11, 2016-2040.
- Le Reste S., X. André, Claustre H., D'Ortenzio F., Poteau A., 2009: First succes of PROVIO floats, *Coriolis Newsletters* numero 5, january 2009, pag 6-8
- McClain, C.R., Feldman, G.C., Hooker, S.B., 2004. An overview of the SeaWiFS project and strategies for producing a climate research quality global ocean bio-optical time series. *Deep Sea Research Part II* 51 (1-3), 5-42.
- Morel, A., Maritorea, S., 2001. Bio-optical properties of oceanic waters: a reappraisal. *Journal of Geophysical Research* 106 (C4), 7163-7180.

Niewiadomska, K., Claustre, H., Prieur, L., d'Ortenzio, F.: 2008. Submesoscale physical-biogeochemical coupling across the Ligurian Current (northwestern Mediterranean) using a bio-optical glider. *Limnology and Oceanography* 53 (5), 2210-2225.

Perry, M.J., Sackmann, B.S., Eriksen, C.C., Lee, C.M., 2008. Seaglider observations of blooms and subsurface chlorophyll maxima off the Washington coast, USA. *Limnology and Oceanography* 53 (2), 169–179. .

Pierce, D.W., 2004: Future changes in biological activity in the North Pacific due to anthropogenic forcing of the physical environment. *Climatic Change* 62 (1-3), 389-418.

Sarmiento, J.L., Slater, R., Barber, R., Bopp, L., Doney, S.C., Hirst, A.C., Kleypas, J., Matear, R., Mikolajewicz, U., Monfray, P., 2004: Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles* 18 (3, DOI 10.1029/2003GB002134).

Tengberg, A.; J. Hovdenes, H. Andersson, O. Brocandel, R. Diaz, D. Hebert, T. Arnerich, C. Huber, A. Körtzinger, A. Khripounoff, F. Rey, C. Ronning, J. Schimanski, S. Sommer, A. Stangelmayer (2006), Evaluation of a lifetime-based optode to measure oxygen in aquatic systems, *Limnol. Oceanogr. Methods*, 4, 7-17.

Winkler, L. W. (1888), Die Bestimmung des in Wasser Gelösten Sauerstoffes, *Berichte der Deutschen Chemischen Gesellschaft*, 21, 2843-2855.

Remote impacts of Sub-Mesoscale Dynamics on new production

By Marina Lévy¹, Dorotea Iovino¹, Sébastien Masson¹, Gurvan Madec¹, Patrice Klein², Anne-Marie Tréguier² and Keiko Takahashi³

¹ LOCEAN/IPSL, CNRS/UPMC/IRD/MNH, Paris, France

² LPO, CNRS/IFREMER/UBO, Plouzané, France

³ ESC, Yokohama, Japan

Abstract

The sensitivity to increased horizontal resolution from $1/9^\circ$ to $1/54^\circ$ of an idealized bio-physical model of the North Atlantic basin forced by seasonal wind and heat and salt fluxes is presented. The simulations are run over the 50 years required to equilibrate the mean circulation and the mean sub-surface nutrient distribution. One original impact of model resolution concerns the significant modification of the mean circulation with the southward displacement of the western boundary current extension and the emergence of a regime of alternating zonal jets in the western part of the basin. The change in mean circulation has important consequences on both the density structure and the sub-surface distribution of nutrients. The subtropical gyre is displaced southward, and is associated with deeper and steeper isopycnals, and with a deeper nutricline. The mean features of the phytoplankton seasonal cycle remain unchanged, but filaments of high phytoplankton concentration become more prominent at higher resolution. The net new production (NP) decreases by 10% at higher resolution, with regional differences reaching +/- 30%. These changes in NP are primarily attributed to changes of the mean transports by mesoscale turbulence, changes that we refer to as *remote* in contrast to the *local* changes within the individual sub-mesoscale structures.

Introduction

This paper deals with the large-scale impacts of mesoscale eddies (~100 km, few months) and sub-mesoscale turbulence (~10 km, few days) on the production of phytoplankton. The impact of (sub-)mesoscale turbulence on biological production is now widely recognized (see Lévy, 2008, for a review). There is growing evidence that primary production (PP) occurring at the (sub-)mesoscale contributes significantly to the global budgets. Models and observations both demonstrate that as spatial sampling resolution increases, so does the measured strength and variability of the lateral and vertical motions in the ocean. These sub-mesoscale motions, driven by strongly nonlinear dynamics, can have profound effects on the local structure and dynamics of the planktonic ecosystem, and on the carbon and nutrient fluxes through the system.

Our view of the impact of mesoscale turbulence on marine biogeochemical cycles has evolved rapidly over the past few years. Initially, the focus was on mesoscale eddies, and the main process involved was the so-called "eddy pumping" (Mc Gillucuddy et al., 1998), with the upwelling of nutrients in the core of cyclonic eddies (or mode water eddies) increasing PP. Then, the focus has shifted to sub-mesoscales, with the upwelling of nutrients not in the cores of eddies, but at their border or in elongated filaments through the process of frontogenesis (Lévy et al., 2001). More recently, dynamical studies have also suggested that important vertical velocities were associated with the instability of these sub-mesoscale filaments (Capet et al., 2008; Klein et al., 2008), with a potentially additional effect on nutrient transport. Moreover, a number of different other processes have been shown to affect PP at the sub-mesoscale, including stratification effects (Lévy et al., 2005), lateral stirring (Abraham et al., 1999; Lehahn et al., 2007), structuration of phytoplankton types (De Monte et al., 2009) and subduction (Lathuilière, 2008; Karleskin, 2008). These different processes have different impacts on the biogeochemical cycles: changes in stratification change the timing of the bloom; lateral stirring redistributes the bloom; different phytoplankton types have different biogeochemical impacts; subduction decreases the phytoplankton content of the surface layer (this last process is particularly efficient in coastal upwelling areas). However, how these short term and local processes add up at the seasonal and basin scale is still an open question. We call *remote* these cumulated effects of small-scale physics on large-scale fields, in opposition to the *local* processes mentioned before. These remote effects are very likely to affect marine biogeochemical cycles through their impact on the sub-surface nutrient reservoir and the main nutrient streams.

In order to investigate these remote effects, we perform bio-physical numerical experiments of an idealized ocean basin run over the multi-year time required to reach an equilibrated mean seasonal cycle. The basin is representative of the north Atlantic, encompassing the oligotrophic subtropical gyre, the northward propagating spring bloom and an eastern boundary upwelling system. Mesoscale eddies emerge in numerical models when horizontal resolution is of $O(10\text{ km})$ while a resolution of $O(1\text{ km})$ is necessary to capture sub-mesoscale turbulence (Siegel et al., 2001). Therefore, two experiments are compared, at mesoscale and sub-mesoscale resolutions, respectively.

Model experiments: the GYRE configuration

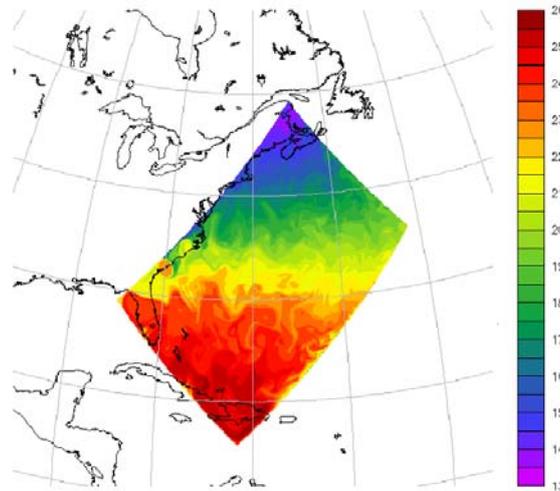


Figure 1

Model configuration. The idealized configuration is representative of a reduced North Atlantic ocean, with a strong baroclinically unstable current separating warm waters in the South and colder waters in the North. Shown is the Sea Surface Temperature

The domain geometry is a rotated, closed rectangular basin on the beta-plane (Figure 1), bounded by vertical walls and by a flat bottom (after Hazeleger and Drijfhout, 1998). The circulation is forced by analytical zonal winds and buoyancy fluxes that vary seasonally and with latitude. There are 30 z-coordinate vertical layers. Two experiments are compared: R9 with $1/9^\circ$ resolution (mesoscale) and R54 with $1/54^\circ$ resolution (sub-mesoscale). The NEMO Primitive equation model (Madec, 2008) is used. Bi-harmonic friction and bi-harmonic diffusion act along horizontal surfaces. The coefficients for the diffusion of momentum are $-5 \cdot 10^{10} \text{ m}^4 \text{ s}^{-1}$ in R9 and $-10^9 \text{ m}^4 \text{ s}^{-1}$ in R54. The diffusion coefficient is $-10^9 \text{ m}^4 \text{ s}^{-1}$ in both R9 and R54. Vertical mixing is parameterized by a 1.5 turbulent closure model. Advection of temperature and salinity is performed with a flux-corrected transport scheme (Levy et al., 2001). An energy conserving scheme is used for the computation of vorticity trends (Le Sommer et al., 2009). Free-slip conditions and no heat and salt flux are applied along solid boundary, except at the bottom where a non-linear friction drag is applied. The physical model is coupled with the biogeochemical model LOBSTER, which comprises phytoplankton, zooplankton, nitrate, ammonium, dissolved organic matter and detritus (Kremer et al., 2009).

R9 and R54 are initialized from the spun-up state of a similar simulation at 1° resolution. Then they are spun-up for 50 years, which is the time required to equilibrate the mean circulation and the mean nutrient distribution to the new resolutions. At this point, an additional 5 year-run is conducted. We present results from the mean state computed over these last 5 years. These computationally expensive experiments were performed on the Earth Simulator (Yokohama, Japan).

Changes of the dynamics with resolution

The GYRE experiments confirmed the emergence of energetic sub-mesoscale filaments and the explosion of mesoscale eddies at $1/54^\circ$ in comparison to $1/9^\circ$, with an increase of the eddy kinetic energy by more than 50%. But most of all, these experiments revealed the tremendous modification of the large-scale circulation resulting from the non-linear dynamics associated with mesoscale turbulence: reinforcement of the main currents, change in the separation latitude of the western boundary current, generation of alternative zonal jets modification of the shape and stratification of the main thermocline. These changes are rationalized in Lévy et al. (2009) and are briefly reminded here.

The changes of the mean circulation from R9 to R54 are illustrated by the surface currents and mean barotropic stream function (BSF) shown in Figure 2. Sub-mesoscales make the separation latitude of the western boundary current to shift southward by 4° and its offshore extension to become more zonal, to intensify and to penetrate farther to the east (Figure 2c-d). Figure 2d also reveals the presence of a secondary surface intensified zonal jet in R54 that is weaker and less zonal in R9. The presence of the zonal jets, further discussed in Lévy et al. (2009), strongly modifies the barotropic transport; in both runs, the BSF displays two main gyres, cyclonic in the north and anticyclonic in the south (Figure 2a-b). In R54, both gyres show strong perturbations (Figure 2b). In the north, the mean cyclonic circulation is perturbed by an anti-cyclonic re-circulation between 40°N and 45°N . This structure was already present in R9, but it is intensified in R54. In the south, the mean anticyclonic circulation is strongly perturbed by a cyclonic re-circulation around $30\text{-}32^\circ\text{N}$.

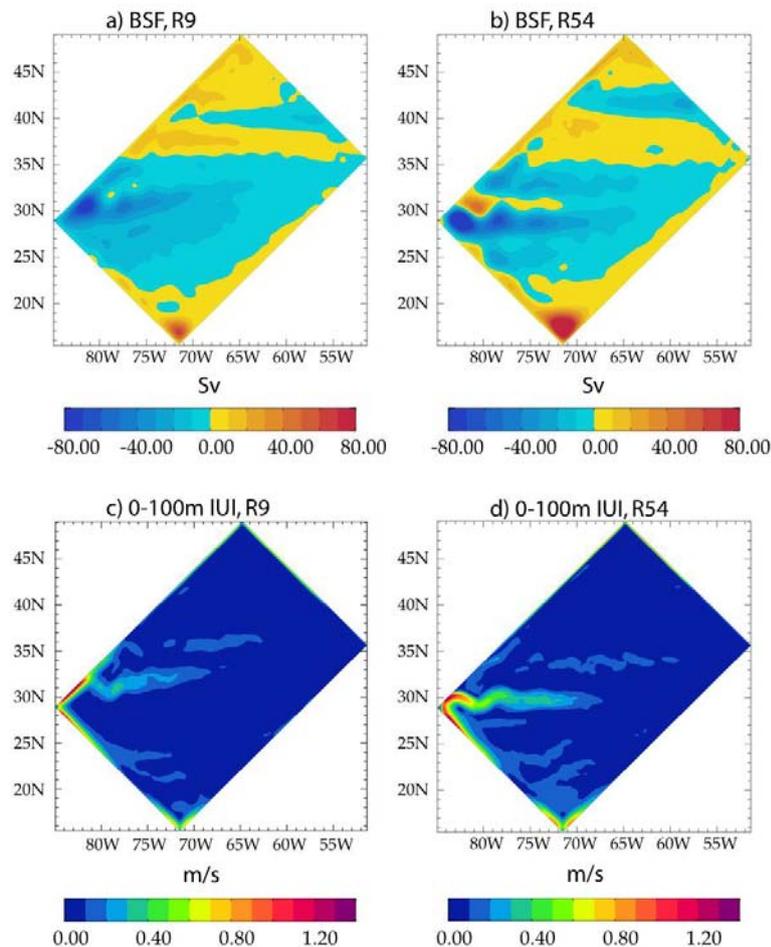


Figure 2

5y-mean Barotropic Stream Function (in Sverdrup) and module of the mean horizontal velocity in the 0-100m layer (in m/s), in experiments R9 and R54

Changes in the structure of the density field with resolution

The large-scale density field displays a strong N-S gradient with the subtropical gyre involving saltier and warmer waters than the subpolar gyre. The modification of this large-scale density field by mesoscale turbulence is intimately linked to the related changes in the mean circulation through the thermal wind balance. As an illustration, Figure 3a-b shows the depth of the isopycnal 25.0 in R9 and R54. It highlights the typical bowl shape of isopycnals in the subtropical gyre, which outcrop in the subpolar gyre. Resolution modifies the shape of the gyres, the isopycnal depths and the isopycnal slopes. In accordance with the thermal wind balance, the strengthening of the western boundary current extension in R54, with respect to R9, is associated with the steepening of the isopycnal slopes. In addition, deeper isopycnals in the subtropical gyre and shallower isopycnals between 30-35°N correspond to a southward shift of the bowl shape. All together, the main impact of resolution leads to deeper isopycnals in the subtropical gyre, shallower isopycnals and in 30-35°N region and steeper isopycnal slopes.

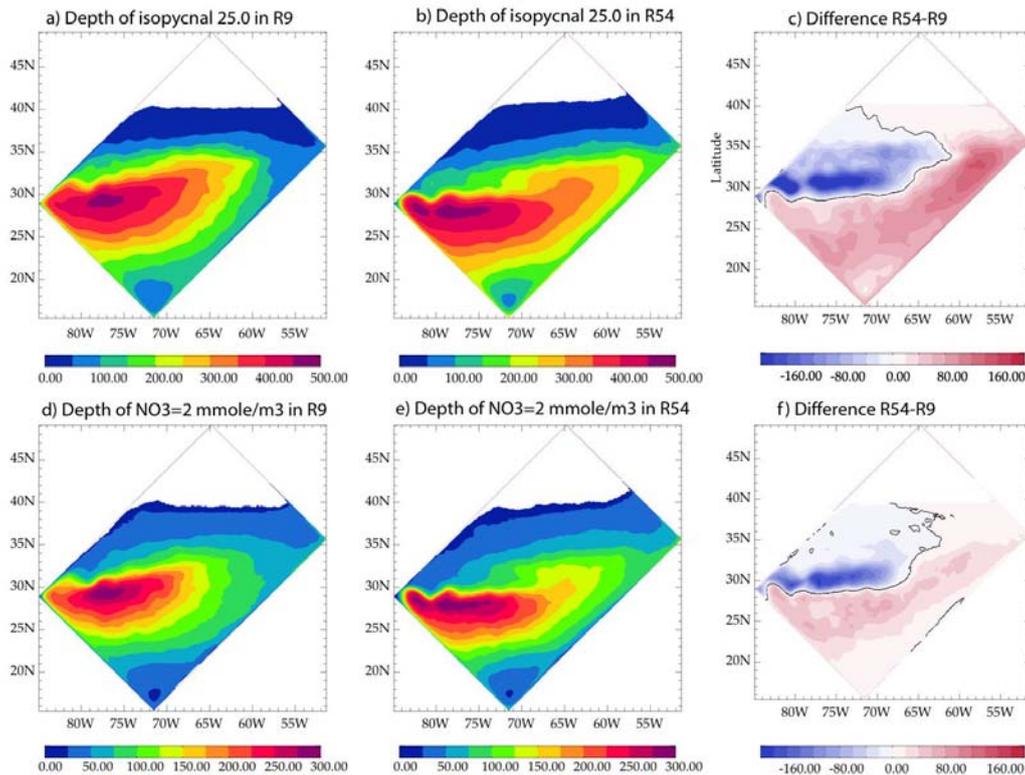


Figure 3

a-c) Depth of the 5-year mean isopycnal 25.0 in R9 and R54, and difference between the two depths (in meters). d-f) depth of the level where the 5-year mean nitrate concentration is equal to 2 mmole/m³ in R9 and R54, and difference between the two depths (in meters)

Changes in the structure of the nutrient field with resolution

The distribution of nutrients below the euphotic layer depends both of on the remineralization of organic matter and of the transport of nutrients (Kremer et al., 2009). Figure 3d-e shows the depth of the level at which the nitrate concentration is equal to 2 mmoleN/m³ in R9 and R54. The general feature is deeper nutrients in the subtropical gyre and shallower in the 30-35°N region, in agreement with the bowl shape of the subtropical gyre. The difference between the two runs (Figure 3f) is very similar to the difference of the 25-isopycnal depths (Figure 3c). This clearly suggests that transport rather than remineralization is responsible for the differences of the sub-surface nutrient reservoir. In the subtropical gyre, nutrients are significantly deeper in R54 than in R9 (by approx 50m) due to the general deepening of the thermocline. Between 30-35°N, nutrients are shallower in R54 than in R9, due to the southward displacement of the subtropical gyre northern boundary in R54.

Changes in phytoplankton and production with resolution

The main feature of the seasonal cycle of phytoplankton are unchanged with resolution: the sub-tropical gyre is very oligotrophic, the mid-latitudes are characterized by a strong spring bloom that propagates northward in the subpolar gyre, the western boundary current extension marks a clear boundary between these two provinces, the south-eastern coast is productive due to coastal upwelling. As an illustration, Figure 4 shows a snapshot of sea-surface phytoplankton concentration during the spring bloom. Sub-mesoscale features are present in both runs but are much more intense and well defined in R54, with in particular increased concentration at sub-mesoscale fronts.

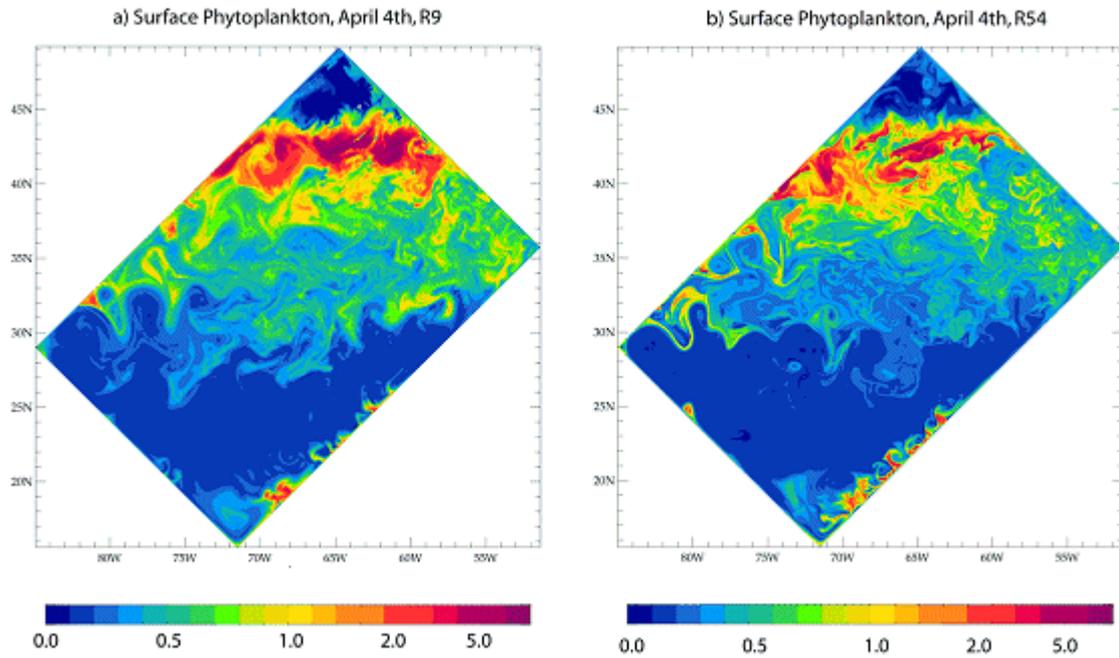


Figure 4

Snapshot of the sea surface phytoplankton concentration in spring (in mmole/m^3) in R9 and R54

On an annual mean, phytoplankton New Production (NP) (Figure 5) further highlights this large-scale contrast between eutrophic and oligotrophic provinces at the gyre scale. The difference in NP between the two runs (Figure 4c) is characterized by distinct areas where NP is higher either in R54 or in R9, in an intricate manner. The rationalization of these differences is underway. In most of the subtropical gyre, NP is lower in R54, due to the deeper nutricline. There is however a small band of compensation, near 25°N , where NP is slightly higher in R54 despite a deeper nutricline. Along the eastern boundary, the upwelling system is significantly less efficient in R54 because of a deeper nutricline resulting in decreased NP. On the contrary, along 30°N , NP is significantly higher in R54, due to the southward displacement of the sub-tropical gyre and in agreement with the mean nutrient distribution (Figure 3). Along the western flank at 40°N , NP is also higher in R54, and preliminary analysis indicate that this increase is associated with higher nutrient transport. The annual basin mean NP in R9 exceeds NP in R54 by 10%. This mean result is however the net result of local changes of higher amplitude (up to $\pm 30\%$ along 30°N and in the coastal upwelling).

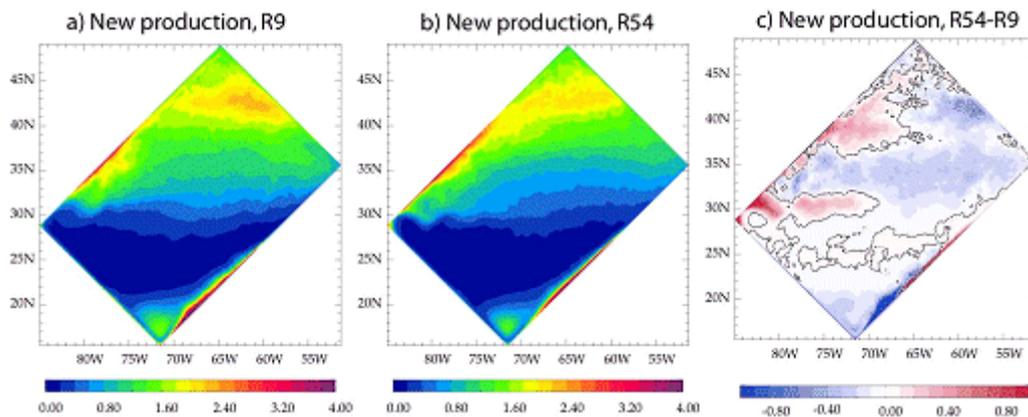


Figure 5

5 year-mean New Production (defined here as the nitrate uptake by phytoplankton) in R9 and R54, and difference between the two (in $\text{mmole/m}^3/\text{day}$)

Conclusion

The impact of model resolution on the primary production budget of an idealized seasonal cycle of the North Atlantic is analyzed. By comparing an eddy-resolving (R9) and a sub-mesoscale resolving (R54) simulation we have shown that the NP budgets show significant differences between the two runs: it increases in some areas and decreases in others, with a net result of a 10% decrease at sub-mesoscale resolution. This net result is rather counter-intuitive because the common *local* view is that sub-mesoscales fertilize the ocean through vertical injection of nutrients (Lévy, 2008). Our preliminary results suggest that the *remote* impacts of sub-mesoscales on phytoplankton production play an important role in the mean production budget at the scale of oceanic gyres, through the modification of the mean transports.

Acknowledgements

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References

- Abraham, E. R. The generation of plankton patchiness by turbulent stirring. *Nature* 391, 577, 1998.
- Capet, X., J. C. McWilliams, M. J. Molemaker, and A. F. Shchepetkin, Mesoscale to Submesoscale Transition in the California Current System. Part I: Flow Structure, Eddy Flux, and Observational Tests, *J. Phys. Ocean.*, 38, 29-43, 2008.
- De Monte, S., d'Ovidio, F., S. Alvain, Y. Dandonneau and M. Lévy, a multisatellite approach for mesoscale phytoplankton community structure, proceedings of OceanObs'09, 21-25 Sept 2009, Venice, Italy.
- Hazeleger, W., and S. S. Drijfhout, Mode water variability in a model of the subtropical gyre; response to anomalous forcing, *J. Phys. Oceanogr.*, 28, 266-288, 1998.
- Karleskind, P. : Modélisation de la production primaire et de l'export dans l'Atlantique nord-est: bilans annuels, Thèse de l'Université de Bretagne Occidentale, Brest, 2008.
- Klein, P., Hua B.L., G. Lapeyre, X. Capet, S. LeGentil and H. Sasaki, Upper Ocean Dynamics from High 3-D Resolution Simulations, *J. Phys. Ocean.*, 38, 8, 1748–1763, 2008.
- Kremer, A.-S., M. Lévy, O. Aumont and G. Reverdin, Impact of the subtropical mode water biogeochemical properties on primary production in the North Atlantic: new insights from an idealized model study, *J. Geophys. Res.*, 114, C07019, doi:10.1029/2008JC005161, 2009.
- Lathuilière, C : Echanges biogéochimiques côtes-large dans un upwelling de bord-est (Canaries), Thèse de l'Université Pierre et Marie Curie, Paris, 2008.
- Lehahn, Y., F. d'Ovidio, M. Lévy and E. Heifetz: Stirring of the northeast Atlantic spring bloom: A Lagrangian analysis based on multisatellite data, *J. Geophys. Res.*, 112, C08005, 2007.
- Le Sommer, J., Penduff, T., Theetten, S., Madec, G., & Barnier, B, How momentum advection schemes influence current-topography interactions at eddy-permitting resolution. *Ocean Modelling*, 29(1), pp. 1-14, 2009.
- Lévy, M., A. Estubier and G. Madec: Choice of an advection scheme for biogeochemical models, *Geophys. Res. Lett.*, 28, 3725-3728, 2001.
- Lévy, M., P. Klein and A. M. Tréguier: Impacts of sub-mesoscale physics on phytoplankton production and subduction, *J. Mar. Res.*, 59:4, 535-565, 2001.
- Lévy, M., M. Gavart, L. Mémerly, G. Caniaux and A. Paci: A four-dimensional mesoscale map of the spring bloom in the northeast Atlantic (POMME experiment): results of a prognostic model. *J. Geophys. Res.* 110, C07S21, 2005.
- Lévy, M. The modulation of biological production by oceanic mesoscale turbulence, *Lect. Notes Phys.*, 744, 219-261, in: *Transport in Geophysical flow: Ten years after*, J. B. Weiss and A. Provenzale (Eds), 2008.

Lévy, M., P. Klein, A.-M. Tréguier, D. Iovino, G. Madec, S. Masson and K. Takahashi, Modification of gyre circulation by sub-mesoscale physics, *Ocean Modelling*, in revision, 2009.

Madec G., NEMO ocean engine, Note du Pôle de modélisation, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN No 1288-1619, 2008.

McGillicuddy, D. J., A. R. Robinson, D. A. Siegel, H. W. Jannasch, R. Johnson, T. D. Dickey, J. McNeil, A. F. Michaels and A. H. Knap: Influence of mesoscale eddies on new production in the Sargasso Sea, *Nature*, 394, 263, 1998.

Siegel, A., J. B. Weiss, J. Toomre, J. C. McWilliams, P. S. Berloff, and I. Yavneh, Eddies and vortices in ocean basin dynamics, *Geophys. Res. Lett.*, 28, 3183-3186, 2001.

Autonomous CO₂ measurements in the Tropical Atlantic

By **Nathalie Lefèvre¹**, **Denis Diverrès²**, **Francis Gallois³**, **Gaëlle Parard¹**, **Jacqueline Boutin¹**, **Guy Caniaux⁴**, **Laurence Beaumont⁵**, **Théo Danguy⁵**

¹ LOCEAN UPMC-IRD-CNRS-MNHN, 4 place Jussieu, Paris, France

² US 191, IRD Brest, Plouzané, France

³ US 191, IRD Nouméa, Nouvelle Calédonie

⁴ Météo France CNRM, Toulouse, France

⁵ DT INSU, 1 place A. Briand, Meudon, France

Abstract

An observational CO₂ network has been set up to better document the variability of the fugacity of CO₂ (fCO₂) in the Atlantic ocean, to determine its long term trend, and to provide accurate estimates of the air-sea CO₂ flux. Two merchant ships sailing from France to French Guiana and France to Brazil have been equipped with an autonomous CO₂ system measuring underway fCO₂ in the ocean and in the atmosphere. In addition, a CARIOCA CO₂ sensor and an oxygen optode have been installed on the PIRATA moorings at 6°S, 10°W and 8°N, 38°W to monitor fCO₂ and dissolved oxygen in the surface layer of the ocean. The fCO₂ distribution obtained along the track of the France-Brazil line exhibits a strong north-south CO₂ gradient with high fCO₂ observed in the South Equatorial Current (SEC) and lower fCO₂ in the North Equatorial Counter Current (NECC). Observations at the mooring located in the SEC from 2006 to 2008 show that a CO₂ outgassing occurs throughout the year with a minimum in June and a maximum in October. In the NECC low fCO₂ are associated with low salinities. In the western equatorial Atlantic south of 12°N and east of 30°W, dissolved inorganic carbon, alkalinity and fCO₂ are strongly correlated with salinity. Over 90% of the variance of fCO₂ is explained by salinity only because of the large freshwater supply of the Amazon River. Zonal cruises carried out when Amazon waters are advected eastward suggest that the propagation of Amazon waters depends on the structure and the strength of the NECC.

Introduction

The ocean is an important sink of CO₂ for the atmosphere absorbing about one third of the CO₂ emissions. It is not clear whether it will be able to absorb CO₂ emissions at the current rate as there is recent evidence of a declining rate of absorption in the North Atlantic (e.g. Lefèvre et al., 2004; Schuster and Watson, 2007). It is crucial to better document the CO₂ variability in the ocean and to understand the processes affecting its variability in order to predict the ocean behaviour under increasing atmospheric CO₂ levels.

The tropical Atlantic is a source of CO₂ to the atmosphere but the magnitude of this source and its seasonal variability are still poorly documented. In the eastern equatorial Atlantic, the coastal upwelling off Angola and the equatorial upwelling merge to form a cold tongue, rich in CO₂, south of about 2°N. This water mass is transported westward in the South Equatorial Current (SEC). Further north, lower sea surface salinities are observed in the North Equatorial Counter Current (NECC) that develops between approximately 2°N and 10°N. In order to evaluate carbon fluxes between ocean and atmosphere, the seawater CO₂ fugacity is measured (closely related to CO₂ partial pressure for perfect gases, ie, the quantity of CO₂ in a quantity of seawater for a given fluid pressure). Indeed, the seawater CO₂ fugacity depends on temperature and salinity. Then, knowing atmospheric fugacity, the differences are computed, and associated with wind intensity, the results indicate areas of oceanic source, or sink of CO₂. A few cruises have been carried out in the tropical Atlantic. Andrié et al. (1986) showed that the fugacity of CO₂ in sea water (fCO₂) increases westward due to the warming of surface waters as they are transported by the SEC flowing from the African coast to the American coast between 15°S to 2°N. Oudot et al. (1987) reported high fCO₂ in this current but noticed lower fCO₂ further north in the NECC. The monthly climatology of Takahashi et al. (2009) shows a smaller source of CO₂ in the NECC than in the SEC but a source of CO₂ is observed throughout the year in these two regions.

However, areas of CO₂ sinks have been reported in the tropical Atlantic. A sink of CO₂ has been observed in the western tropical Atlantic due to the Amazon discharge (Ternon et al., 2000; Körtzinger, 2003). Because of high turbidity, primary productivity does not occur in the Amazon River but when the water mixes with oceanic water, the supply of nutrients from the Amazon creates high biological activity, mainly diatom blooms that cause a strong CO₂ drawdown. In boreal autumn, the retroreflection of the North Brazil Current carries the Amazon waters eastward in the NECC. Because of the slow exchange of CO₂ with the atmosphere, CO₂ undersaturations can be observed as far east as 25°W (Lefèvre et al., 1998). Monitoring fCO₂ in this region will help in documenting its variability and determine the impact of low fCO₂ on the CO₂ budget of the tropical Atlantic.

Monitoring fCO₂ and O₂ in the tropical Atlantic

As part of the European project, CARBOOCEAN, a network of fCO₂ observations has been setup in the Atlantic using ships of opportunity and instrumented moorings (Figure 1). The *MN Colibri*, sailing from Le Havre (France) to Kourou (French Guiana), has been equipped with an autonomous CO₂ system measuring the oceanic and atmospheric fugacity of CO₂ underway. The fugacity of CO₂ is measured by infrared detection to an accuracy estimated at $\pm 2 \mu\text{atm}$. In the open ocean, the fugacity ranges from about 280 to 420 μatm . Data have been collected since February 2006 (table 1). In February and March 2006, the voyages were attended to check the functioning of the fCO₂ system and seawater samples were taken for dissolved inorganic carbon (DIC) and total alkalinity (TA) analyses. The carbon system includes four parameters: fCO₂, pH, DIC and TA, and measuring two of them allows the calculation of the other two. Another merchant ship, the *Monte Olivia*, sailing from Le Havre to Santos (Brazil), has been equipped with a similar CO₂ system and has collected data from 2008 to 2009 (table 1). The system had to be taken off the ship in April 2009 as the route has changed. Another ship has to be found to continue the sampling. A great advantage of this route is that the ship repeats exactly the same track on its way back to France, providing a time-series transect without any spatial bias.

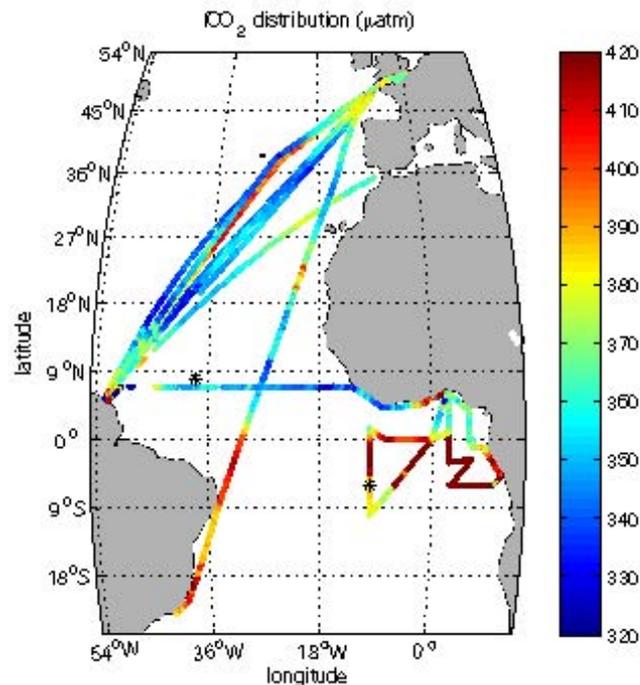


Figure 1

fCO₂ distribution (in μatm) along the track of the *MN Colibri* (February, and December March 2006, February, April, May, June and August 2007, March and July 2008, February 2009), of the *Monte Olivia* from France to Santos (Brazil) in January 2009, of the zonal transect from French Guiana to Africa in August 2008, and of the EGEE 3 cruise in the eastern equatorial Atlantic in June 2006. The CO₂ measurements made at the PIRATA moorings (6°S, 10°W and 8°N, 38°W) are indicated by a star

Dates	Track	Vessel
25 Feb–6 Mar 2006	Le Havre – Kourou	MN Colibri
8-26 Mar 2006	Kourou – Le Havre	
23-31 Dec 2006	Le Havre-Kourou	MN Colibri
23 Feb-2 Mar 2007	Le Havre-Kourou	MN Colibri
20-30 Apr 2007	Le Havre – Kourou	MN Colibri
7-15 May 2007	Le Havre – Kourou	MN Colibri
11-19 Jun 2007	Le Havre – Kourou	MN Colibri
22-23 Jun 2007	Kourou – Le Havre	
20-26 Aug 2007	Le Havre – Kourou	MN Colibri
22-31 Mar 2008	Le Havre – Kourou	MN Colibri
25 Jun-5 Jul 2008	Le Havre – Kourou	MN Colibri
19-26 Jul 2008	Kourou – Le Havre	
22 Feb-3 Mar 2009	Le Havre – Kourou	MN Colibri
7-17 Mar 2009	Kourou – Le Havre	
27-28 Jan 2008	Le Havre-Santos	Monte Olivia
12-20 July 2008	Le Havre-Santos	Monte Olivia
4-12 Aug 2008	Santos-Le Havre	
3-13 Oct 2008	Le Havre-Santos	Monte Olivia
27 Oct-6 Nov 2008	Santos-Le Havre	
14-21 Nov 2008	Le Havre-Santos	Monte Olivia
6-16 Dec 2008	Santos-Le Havre	
27 Dec 2008-5 Jan 2009	Le Havre-Santos	Monte Olivia
18-28 Jan 2009	Santos-Le Havre	
5-17 Feb 2009	Le Havre-Santos	Monte Olivia
1-11 Mar 2009	Santos-Le Havre	
12-23 Apr 2009	Le Havre-Santos	Monte Olivia

Table 1

Dates and route of the voyages of the *MN Colibri* and the *Monte Olivia*

In addition to the monitoring of fCO₂ by merchant ships, two time-series stations have been set up in the tropical Atlantic. An fCO₂ sensor (CARIOCA type sensor) and an oxygen optode have been installed on the PIRATA mooring at 6°S, 10°W in June 2006 (Lefèvre et al., 2008). The measurement of fCO₂ is made by spectrophotometry with an accuracy of $\pm 3 \mu\text{atm}$ and is based on the optical absorbance of a pH sensitive dye diluted in seawater (Hood and Merlivat, 2001). CO₂ in the surrounding water equilibrates with the solution across a gas permeable membrane and the resulting change in optical absorbance is measured by the spectrophotometer. A similar system has been adapted to work on merchant ships and is currently being tested on board the *MN Colibri*. The comparison between the CARIOCA system and the infrared system shows encouraging results.

The oxygen concentration on the mooring is measured by an Andraea optode by quenching fluorescence. The fCO₂ sensor and the optode are replaced each year during the PIRATA cruise. The sensors have been replaced in June 2007, September 2008 and July 2009. The PIRATA mooring at 8°N, 38°W has also been equipped by an fCO₂ sensor and an oxygen optode in April 2008 and replaced in March 2009.

This large dataset has been completed by three cruises in the equatorial Atlantic. As part of the oceanic component of the AMMA project, oceanic and atmospheric fCO₂ were measured underway during the EGEE 3 cruise in June 2006 in the eastern equatorial Atlantic. A zonal cruise, Plumard, was carried out between Africa and French Guiana in October 2007 along 7°30'N and samples were taken for DIC and TA analyses. In August 2008, oceanic and atmospheric fCO₂ were measured underway along 7°N from French Guiana to Africa.

Large scale variability of fCO₂

The surface fCO₂ distribution of several voyages of the *MN Colibri*, of the *Monte Olivia* in January 2009, of the EGEE 3 cruise in June 2006 and of the zonal transect in August 2008 shows large spatial variability (Figure 1). In general, along the track of the *MN Colibri*, relatively low fCO₂ are recorded except during summer when high fCO₂ values are observed at mid-latitudes near 30°N. The *Monte Olivia* shows a similar variability except that a small area of high fCO₂ appears close to the Mauritanian upwelling near 20°N. High fCO₂ variability is observed close to the European and American shelves.

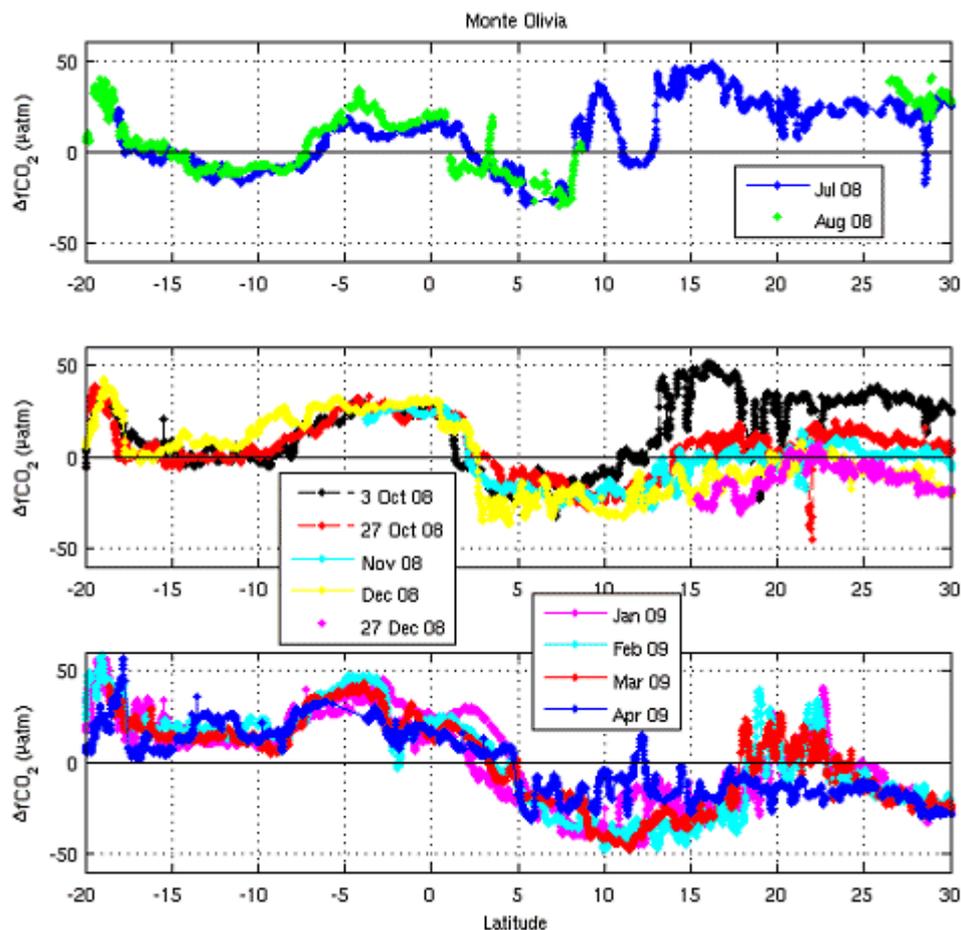


Figure 2

Difference of fugacity of CO₂ between the ocean and the atmosphere as a function of latitude for the voyages of the *Monte Olivia*. Negative (positive) values correspond to a sink (source) of CO₂ for the atmosphere

In the equatorial Atlantic, a strong north-south fCO₂ gradient appears around 2°N along the track of the *Monte Olivia*. The voyages of the *Monte Olivia* provide almost a complete seasonal cycle of fCO₂. The difference of fCO₂ between the ocean and the atmosphere, ΔfCO₂, indicates whether the region is a sink or source of CO₂. A negative difference means that the ocean is a sink of CO₂, as atmospheric CO₂ will go from the atmosphere to the ocean to reach equilibrium conditions. Along the track of the *Monte Olivia*, a source of CO₂ is observed throughout the year from 10°S to 2°N whereas a sink of CO₂ occurs from about 2°N to 10°N in the NECC (Figure 2). On monthly average, the 2°N-10°N region is always a sink of CO₂ along the track of the *Monte Olivia* whereas the 10°S-2°N region is always a source of CO₂. The salinity is always lower in the NECC than in the SEC. Within the NECC, the highest salinities are observed from January to April, with a mean value of 35.56 (compared to 36.01 in the SEC), when the intertropical convergence zone (ITCZ) is at its most southern location. The temperature difference between the NECC and the SEC is a possible explanation for the persistence of the north-south gradient of fCO₂, at this period, as cooling would tend to decrease fCO₂.

	SST (in °C)			SSS		
	Jul-Aug	Oct-Dec	Jan-Apr	Jul-Aug	Oct-Dec	Jan-Apr
2°N-10°N	28.17	28.27	26.25	34.84	34.44	35.56
10°S-2°N	26.97	27.32	28.11	35.67	35.96	36.01

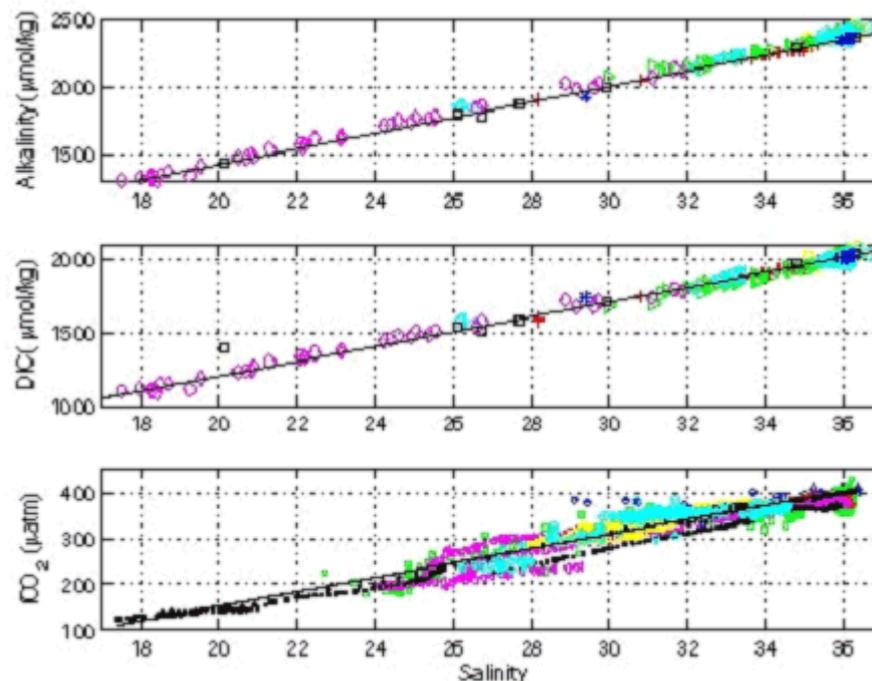
Table 2

Mean surface temperature (SST) and surface salinity (SSS) measured on board the Monte Olivia between 2°N-10°N and 10°S-2°N

The strongest $\Delta f\text{CO}_2$ is observed from January to April in the SEC, with a mean value of 23.7 μatm , when the temperature and the salinity are the highest (Table 2) as an increase of these parameters increases $f\text{CO}_2$. The smallest $\Delta f\text{CO}_2$ in the SEC, with a mean of 7.9 μatm occurs in boreal summer when the SST and SSS have the lowest values. This might be surprising as the equatorial upwelling takes place from July to September and supply CO₂-rich waters to the surface. However, the warming of surface waters causes an increase of $f\text{CO}_2$ and $f\text{CO}_2$ could be higher than during the upwelling season.

The north-south gradient is also observed further east during the EGEE 3 cruise (Figure 1). South of 2°N very high $f\text{CO}_2$ (>410 μatm) were measured. At this period of the year, the equatorial and the coastal upwelling off Angola start developing and merge to form a cold tongue, rich in CO₂, that is advected westward in the SEC. North of about 2°N, in the Guinea Current, warm and fresh waters are associated with low CO₂ (Lefèvre, 2009). The Guinea Current is actually an extension of the NECC and the $f\text{CO}_2$ distribution is very similar to the one observed in the NECC.

Salinity control of $f\text{CO}_2$ in the western equatorial Atlantic

**Figure 3**

Alkalinity and DIC as a function of salinity for the Plumand (red crosses), Cither (yellow circles), Colibri February 2006 (blue stars) and Etambot 1 (green right-pointing triangles) and 2 (cyan left-pointing triangles), Amandes 1 (black squares), Sabord (magenta diamonds) cruises. Bottom panel: fugacity of CO₂ as a function of salinity for the Colibri cruises in February 2006 (blue circles), March 2006 (green squares), April 2007 (red crosses), June 2007 (magenta left-pointing triangles), August 2007 (black dots), July 2008 (yellow upward-pointing triangles) and the transit in 2008 (cyan diamonds)

One objective of measuring $f\text{CO}_2$ in this region is to determine the impact of the Amazon outflow on the ocean $f\text{CO}_2$ distribution. The lowest surface salinity are measured near the American shelf with salinity as low as 18 recorded during the voyage of the *MN Colibri* in August 2007. Low salinities are associated with low $f\text{CO}_2$. In the western equatorial Atlantic, DIC, TA and $f\text{CO}_2$ are strongly correlated with sea surface salinity (Figure 3). Using the Colibri and the zonal cruises data, for the area south of 12°N and west of 30°, the following relationships can be determined:

$$\text{TA} = 58.07 \text{ S} + 264.91 \quad r^2 = 0.997 \text{ (1)}$$

$$\text{DIC} = 50.59 \text{ S} + 189.42 \quad r^2 = 0.988 \text{ (2)}$$

They are very similar to the regressions obtained by Ternon et al. (2000) using data from the Etambot 1, Etambot 2 and Sabord cruises made in September 1995, April 1996 and April 1995 respectively, near the French Guiana shelf.

The relationship between fCO₂ and salinity is determined for salinity less than 35:

$$\text{fCO}_2 = 15.66 \text{ S} - 161.17 \quad r^2 = 0.92 \text{ (3)}$$

The slope of the regression is slightly different from those obtained by Ternon et al. (2000), of 11 μatm/ psu and by Körtzinger (2003), of 13 μatm/ psu. The dispersion around the fit is quite high and is reduced when fCO₂ is normalized to a constant temperature of 28°C. Given the seasons and years of measurements, the relationships are robust and do not seem to show a seasonal cycle.

In the Amazon River, fCO₂ is one order of magnitude higher than in the ocean due to *in situ* respiration of organic carbon (Richey et al., 2002; Mayorga et al., 2005). Values of fCO₂ over 4000 μatm have been reported making this river a strong source of CO₂. When the Amazon water mixes with the oceanic water, the turbidity decreases and biological productivity can occur. The very low DIC and fCO₂ values measured in the ocean correspond to the large CO₂ drawdown caused by strong biological activity but the high correlation observed with very low salinity confirms that this biological activity is due to the freshwater supply of the Amazon mixing with oceanic waters.

Surface TA is related to surface salinity in the world ocean but the TA-S relationship varies according to the ionic composition. However, a departure from the TA-S relationship is observed when calcifying organisms are present because of the precipitation of calcium carbonate. The biological activity in the western equatorial Atlantic is due to diatoms (Cooley et al., 2007) so that assuming a conservative mixing of alkalinity in this region is reasonable. The river endmember at S=0, given by equation (1) is TA_r = 265 μmol/ kg. The ocean endmember is determined when seawater and atmospheric fCO₂ are close, as done by Ternon et al. (2000) and Körtzinger (2003). This corresponds to a salinity of 34.7 and an alkalinity endmember for seawater, TA_s, of 2277 μmol/ kg. The percentage of Amazon River, *r*, is calculated from the following set of equations:

$$r \cdot \text{TA}_r + s \cdot \text{TA}_s = \text{TA}_{\text{obs}} \quad (4)$$

$$r + s = 100 \% \quad (5)$$

where *s* is the percentage of seawater, TA_{obs} is the alkalinity observed during the cruises. The freshwater changes by precipitation/ evaporation are neglected compared to the freshwater supply of the river. The propagation of Amazon waters can be estimated for each cruise by the percentage of river as a function of longitude (Figure 4). The Colibri voyages and the zonal cruises are located in Figure 1.

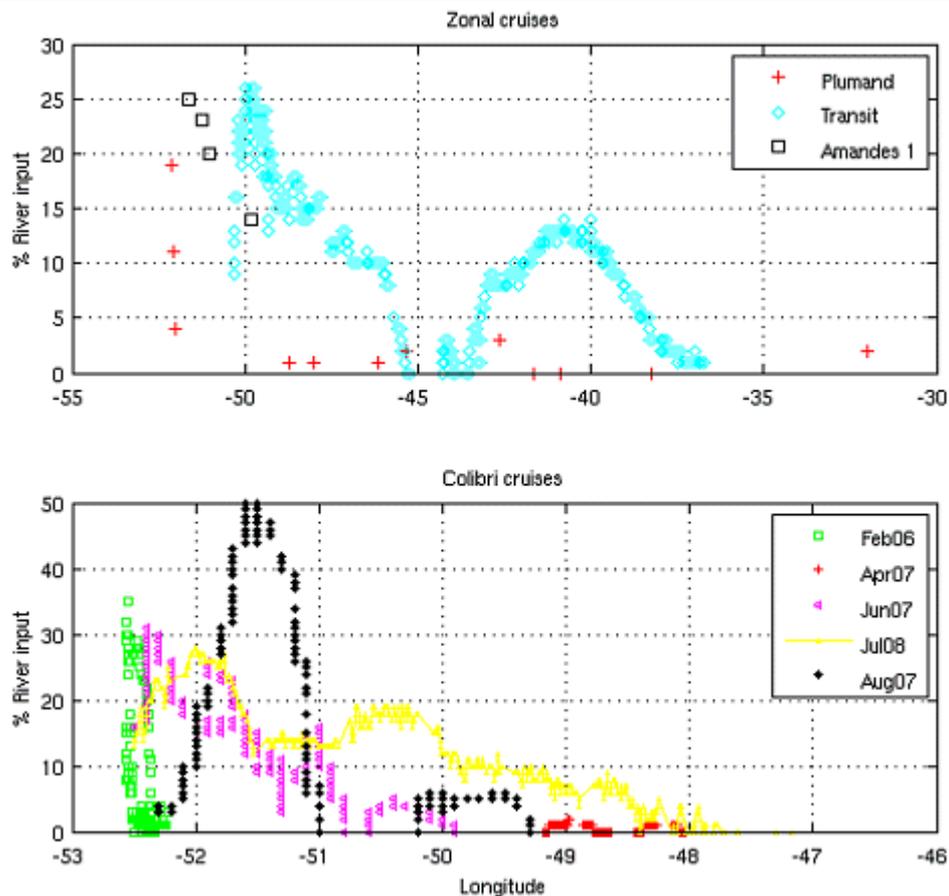


Figure 4

Percentage of freshwater supply from the Amazon to the ocean as a function of longitude for the zonal cruises west of 30°W (top panel) and for the voyages of the *MN Colibri* south of 12°N (bottom panel)

The percentage of river supply is highly variable. The Amazon water is more present in July and August during the voyages of the *MN Colibri*. At this time of the year, the retroflection of the North Brazil Current (NBC) starts so Amazon waters appear further offshore than in February. During the zonal cruises, Amazon waters can be observed near 40°W in August 2008, the corresponding salinity is 30 while in October 2007, the eastward propagation is not observed. Although both cruises are made during the retroflection of the NBC, the eastward propagation of Amazon waters depends on the NECC. The surface current measured by the ADCP revealed a strong difference in magnitude and direction between both cruises. In August 2008, the eastward component of the NECC was stronger than in October 2007 when the current was weak. Also, in August 2008, the velocity field showed a wave structure confirming the propagation of surface waters as NBC rings (Fratantoni and Glickson, 2001). This explains the absence of Amazon waters at 45°W but a 12% river supply at 40°W.

In August 2008, CO₂ undersaturations were observed on a large longitudinal range whereas in October 2007, the dominant pattern was a source. This is consistent with a stronger river supply in August 2008 compared to October 2007. During the zonal cruise, Cither, in February 1993 along 7°30'N, a source of CO₂ was observed (Oudot et al., 1995). It is still not clear if low fCO₂ in the NECC occur at a given season. Continuing the monitoring with the merchant ships and with the mooring at 8°N, 38°W should better document the variability of these area of low fCO₂ in the NECC, their location and their extent.

Time series measurements at the PIRATA mooring at 6°S, 10°W

In the SEC, high fCO₂ values are expected as the result of the equatorial upwelling and the warming of surface water. The PIRATA mooring at 6°S, 10°W, located in the SEC, provides hourly measurements since June 2006. However, failures of one of the CO₂ sensor are responsible for the data gap between 2007 and 2008. Also, data are missing for the first 6 months of 2009 due to an electronic breakdown of the sensor.

The time-series of fCO₂ shows values ranging from 350 μatm to 460 μatm. A decrease of fCO₂ is observed in June 2006 and 2007. Low values south of 6°S were also measured during the EGEE 3 cruise (Figure 1), but the origin of these lower fCO₂ is not understood yet. From July to September, during the upwelling season, the spreading of the cold tongue is responsible for the fCO₂

increase. After the upwelling, the surface seawater warms up which contributes to increase fCO₂ so that maximum fCO₂ values are reached in October, after the upwelling season. This mechanism was also observed with the Monte Olivia data when $\Delta f\text{CO}_2$ in the SEC was higher in January-April than in July-August.

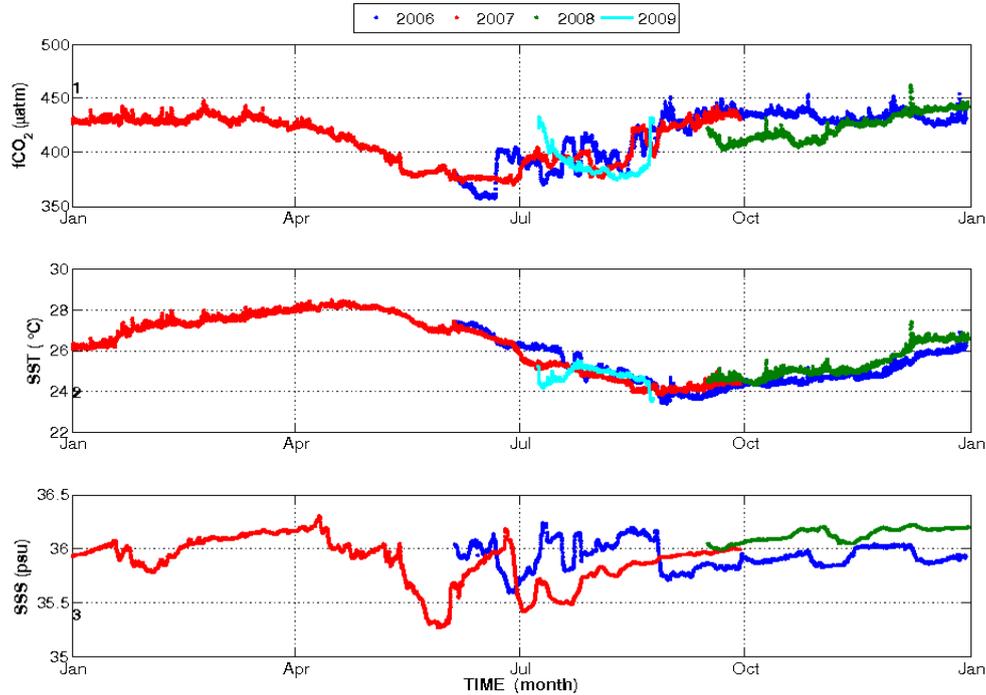


Figure 5

Time-series of fCO₂, SST and sea surface salinity at the PIRATA mooring at 6°S, 10°W from June 2006 to 2009

The air-sea CO₂ flux is calculated as the product of a gas exchange coefficient, expressed as a function of the wind speed, and the difference of fCO₂ between the ocean and the atmosphere. At this location, the winds are quite steady and average 7 m/s so the flux is mainly driven by the fCO₂ difference. A source of CO₂ is observed throughout the year (Table 3). The pattern of the CO₂ flux follows the distribution of seawater fCO₂ (Figure 5) with a minimum in June and a maximum in October 2006 and 2007. Some year to year variability is observed with a smaller source of CO₂ in 2008 from September to October compared to 2006 and 2007. This might be due to the strength of the equatorial upwelling but further investigation is needed to determine the cause of this variability.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006						1.7	4.0	5.9	8.3	10.3	10.1	8.4
2007	7.8	8.3	9.2	8.9	5.1	1.5	4.7	5.3	8.8	9.9		
2008									5.8	7.1	10.7	10.6

Table 3

Monthly flux of CO₂ between the ocean and the atmosphere in mmol.m⁻².d⁻¹ at 6°S, 10°W from 2006 to 2008.

Superimposed on this seasonal variability, the time series of CO₂ and O₂ show a diurnal cycle. This is particularly noticeable when the advection of the cold tongue is less pronounced, outside the upwelling season. Data recorded during the first week of December 2006 illustrates such a high frequency variability on fCO₂ (Figure 6)

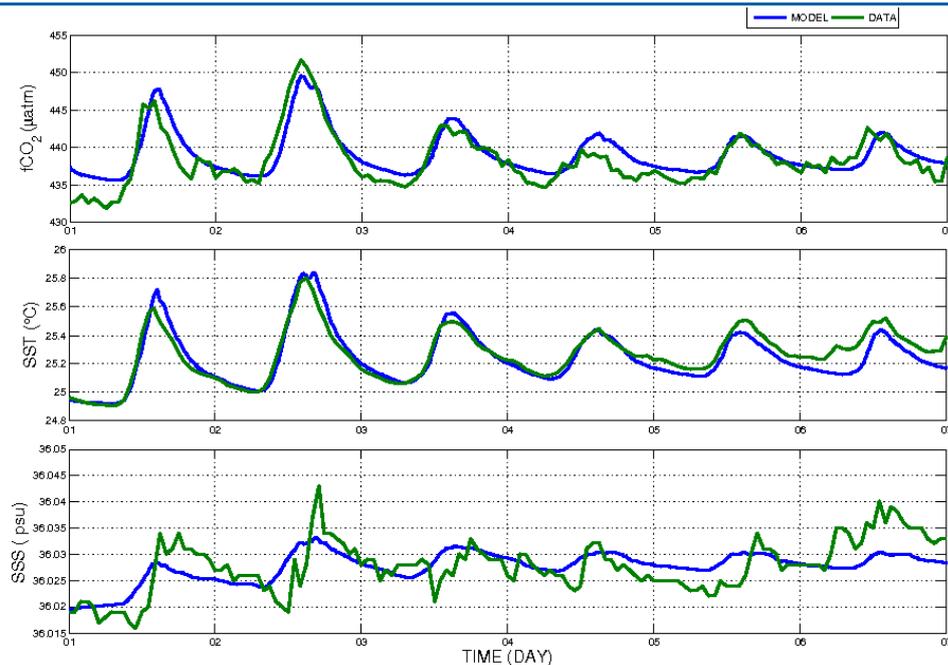


Figure 6

Comparison of the modelled diurnal cycles of $f\text{CO}_2$, SST and SSS (in blue) at 6°S , 10°W with the observations (in green) from 1 to 7 December 2006

During this period, the amplitude of the $f\text{CO}_2$ diurnal cycle ranges between $7 \mu\text{atm}$ and $17 \mu\text{atm}$ and the amplitude of the SST diurnal cycle amplitude is 0.5°C . The $f\text{CO}_2$ variations follow the SST with an increase of $f\text{CO}_2$ associated with an increase of SST of the order of $4\%/^\circ\text{C}$, which is the increase expected when thermodynamic processes dominate the $f\text{CO}_2$ variability.

A one dimensional model (Gaspar et al., 1990) including a biological model (Taylor et al., 1991) simulates the high frequency variability of $f\text{CO}_2$ measured at 6°S , 10°W during this period (Figure 6). The simulation confirms that the main factor influencing the $f\text{CO}_2$ variability is the thermodynamic effect: the seawater water causes an increase of $f\text{CO}_2$ of $4\%/^\circ\text{C}$. Similar diurnal cycles are observed throughout the time-series for both $f\text{CO}_2$ and O_2 . The main processes are the thermodynamic effect and the biological activity.

Conclusion

The CO₂ monitoring in the tropical Atlantic highlighted the high variability of the $f\text{CO}_2$ on spatial and temporal scales. A strong north-south gradient of $f\text{CO}_2$ is observed between the two current systems of the NECC and SEC. Along the track of the *Monte Olivia* a sink of CO₂ is even observed throughout the year between 2°N and 10°N . If this feature applies to the whole zonal band, current estimates of the CO₂ budget in the tropical Atlantic might be overestimated. In addition, the western tropical Atlantic shows a sink of CO₂ caused by the Amazon outflow and the propagation of Amazon waters can contribute to the low $f\text{CO}_2$ observed further east during the periods of the retroflexion of the North Brazil Current.

In the SEC, high $f\text{CO}_2$ are observed but the time-series of $f\text{CO}_2$ shows an unexpected decrease in June. The cause of the decrease is not well understood but it is probably linked to the features of the ocean circulation. Also, the current record is not long enough to conclude that this happens every year. However, this location is a source of CO₂ throughout the year with a maximum occurring in October for the years 2006 and 2007, slightly after the upwelling season. This is due to the warming of the recently upwelled waters.

Outputs of the Mercator ocean circulation model will be used to document the oceanic circulation and to relate it to the $f\text{CO}_2$ features observed along the tracks of the ships and at 6°S , 10°W in a broader region. In particular, it will be useful to determine whether the boundaries of the sources and sinks regions are associated with the displacement of oceanic fronts.

Monitoring the tropical Atlantic will help in providing accurate CO₂ budgets of the tropical Atlantic. This should also assess whether the CO₂ undersaturated area significantly affect the magnitude of the source of CO₂ in the tropical Atlantic.

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References

- Andrié, C. Oudot, C. Genthon, C., and Merlivat L. 1986 CO₂ fluxes in the tropical Atlantic during FOCAL cruises, *Journal of Geophysical Research*, 91 (C10), 11,741-11,755.
- Cooley, S.R., V.J. Coles, A. Subramaniam, and P.L. Yager, 2007: Seasonal variations in the Amazon plume-related atmospheric carbon sink, *Global Biogeochemical Cycles*, 21, doi:10.1029/2006GB002831.
- Fratantoni, D.M., and D.A. Glickson, 2001: North Brazil Current ring generation and evolution observed with SeaWiFS, *Journal of physical Oceanography*, 32, 1058-1074.
- Gaspar, P., Y. Gregoris, and J.M. Lefèvre, 1990: A simple eddy kinetic energy model for simulations of the oceanic vertical mixing: Tests at station Papa and Long-Term Upper Ocean Study Site site, *Journal of Geophysical Research*, 95, 16,179-16,193.
- Hood, E.M., and Merlivat, L. 2001: Annual to interannual variations of fCO₂ in the northwestern Mediterranean Sea: Results from hourly measurements made by CARIOCA buoys, 1995-1997. *J. of Mar. Res.*, 59 (1): 113-131.
- Körtzinger, A. 2003: A significant sink of CO₂ in the tropical Atlantic Ocean associated with the Amazon River plume, *Geophysical Research Letters*, 30(24), 2287, doi:10.1029/2003GL018841.
- Lefèvre, N., G. Moore, J. Aiken, A. Watson, D. Cooper, and R. Ling, 1998: Variability of pCO₂ in the tropical Atlantic in 1995, *Journal of Geophysical Research*, 103 (C3), 5623-5634.
- Lefèvre, N., A.J. Watson, A.J., Olsen, A., Rios, A.F., Perez, F.F., and Johannessen, T. 2004: A decrease in the sink for atmospheric CO₂ in the North Atlantic, *Geophysical Research Letters*, 31 (L07306), doi:10.1029/2003GL018957.
- Lefèvre, N., A. Guillot, L. Beaumont, and T. Danguy, 2008: Variability of fCO₂ in the Eastern Tropical Atlantic from a moored buoy, *Journal of Geophysical Research*, 113, C01015, doi:10.1029/2007JC004146.
- Lefèvre, N., 2009: Low CO₂ concentrations in the Gulf of Guinea during the upwelling season in 2006, *Marine Chemistry*, 113, 93-101.
- Mayorga, E., A.K. Aufdenkampe, M. C.A. Masiello, A.V. Krusche, J.I. Hedges, P.D. Quay, J.E. Richey, and T.A. Brown, 2005: Young organic matter as a source of carbon dioxide outgassing from Amazonian rivers, *Nature*, 436, 538-541.
- Oudot, C., C. Andrié, and Y. Montel, 1987 : Evolution du CO₂ océanique et atmosphérique sur la période 1982-1984 dans l'Atlantique tropical, *Deep Sea Research*, 34 (7), 1107-1137.
- Oudot, C., J.F. Ternon, and J. Lecomte, 1995: Measurements of atmospheric and oceanic CO₂ in the tropical Atlantic: 10 years after the 1982-1984 FOCAL cruises, *Tellus*, 47B, 70-85.
- Richey, J.E., J.M. Melack, A.K. Aufdenkampe, V.M. Ballester, and L.L. Hess, 2002: Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO₂, *Nature*, 416, 617-620.
- Schuster, U., and Watson, A.J. 2007: A variable and decreasing sink for atmospheric CO₂ in the North Atlantic, *Journal of Geophysical Research*, 112, doi:10.1029/2006JC003941.
- Takahashi, T., S.C. Sutherland, R. Wanninkhof, C. Sweeney, R.A. Feely, D. Chipman, B. Hales, G.E. Friederich, F.P. Chavez, A. Watson, D.C.E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, Y. Nojiri, C. Sabine, J. Olafsson, T.S. Arnasson, B. Tilbrook, T. Johannessen, A. Olsen, R.G.J. Bellerby, A. Kortzinger, T. Steinhoff, M. Hoppema, H.J.W. De Baar, C.S. Wong, B. Delille, and N.R. Bates, 2009: Climatological mean and decadal change in surface ocean pCO₂, and net sea-air CO₂ flux over the global oceans, *Deep Sea Research*, doi:10.1016/j.dsr2.2008.12.009.
- Taylor, A.H., A.J. Watson, M. Ainsworth, J.E. Robertson, and D.R. Turner, A modelling investigation of the role of phytoplankton in the balance of carbon at the surface of the North Atlantic, *Global Biogeochemical Cycles*, 5, 151-171, 1991.
- Ternon, J.F., Oudot, C., Dessier, A., and Diverres, D. 2000: A seasonal tropical sink for atmospheric CO₂ in the Atlantic ocean: the role of the Amazon River discharge, *Marine Chemistry*, 68 (3), 183-201.

Mercator-Vert: Extension towards Marine Resources

By Patrick Lehodey¹, Inna Senina¹, Julien Jouanno¹, Francois Royer¹, Philippe Gaspar¹, Beatriz Calmettes¹, Mélanie Abécassis^{1,2}, Jeffrey Polovina², George Balazs², Molly Lutcavage³ and John Sibert⁴

¹ MEMMS (Modélisation des Ecosystèmes Marins et Monitoring par Satellites), CLS, Département Oceanographie Spatiale, 8-10 rue Hermes, 31520, Ramonville, France

² NOAA, NMFS Pacific Islands Fisheries Science Center, Honolulu Hawaii, USA

³ Large pelagic Research Center, University of New Hampshire, USA

⁴ Pelagic Fisheries Research Project, University of Hawaii, USA

Abstract

The "MERCATOR-VERT" project is working on a prototype of coupled physical/ biogeochemical model with the objective to routinely estimate and forecast the biogeochemical variables of the global ocean. Such operational models should provide in a near future the necessary inputs for ecosystem models of the upper trophic levels, allowing the development of new tools and products for a real-time management and monitoring of marine ecosystems and resources. An original approach is presented here and illustrated with examples of potential applications.

Introduction

The principal objective of the Reinforced Partnership Project (PPR) "MERCATOR-VERT" was to implement a marine biogeochemical and ecosystem component into the MERCATOR operational system. The prototype of a coupled physical/biological assimilation system has been developed with the objective to routinely estimate and forecast biogeochemical variables over the globe using the Mercator operational setup (Brasseur et al., 2005). The biogeochemical model component is PISCES, which simulates 24 biogeochemical/ecological variables representing four plankton functional types (nano-phytoplankton, diatoms, meso- and micro-zooplankton) and co-limitations by N, P, Si, Fe and light (Aumont et al., 2004).

Achieving realistic high resolution and operational prediction of the "green" ocean is a challenge that still embraces technical and scientific issues, e.g., the high resolution, the data assimilation techniques, or the regional and coastal downscaling (Brasseur et al. 2009). Good progress in these different domains are expected in the coming few years, and we need to develop without delay the new tools that based on these achievements will serve for a modern management and monitoring of exploited and protected marine species. Thus, a work package of the MERCATOR VERT project was proposed as a first step to demonstrate the interest of the operational oceanography for the study and management of exploited marine resources, in particular for large pelagic species that are either targeted by fisheries (e.g., tunas, swordfish and marlin), strictly controlled in the by-catch (bluefin, sharks, ...), or fully protected (turtles, seabirds, and marine mammals).

The first necessary step, and the main objective of MERCATOR VERT, is to produce reliable predictions of the physical-biogeochemical oceanic environment. These predictions are the basic input needed to develop ecosystem models of higher biological levels. One key explanatory variable that is usually missing to understand individual behaviour to population dynamics of large oceanic predators is the dynamic of their prey species, i.e., the micronekton that is at the Mid-Trophic Level (MTL) in the ecosystem. By definition, micronekton are small organisms that can swim, but due to their small sizes they are however strongly impacted by oceanic circulation from large to mesoscale. Existing modeling approaches to describe the basin-scale spatiotemporal dynamics of MTL are still rare and in an early stage of development. We present one approach that considers a definition of several mid-trophic functional groups and a modeling based on physical and biogeochemical variables. Once a reasonable prediction of MTL organisms is achieved, the number of applications for real-time management and monitoring of marine resources should increase rapidly, as illustrated by the few examples provided in the following sections.

Bridging the gap: modeling the Mid-Trophic Level

Despite their central position in the marine ecosystem, pelagic mid-trophic species are virtually unknown because they are not exploited and cannot be observed through a continuous synoptic approach, i.e., with satellites. Developing modeling approaches that capture the essential features of these organisms is thus a critical and challenging step for a better understanding of the ocean ecosystem. At global scale, simple ecological theory, using primary production and temperature as inputs, can be used to formulate a model for predicting potential biomass, production, size and trophic structure of consumer communities (Jennings et al 2008). This approach is useful to provide a first baseline of absolute biomass by a range of organisms' body weight. A more elaborate approach that includes size-structure and energy flow is developed by Maury et al. (2007). This model incorporates much more details in physiology derived from the Dynamic Energy Budget theory (Kooijman, 1986), with spatial dynamics based on a system of advection-diffusion-reaction (ADR) equations that take into account ocean circulation. A third original approach is used in the

Spatial Ecosystem And POPulation DYNAMics Model (SEAPODYM), coupling a spatial age-structured population dynamics model of large oceanic predator (Lehodey et al. 2008) with a MTL model (Lehodey et al., *in press*). The SEAPODYM-MTL is also based on an ADR system of equations but rather than a size spectrum, it describes several functional groups following a temperature-linked time development relationship.

The functional groups in SEAPODYM-MTL are based on the vertical behaviour of organisms.

Indeed, one distinctive characteristic of most of these organisms is to perform daily vertical migrations, moving between deep layers during the day to the surface layer at night. This evolutionary adaptation likely decreases the predation pressure during the day in the upper layer. The essential result is that the flow of energy generated by autotrophic organisms in the euphotic surface layer is transferred to the deeper layers known as meso- and bathy-pelagic layers. Acoustic and micronekton sampling studies indicate that most of the micronekton biomass occupies the meso- and bathy-pelagic layers during the day, while ~50% is concentrated during the night in the first hundred meters.

Predators of these mid-trophic organisms have evolved to prey upon these species, i.e., either they chase the prey species migrating in the layer they inhabit, or they make temporary excursions in the layers where these species remain. Through evolution, the predators have thus developed sensory, morphological and physiological adaptations allowing them to exploit cold, dark and sometimes oxygen depleted deep layers. Hence, vertical movements appear to be a key process in structuring the ocean ecosystem, and therefore an essential mechanism that has to be accounted for when designing a functional view of the system.

Following this idea, and based on existing knowledge, a simple conceptual model of the mid-trophic level components can be proposed with six functional groups in three vertical layers: epipelagic, mesopelagic and bathypelagic (Figure 1). The pelagic micronekton is therefore divided into epipelagic, mesopelagic and bathypelagic groups, the last two groups being subdivided into vertically migrant and non-migrant species. Since light intensity is likely a major factor that controls diel vertical migrations of meso- and bathypelagic organisms, the euphotic depth appears as a logical and convenient way to define the vertical boundaries of the three layers. Preliminary examinations of predicted euphotic depths from biogeochemical models indicate that using the euphotic depth as the boundary for the epipelagic layer and defining the boundary between meso- and bathypelagic layers by three times the euphotic depth would produce values similar to those defined from biological observations, e.g., between 50 and 150 m for epipelagic and 150 and 450 m for mesopelagic layers in the eastern and western tropical Pacific Ocean respectively.

Recruitment, ageing, mortality and passive transport with horizontal currents are modeled by a system of ADR equations, taking into account the vertical behavior of organisms. Since the dynamics is represented by the established relationship of temperature-linked time development, there are only six parameters in the model that have to be estimated. The first one (E) defines the total energy transfer between primary production and all the MTL groups. The others are the relative coefficients (E'_n) redistributing this energy through the different components (the sum of which being 1). The parameterization of E requires absolute biomass estimates of MTL, while the matrix of E'_n coefficients can be estimated simply using relative day and night values integrated in the three vertical layers of the model. In lieu of existing *in situ* data, the six parameters of the MTL sub-model are currently tuned according to limited information from the literature (Lehodey et al., *in press*).

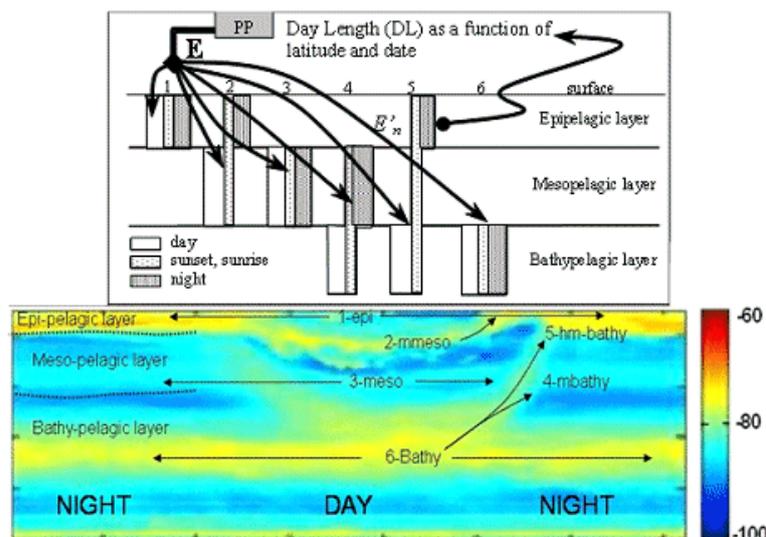


Figure 1

Mid-trophic functional groups. Top: conceptual model of mid-trophic functional groups in SEAPODYM. Middle: echogram showing monthly average (Nov 2004) diurnal variation from the stationary lander located at the Mid Atlantic Ridge (MarEco project; kindly from Nils Olav Handegard, IMR, Norway) with identified mid-trophic groups (m- for migrant and hm- for highly-migrant)

First high resolution simulations using MERCATOR reanalyses

During the last few years, the model SEAPODYM has been developed and applied to tropical Pacific tuna species using low resolution basin-scale reanalyses of the physical-biogeochemical oceanic environment. Typically, such applications are used to investigate the large-scale dynamics of tuna species over the historical fishing period (the last 50 years) under the influence of both the fishing activity and the environmental variability (Lehodey et al. 2008; Senina et al. 2008; Lehodey et al., 2009a). At this stage of development, these studies did not require a representation of the ocean mesoscale activity. However, this latter becomes necessary for achieving further progress and especially to develop future near-real time monitoring applications.

Realistic mesoscale prediction has been achieved in ocean circulation models using assimilation of satellite data (altimetry and SST in particular). Similarly, appropriate assimilation of ocean color satellite data in biogeochemical models should help to obtain sufficiently realistic outputs to connect higher biological levels to these ocean models. As an immediate alternative, primary production can also be deduced from satellite-derived data, for example using the VGPM model of Behrenfeld and Falkowsky (1997). In that case, a clear advantage is to obtain, thanks to the assimilation in the MERCATOR model, a very good match between physics and primary production at the mesoscale level (Figure 2). With the project GLORYS (GLobal Ocean ReanalYsis and Simulations) that is supported by the French Groupe Mission Mercator Coriolis, a first eddy permitting global ocean reanalysis has been produced with the ocean general circulation model configuration ORCA025 NEMO (Barnier et al., 2006). The assimilation method is based on a reduced order Kalman filter (SEEK formulation, Pham et al. 1998) adapted to eddy permitting global ocean model configuration (Tranchant et al., 2008). Such an ocean reanalysis can be used with satellite derived primary production to run a simulation with the SEAPODYM-MTL model (Figure 2). Then, this physical and biological predicted oceanic environment will be used in several studies with the objective of predicting the feeding habitat of some key species. Two examples are presented below.

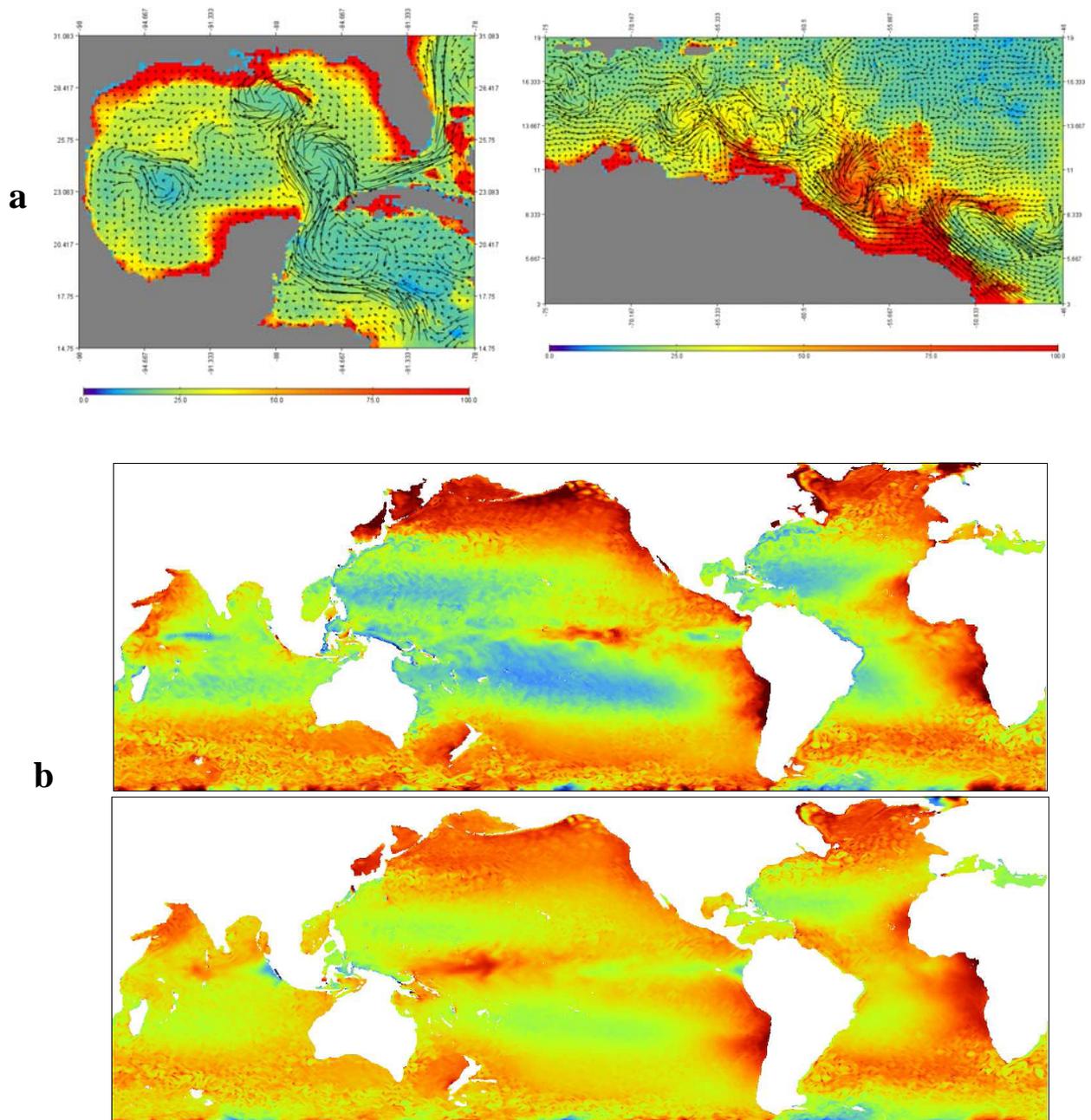


Figure 2

First MTL simulations using Mercator products. *a*) Snapshots showing the SeaWiFS-derived primary production (<http://www.science.oregonstate.edu/ocean.productivity/>) with superimposed surface currents (average in the euphotic layer) predicted in MERCATOR GLORYS reanalysis. *b*) Prediction for the week centered on 7 April 2003 of the biomass of non-migrant mid-trophic functional groups using MERCATOR GLORYS1V1 reanalysis and satellite-derived primary production. From top to bottom: epipelagic, mesopelagic and bathypelagic. Note that the colorscale vary from 0 (deep blue) to 2 (deep red) g m^{-2} for epi- and mesopelagic biomass, but from 0 to 6 for bathypelagic

Predicting bluefin tuna habitat

Atlantic and Mediterranean bluefin (*Thunnus thynnus*, or ABFT) is considered severely overexploited and the International Commission for the Conservation of Atlantic Tunas (ICCAT 2007) in charge of the management of this species has established a recovery plan for the coming few years. Due to high commercial value, other bluefin tuna species, in the North and south Pacific, are also facing high rates of exploitation and need to be carefully monitored. Already, the Australian fishing agency has implemented a regulation of its longline fisheries on the eastern coast based on bluefin habitat maps predicted every two weeks

(Hobday and Hartmann 2006). These habitat maps, simply based on a temperature preference relationship of the species, inform the fishermen that are not allowed to catch bluefin tuna in the areas they should avoid.

At the scale of an ocean however, such a habitat definition based on temperature only would cover a very large portion of the basin. Defining the feeding habitat by combining temperature preferences with prey fields would give a much more focused prediction that could be used by fishing agencies. This is the objective of a one year project funded by the Large Pelagic Research Center (LPRC) of the University of New Hampshire (USA), with the challenge of directly assimilating movement data from electronic tags in the model of habitat as defined in SEAPODYM (Lehodey et al. 2009b). Preliminary tests have shown already that the definition of the feeding habitat combining the distribution of mid-trophic groups and the accessibility to them by the bluefin in relation to its temperature preferences was sufficient to capture the seasonal habitat changes (Figure 4) in the north-west Atlantic.

Despite the fact that the physical reanalysis did not yet include data assimilation at this preliminary stage of the study, the seasonal variability and mesoscale activity of predicted bluefin feeding habitat matched fairly well the movements of individual bluefin (Figure 3) deduced from satellite tags (Lutcavage et al., 2000; Royer et al., 2008). Interestingly, the same habitat definition seems to be also valid in the Mediterranean Sea (Figure 3), indicating a very good robustness of the results and the model. These encouraging results suggest that an optimal model calibration could be achieved by assimilating these tagging data.

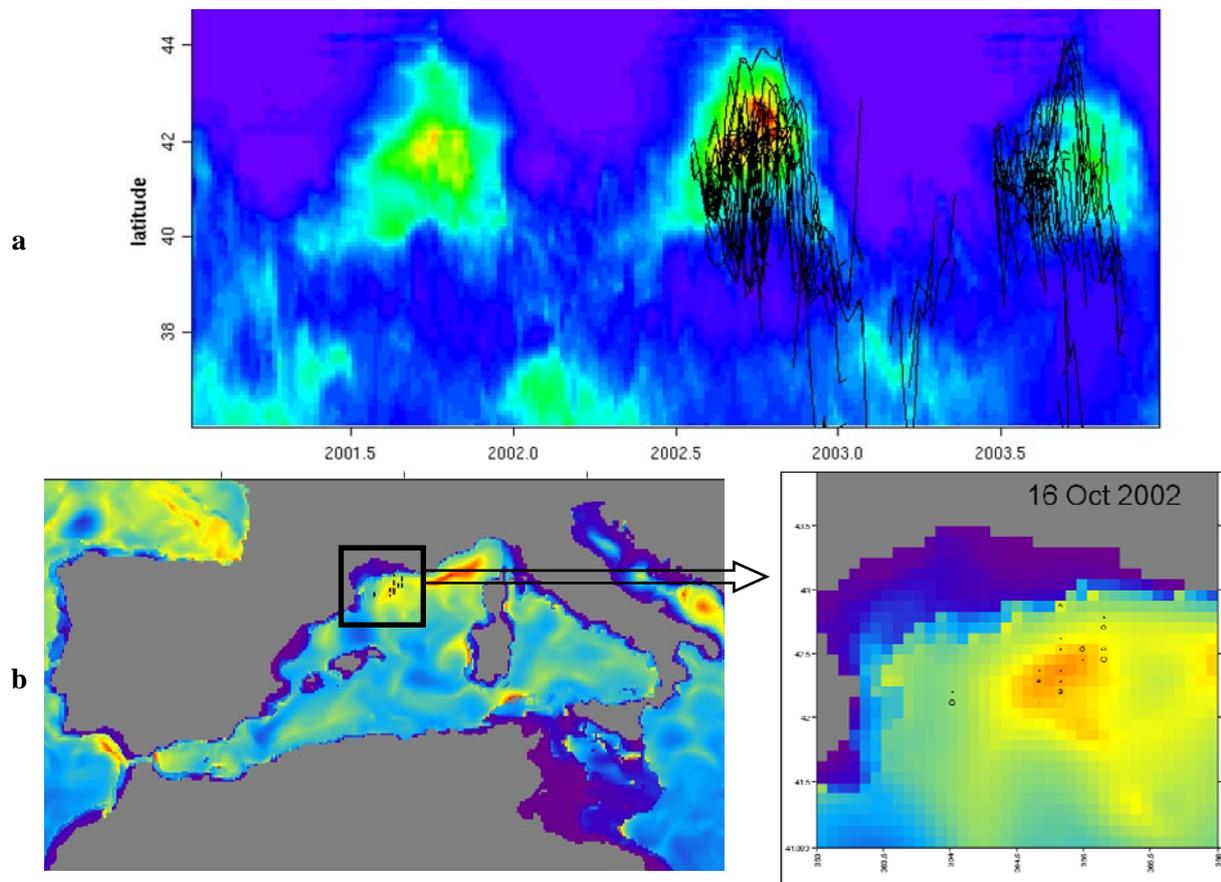


Figure 3

Bluefin tuna. a) Time-longitude Hovmöller diagram for the geographical box 36°N-45°N; 70°W-56°W showing the superimposition of all bluefin tracks tagged in the north-west Atlantic with satellite tags on the predicted feeding habitat. b) Bluefin tuna habitat in the Mediterranean Sea predicted for the week centred on the 16 Oct 2002 with a zoom in the Gulf of Lyon, where juveniles bluefin tuna schools (circles) were identified during aerial surveys during the same week (Royer et al., 2004). Circles are proportional to the size of the schools

Sea turtle by-catch in longline fisheries

With the increasing evidence of dramatic decline in several sea turtle populations in all oceanic regions, the capture of sea turtles in pelagic longline fisheries has gained recent international attention (FAO 2004). Though longline fisheries are only one of the anthropogenic mortality sources faced by these species, they are actually considered as the first reason for marine turtle populations decline worldwide (FAO 2004), especially since the loss of late juveniles and adults has a more dramatic impact on populations than the loss of younger individuals (eggs, hatchlings and younger juveniles) (Crouse et al, 1987; NRC, 1990).

Therefore, though protection of nestling sites is critical, this measure will be unsuccessful without effective protection of large juveniles and adults in the High Seas. Several declining populations have rapidly recovered once mortality caused by this activity was reduced (NMFS-SEFSC, 2001).

Six of the seven recognized marine turtle species are endangered, while there is insufficient information to determine the conservation status of the seventh species (IUCN 2003). Among these species, leatherback (*Dermochelys coriacea*), and loggerhead (*Caretta caretta*) sea turtles that are sometimes caught by the longline boats, especially those targeting swordfish with shallow longlines, are critically endangered. In response to the threat of extinction of these species, the Hawaiian longline swordfish fishery was first closed for over 4 years, then re-opened under strict management measures, including prescribed use of large circle hooks and fish bait, restricted annual effort, annual limits on turtle captures and 100% onboard observer coverage because of turtle interactions (US NMFS 2004).

In concert with initiatives to address other priority threats to sea turtles, actions to reduce longline fisheries by-catch of sea turtles can contribute to the recovery of turtle populations (FAO 2004). It is thus critically required to identify where marine turtles meet fisheries, and how lethal interactions can be appropriately reduced. An obvious strategy to reduce sea turtle by-catch is to avoid by-catch hotspots through fleet communication programmes and area and seasonal closures. To develop and encourage this approach, scientists need first to define statistically and mechanistically the relationships between the ocean conditions and the presence/absence of turtle species on swordfish fishing grounds, or in other terms, to model the turtle habitats. Then it will become possible to predict and forecast these habitats and to communicate with fishermen in real time to help them avoid turtle by-catch.

In the North Pacific, the pelagic habitat of loggerhead turtles has been fairly well described as a result of considerable electronic tagging (Polovina et al., 2004; Kobayashi et al., 2008). In Hawaii, the Pacific Islands Fisheries Science Center (NOAA, USA) used this information to obtain a preliminary understanding of the thermal characteristics of this species habitat, and then to routinely update experimental maps of this habitat (Howell et al., 2008). These maps are posted on a web site (TurtleWatch: <http://www.nmfs.hawaii.edu/eod/turtlewatch.php>) to help longline fishermen to avoid interactions with loggerhead turtles.

A 3-year on-going collaborative project with the Pacific Islands Fisheries Science Center has the objective of developing a model of both swordfish and loggerhead turtle habitats, using fishing and tagging data to define and analyze the pelagic feeding habitat and movements of both species following the mechanisms described in the model SEAPODYM. Once a reasonable parameterization is achieved, model simulations will be used to identify longline fishing strategies that maintain sustainable catches of swordfish while reducing turtle takes. Similarly in the Atlantic Ocean, a PhD study will start at the end of this year to analyse the movement and habitat of the leatherback turtle (*Dermochelys coriacea*).

As in the bluefin tuna case above, individual tracks of turtles suggest that these animals are strongly influenced by the dynamics of mesoscale eddies (Gaspar et al., 2006), and that they are not simply drifting with currents. This is clearly confirmed by our preliminary simulation experiments at low resolution (1/2 deg x month), forced by SODA physical fields (Carton et al., 2000) and SeaWiFS derived primary production. These simulations showed that when including active movements of animals following the gradient of their feeding habitat, that combines temperature preference and epipelagic MTL forage organisms, the resulting spatial distribution after one year gives a totally different result, but in much better agreement with the observations (Figure 4). We can expect that the higher resolution and realistic mesoscale activity from GLORYS reanalysis will help to quickly achieve substantial progress in the modeling of habitat and movements of turtles, as well as many other large pelagic animals.

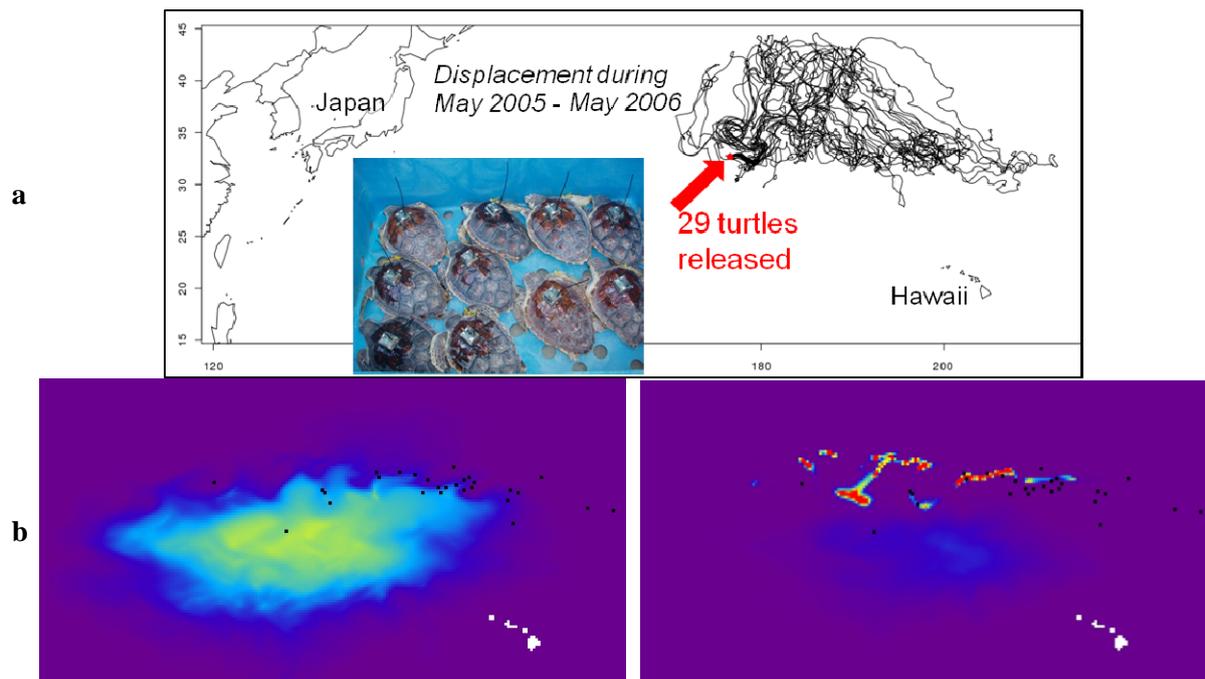


Figure 4

Sea turtles. a) One-year tracks of 29 loggerhead turtles released in the north Pacific in May 2006. b) Predicted distribution after one year of turtles released in the model at the same location and date, and showing the difference when using passive (left) and active (right) movements. Black points are observed positions of released turtles after one year

Conclusion

Marine ecosystems are facing increasing pressure due to anthropogenic activities (fisheries, pollution and climate change) that need to be managed in a holistic (ecosystem-based) and reactive way. While the real-time monitoring of fishing fleets is expanding worldwide with the development of vessel monitoring systems (VMS) – a necessary first step in the control of illegal fishing – the management of marine resources is still based in most cases on annual statistical stock assessment analyses ignoring the environmental and climate variability. Coupled ecosystem and population dynamics models should provide in a near future the new tools needed to move to an ecosystem-based management. These end-to-end ecosystem models will be driven in routine by ocean physical and biogeochemical forecasts. MERCATOR-VERT has been clearing the way towards this new approach. Already, we can envisage potential useful applications that can be developed on the basis of operational oceanography and satellite-derived primary production to manage and monitor exploited or protected species.

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References

- Aumont O., E. Maier-Reimer, S. Blain and P. Monfray (2003). An ecosystem model of the global ocean including Fe, Si, P colimitations. *Global Biogeochem Cycles* 17:1060, doi:10.1029/2001GB001745.
- Barnier et al., 2006: Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy permitting resolution. *Ocean Dynamics*, DOI: 10.1007/s10236-006-0082-1.
- Behrenfeld M.J., Falkowski P.G., (1997). A consumer's guide to phytoplankton primary productivity models. *Limnol. Oceanogr.* 42(7): 1479-1491.
- Bhat, G.S., Vecchi, G.A., Gadgil, S. (2004). Sea surface temperature of the Bay of Bengal derived from the TRMM Microwave Imager. *J. Atmos. Ocean. Technol.* 21:1283–1290.

- Brasseur P., P. Bahrel, L. Bertino, F. Birol, J.-M. Brankart, N. Ferry, S. Losa, E. Rémy, J. Schröter, S. Skachko, C.-E. Testut, B. Tranchant, P.J. van Leeuwen, Verron, J. (2005). Data Assimilation for marine monitoring and prediction: The MERCATOR operational assimilation systems and the MERSEA developments, *Q. J. R. Met. Soc.*, 131: 3561-3582.
- Brasseur, P., Gruber, N., Barciela, R., Brander, K., Doron, M., El Moussaoui, A., Hobday, A., J., Huret, M., Kremer, A.-S., Lehodey, P., Matear R., Moulin, C., Murtugudde, R., Senina, I., Svendsen, E. (2009). Integrating Biogeochemistry and Ecology Into Ocean Data Assimilation Systems. *Oceanography* 22, 3: 206-215
- Carton, J.A., G. Chepurin, Cao, X. (2000). A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995 Part 2: results. *J. Phys. Oceanogr.*, 30: 311-326.
- Crouse D.T., Crowder L.B., Caswell, F. (1987). A stage-based population model for loggerhead sea turtles and implication for conservation. *Ecology* 68: 1412-1423
- FAO (2004). Expert Consultation on Interaction between Sea Turtles and Fisheries within an ecosystem context. FAO Fisheries Report No 738. Food and Agriculture Organisation of the United Nations, Rome.
- Gaspar, P., Georges, J.-Y., Fossette, S., Lenoble, A., Ferraroli S., Le Maho, Y. (2006). Marine animal behaviour: neglecting ocean currents can lead us up the wrong track. *Proceedings of the Royal Society (B)*, 273: 2697-2702
- Hobday, A., J., Hartmann, K. (2006). Near real-time spatial management based on habitat predictions for a longline bycatch species. *Fisheries Management and Ecology* 13: 365-380.
- Howell, E.A., Kobayashi, D.R., Parker D.M., Balazs, G.H, Polovina, J.J. (2008). TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. *Endang. Species Res.*, 5: 267-278
- IUCN (2003). IUCN Red List of threatened species. International Union for Conservation of Nature and Natural Resources, Species Survival Commission, Red List Programme, Cambridge, UK and Gland, Switzerland
- Jennings, S., Mélin, F., Blanchard, J. L., Forster, R.M., Dulvy, N. K., Wilson, R. W. (2008). Global-scale predictions of community and ecosystem properties from simple ecological theory. *Proc. R. Soc. B.* 275: 1375-1383.
- Kobayashi, D.R., J. J. Polovina, D. M. Parker, N. Kamezaki, I. Cheng, I. Uchida, P. Dutton, Balazs, G. (2008). Pelagic habitat characterization of loggerhead sea turtles, *Caretta caretta*, in the North Pacific Ocean (1997-2006): Insights from satellite tag tracking and remotely sensed data. *Journal of Experimental Marine Biology and Ecology* 356: 96-114.
- Kooijman, S. A. L. M. (1986). Energy budgets can explain body size relations. *J. Theor. Biol.*, 121: 269-282.
- Lehodey P., Murtugudde R., Senina I. (in press). Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography* (2009), doi:10.1016/j.pocean.2009.09.008
- Lehodey P., Senina, I., Royer, F., Jouanno, J., Sibert, J., Lutcavage, M., Gaspar, P., & Fromentin, J.-M. (2009b). Parameter estimation of habitat driven spatial dynamics of Atlantic bluefin tuna with tagging data. *GLOBEC Newsletter* 15 (1): 17-19
- Lehodey, P. Senina, I. (2009a). An update of recent developments and applications of the SEAPODYM model. 5th regular Session of the Scientific Committee of the Western Central Pacific Fisheries Commission, 10-21 August 2009, Port Vila, Vanuatu, WCPFC-SC5-2009/EB-WP-10. (<http://www.wcpfc.int/meetings/2009/5th-regular-session-0>)
- Lehodey, P., Senina, I., Murtugudde, R. (2008). A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) – Modeling of tuna and tuna-like populations. *Progress in Oceanography*, 78: 304-318.
- Lutcavage, M.E, Brill, R.W., Goldstein, J.L., Skomal, G.B., Chase, B.C., and J. Tutein. 2000. Movements and behavior of adult North Atlantic bluefin tuna (*Thunnus thynnus*) in the northwest Atlantic determined using ultrasonic telemetry. *Marine Biology* 137: 347-358.
- Maury, O., Faugeras, B., Shina, Y.-J., Poggialeb, J.-C., Ben Aria, T., Marsac, F. (2007). Modeling environmental effects on the size-structured energy flow through marine ecosystems. Part 1: The model. *Progress in Oceanography*, 74: 479-499.
- National Research Council (1990). Decline of the sea turtles. Causes and prevention. National Academy Press, Washington, DC. 259 pp.
- NMFS-SEFSC (2001). Stock Assessments of Loggerhead and Leatherback Sea Turtles and An Assessment of the Impact of the Pelagic Longline Fishery on the Loggerhead and Leatherback Sea Turtles of the Western North Atlantic. NOAA Technical Memorandum, NMFS-SEFSC-455, 226 pp.
- Pham, D. T., Verron, J., Roubaud, M.C. (1998). A singular evolutive extended Kalman filter for data assimilation in oceanography, *Journal of Marine Systems*, 16, 323-340.

Polovina, J.J., Balazs, G.H., Howell, E.A, Parker, D.M., Seki, M.P., Dutton, P.H. (2004). Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific Ocean. *Fish. Oceanogr.*

Royer F., Fromentin, J.-M., Gaspar, P. (2004). Association between bluefin tuna schools and oceanic features in the western Mediterranean. *Mar. Ecol. Prog. Ser.*, 269: 249-263.

Royer F, Wilson S, Lutcavage M (2008) Spatial dynamics of Atlantic bluefin tuna in the North-Western Atlantic: Seasonal distribution, depth behavior and effect of the Gulf Stream variability. *Marine Ecology Progress Series*. In press

Senina, I., Sibert, J., Lehodey, P. (2008). Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: Application to skipjack tuna. *Progress in Oceanography*, 78: 319-335.

Tranchant, B., Testut, C.-E., Renault, L., Ferry, N., Birol, F., Brasseur P. (2008). Expected impact of the future SMOS and Aquarius Ocean surface salinity missions in the Mercator Ocean operational systems: New perspectives to monitor the ocean circulation. *Remote Sensing of Environment*, 112, 1476-1487.

US NMFS (2004). Endangered species Act Section 7 Consultation. Biological Opinion. Proposed Regulatory Amendments to the Fisheries Management Plan for the Pelagic Fisheries of the Western Pacific Region. Pacific Islands Regional Office, Honolulu, HI, USA.

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Contact :

Please send us your comments to the following e-mail address: webmaster@mercator-ocean.fr

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