GUIDELINES TOWARDS AN INTEGRATED OCEAN OBSERVATION SYSTEM FOR ECOSYSTEMS AND BIOGEOCHEMICAL CYCLES

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ABSTRACT

The observation of biogeochemical cycles and ecosystems has traditionally been based on ship-based platforms. The obvious consequence is that the measured properties have been dramatically undersampled. Recent technological advances in miniature, low power biogeochemical sensors and autonomous platforms open remarkable perspectives for observing the "biological" ocean, notably at critical spatio-temporal scales which have been out of reach until present. The availability of this new observation technology thus makes it possible to envision the development of a globally integrated observation system that would serve both scientific as well as operational needs. This in situ system should be fully designed and implemented in tight synergy with two other essential elements of an ocean observation system, first satellite ocean color radiometry and second advanced numerical models of biogeochemical cycles and ecosystems.

This paper gives guidelines and recommendations for the design of such system. The core biological and biogeochemical variables to be implemented are first reviewed, trying also to identify those for which the observational demand is high although the technology is not yet mature. A review of the five platforms now available (gliders, floats, animals with sensors, mooring at eulerian site and ships) allows their specific strengths with regards to biological and biogeochemical observations to be identified as well as to point out the community plans with respect to ongoing implementation. The critical issue of data management is addressed, acknowledging that the availability of

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tremendous amounts of data allowed by these technological advances will require an extraordinary effort on behalf of the community with respect to data management, i.e. data availability in open access and the development of various quality control procedures (in real time as well as delayed mode).

Because physical forcing determines the response of the biological and biogeochemical system, it is possible and highly desirable for maximum utility that the new technology will allow the measurement of physical and biological variables to be conducted at the same resolution. Similarly, the obvious complementarities between satellite ocean color radiometry, which is synoptic but limited to the surface layer, with in situ measurements, which extend the satellite data into the ocean interior, have to be the starting point for developing fully 3D/4D assimilative forecasts of the biological ocean. Finally, while implementing a globally integrated system is obviously the long-term target for our community, we recommend starting "simple" by implementing the concept of such an integrated system first at the regional scale. It is proposed to begin to study regional biogeochemical hot spots of global biogeochemical relevance. For example, the Eastern boundary currents with associated oxygen minimum zones, as well as the North Atlantic, could represent interesting "super site" case studies where an international coordinated effort could be undertaken for such "prototype" integrated systems to be set up.

1 AN UNDER-SAMPLED OCEAN: CONTEXT AND CHALLENGES

Physical forcing of the upper ocean accounts for much of the variability in oceanic biological and biogeochemical processes; in particular, it is responsible for nutrient injection in upper sunlit layers, which scales the level of photosynthetic production and hence elemental cycling, ecosystem structure, and the magnitude of living resources. Because climate change affects physical forcing (magnitude and variability) it is likely to alter the oceanic biological and biogeochemical response. Physical forcing (and associated biological responses) occurs over a continuum of spatial (sub-meso-/ meso-/ basin/ global) and temporal scales (diurnal, seasonal, decadal).

With respect to oceanic observations required to evaluate our changing oceanic environment, the last century can be described as a century of undersampling (Munk, 2000); this is especially true for biology and biogeochemistry. Our current understanding mostly relies on ship-based observations and a few time series. A large part of the variability in oceanic biological processes hence is not captured in the loose net of this traditional sampling.

Rapid technological advances in ocean observation have nevertheless been undertaken during the last decade, particularly with respect to physical climate variables. For example at the end of 2007, the international Argo program reached its goal (defined 8 years before) of deploying over 3000 autonomous profiling floats worldwide which are now regularly collecting temperature and salinity profiles oceanwide (Freeland et al., 2010). Within a few years, with such an exemplary program, physical oceanographers have been able to acquire tremendous amounts of data, allowing a variety of topics to be addressed, from the evolution of water mass properties as a result of climate change to the initialization and validation of models, including operational ones.

With a certain time lag, biological and biogeochemical oceanography is following a similar technological path. Thanks to the miniaturization of biological and biogeochemical sensors, biological oceanographers are beginning to develop and deploy biogeochemical floats (e.g. Körtzinger et al. 2004; Boss et al., 2008; Bishop and Wood, 2009) or gliders (e.g. Davis *et al*., 2008; Perry et al., 2008; Niewiadomska et al., 2008) which allow new observational scales in ocean biogeochemistry to be tackled. In parallel, certain marine mammals have now been equipped with biogeochemical sensors allowing sustained data acquisition to be initiated in areas where data scarcity is generally the rule (e.g. Boehme et al., 2010). Biological oceanography is thus emerging from its data-limited foundations.

Based on these technologies, pilot projects have been launched or are planed (Boehme et al., 2010; Claustre et al., 2010; Gruber, et al., 2010; Johnson et al., 2009, Testor et al., 2010). If, from these individual initiatives and biogeochemical pilot projects, we begin to think and implement in terms of networks, arrays and coordinated international efforts, we can expect a revolution in biogeochemical oceanography. Our community will have access to an unprecedented observational array of vertically resolved biogeochemical variables. Developing such an in situ automated observation system will constitute an essential step towards a better understanding of biogeochemical cycles and ecosystem dynamics, especially at spatial and temporal scales that have been unexplored until now. The present paper is focused on providing guidelines for implementing such a system over the next decade.

Two main outcomes can be expected from a well-designed integrated observation system. The scientific outcomes include a better exploration and an improved understanding of change and variability in ocean biology and biogeochemistry (over a large range of spatial and temporal scales). Associated with this, the reduction of uncertainties in the estimation of biogeochemical fluxes is an obvious target. Besides these primary scientific objectives, the operational (long-term) outcomes are the development of skillful predictions of ocean biogeochemistry and ecosystem dynamics as well as the delivery of real-time and open-access data to scientists, users and decision makers. Reduced uncertainties result in better policy.

Both scientific and operational objectives require the in situ system to be designed and implemented in tight synergy with two other essential bricks of an integrated ocean observation system: modeling and satellite observation.

Modeling biogeochemical cycles is now moving from an era of "simple" NPZD (Nitrate-Phytoplankton-Zooplankton-Detritus) models (Fasham et al., 1990) towards more complex models, the so-called Dynamic Green Ocean Models (DGOMs) taking explicitly into consideration the physiology of marine organisms through their grouping into plankton functional types (PFTs) (Lequéré et al., 2005). The elaboration of this new class of models has benefited from improved availability of biological data required to parameterize and validate/evaluate them. As well, new approaches to assimilation of biological and chemical data into these models is advancing rapidly (Brasseur et al. 2009). Notably, the progressive integration of biogeochemical variables in the next generation of operational oceanography systems is one of the long-term objectives of the GODAE OceanView international program (Le Traon et al., 2010). Nevertheless, and in view of refining these models for improving their representativeness and predictive capabilities, the presently available datasets remain too scarce. There is an obvious and imperative need to reinforce biological and biogeochemical data acquisition and to organize databases (Lequéré et al., 2010).

The pessimistic view of an under-sampled ocean with respect to its biogeochemical properties has to be tempered however since the availability of satellite ocean color radiometry (OCR) data. Satellite OCR is the only observational tool that can make synoptic measurements of the global ocean related directly to ecological and biogeochemical processes. Satellite OCR is now central in oceanographic research, particularly in studies of variability at meso-scale (10-100km) to ocean basin spatial scales and time scales ranging from days to inter-annual (Yoder and Kennelly 2006). Global estimates of ocean primary production are now based on satellite OCR data (Antoine et al., 1996; Behrenfeld and Falkowski, 1997; Behrenfeld et al., 2005). Time series have been built, from which climate-relevant trends can be extracted (Antoine et al., 2005; Polovina et al. 2008; Devred et al., 2009; Martinez et al., 2009). *In situ* and satellite data are highly complementary. While *in situ* data extend the satellite information into the ocean interior (unseen by the remote sensor) and provide indispensable sea truth data, the satellite data fills the gap of poor spatio-temporal resolution of *in situ* data. Besides Chl*a*, new « satellite » biogeochemical products are now being produced (e.g. Claustre et al., 2010), that also usefully serve the data requirements of the modeling community.

Taking into consideration that automatic *in situ* acquisition and remotely operated platforms appear as the future solution to (at least partly) circumvent the issue of under-sampling biogeochemical and ecosystem variables, the present paper aims at making the appropriate recommendations for developing and maintaining a sustained in situ observation system. It is organized as follows. We first identify the key variables, whose scientific relevance is acknowledged and whose autonomous measurements are now mature enough to become core variables of a future integrated observation system. We then complement this analysis by the review of other essential variables for which technologic refinement or even development are still required to become fully integrated in the next decade. The different observation platforms of the future ocean observation system are then presented with five *in situ* elements (floats, gliders, animals, time-series, ship repeated transects) complemented by OCR satellite. We emphasize the critical issue of developing and implementing a dedicated data management system which will be crucial for the operational and scientific success of this future observation system. Various aspects of the integration of the different components of the observation system are then analyzed in the context of developing synergies for the benefit of observation and scientific outputs. The paper concludes with a summary of recommendations.

2 SELECTING THE CORE "BIO-VARIABLES"

2.1. The core ecosystem and biogeochemical variables: which ones now?

Besides their scientific relevance (in particular with respect to modeling requirements) the key biogeochemical and ecosystem variables discussed here are primarily selected because they are amenable to non-intrusive and automatic measurements, ideally through miniature, low-power, *in situ* sensors (already developed or in development). Variables requiring water collection and sample manipulation, although essential in any sustained observation systems, are not considered in what follows (but will be evoked later, in particular for the issues of sensor calibration and for ship-based investigations).

2.1.1 Chemical variables and variables of the CO_2 system

Nitrate. Nitrate is a key variable in ocean biogeochemistry and is an essential state variable of biogeochemical models (Lequéré et al., 2010). Low concentrations in about 60% of the ocean limit rates of new primary production. In the remaining 40%, changes in nitrate can be used as a tracer of new primary production (e.g., Macready and Quay, 2001). Optical sensors for dissolved nitrate are now available (Johnson and Coletti, 2002). In combination with autonomous platforms, this sensor can be used to track nutrient injection events that may stimulate productivity in oligotrophic regions (e.g., Sakamoto et al., 2004) or to map plankton metabolism (Johnson and Needoba, 2008).

Oxygen. The oceanic dissolved oxygen concentration is a key quantity for ocean ecology and biogeochemistry. It permits study and quantification of a diverse and crucial set of processes, such as the magnitude and variability of net community and export production, the detection of the impact of global warming on ocean biogeochemistry and circulation, the assessment of changes in low oxygen regions, and improved estimates of the oceanic uptake of anthropogenic CO_2 (Gruber et al., 2010). Dissolved oxygen sensors that are both precise and stable over extended periods have been recently developed. They can be easily integrated with the currently used Argo floats. A few issues remain with respect to the overall accuracy and time constant of the sensors. In this regard further improvement is needed. Also, various calibration methods (laboratory vs. in-situ, potential use of atmospheric oxygen measurement by optode sensor as drift control, etc.) need to be further developed. In general, the sensor status currently achieved for autonomous measurement of oxygen in the ocean is impressive and perhaps most advanced in the realm of chemical sensors.

CO_2 system at fixed depth. Systematic and accurate measurements of variables of the CO_2 system are essential to document the evolving response of the ocean to anthropogenic inputs of carbon dioxide. Autonomous sensors for long-term subsurface measurement of the CO_2 partial pressure (pCO_2) have been commercially available for some time now. Two rather different measurement principles are followed: (1) Equilibration of a pH indicator dye solution (with specifically adjusted alkalinity) through a silicone membrane tube with ambient seawater. Depending on ambient pCO_2, a pH change in dye solution occurs that can be detected spectrophotometrically through variations in the concentrations of the corresponding dye species. (2) Membrane-based air-seawater equilibration with subsequent measurement of CO_2 concentration in the equilibrated gas by non-dispersive infrared detection (NDIR).

Both approaches can be used for subsurface pCO_2 measurements over extended period between several months to about 1 year. These sensors have been shown to be of great use in observing ocean variability such as on seasonal timescales (e.g. Körtzinger et al., 2008a;b) from stationary platforms such as moorings. The achievable accuracy is nevertheless significantly inferior to what is currently achieved with shipboard underway pCO_2 instruments based on air-water equilibration (~2-3 μatm).

2.1.2 Bulk bio-optical variables

Chlorophyll a is the discriminative proxy for phytoplankton biomass, a key variable in biogeochemical studies. It can be measured by fluorescence. Miniature fluorescence sensors are available to be mounted on a variety of platforms (e.g. gliders, floats, animals) (Boss et al., 2008; Niewiemdomska et al., 2008). When converting to biomass several issues need to be taken into account, e.g. variable pigment/carbon ratio and variable fluorescence/chlorophyll concentration ratio due to non-photochemical quenching, species composition, and temperature.

Optically-resolved Particulate Organic Carbon (POC). In open ocean waters, POC is the main source of particles and the load in particles is the main driver of water turbidity or transparency. Turbidity can be quantified by the measurement of the backscattering coefficient (backscattering-meter), while transparency is measured by the particle attenuation coefficient (transmissometer). Both optical measurements can be converted to a concentration of POC with a reasonable accuracy (e.g. Bishop and Wood, 2009). Variability in the conversion factor exists due to potential presence of inorganic compounds (e.g. cocolithophores' lith) and variability in size and composition in the POC.

2.2. The core ecosystem and biogeochemical variables: which ones next?

Because a very long time frame is involved from the bench top prototypes to operational sensors (Brasseur et al., 2010), few variables are amenable to automatic *in situ* measurements by remotely operated platforms. There is nevertheless very active research aiming at rendering other key variables amenable to autonomous sensor-based detection. The degree of sensor maturity depends on the targeted variable. Following is a short review on present status and on-going and planned development with respect to other key measurements.

2.2.1. Variables of the CO_2 system over the vertical dimension

It is essential to reinforce sensor development, allowing the density of global and accurate ocean carbon measurements to be increased, including in the ocean interior (Byrne et al., 2010; Schuster et al., 2010). ISFET pH sensors appear to have sufficient stability (<0.01 pH) for multi-year operation on profiling floats. However, the chip packaging that enables long-term stability (e.g. Oelßner et al., 2005) is not tolerant to high pressure. Improved packaging systems must be developed.

With respect to the use of pCO_2 sensors by autonomous profiling platforms such as floats and gliders, major obstacles exist and need to be overcome. These include the long time constants of the sensors (typically > 10 min) as well as their comparatively large size and power consumption (Byrne et al., 2010). Also their temperature and pressure hysteresis need to be better characterized. Several of these aspects are currently being worked on and major improvements can be expected in the near future. First field deployments of autonomous membrane-based $p\mathrm{CO}_2$ sensors on profiling floats are currently being carried out at the Cape Verdean long-term Ocean Observatory (Fiedler & Körtzinger, unpublished). The results are promising in general but also point to major improvements of the technology that need to be made. It remains to be seen whether the time constant aspect can be solved to the level desired for profiling float applications (i.e. < approx. 5 s).

2.2.2. Nutrients

New insights into global geochemical cycles definitively require the use of in situ nutrient sensors. The wet techniques exhibit the best accuracy and have demonstrated their reliability, although possible drift of standards over long-term deployment might be an important issue (Adornato et al., 2010). Alternative techniques might involve optical (e.g. for nitrate) of potentiometric (e.g. for ammonia) measurements. Resources must be expended to address critical sensor development needs that include reductions in size, cost, power consumption, reagent use and waste generation, and increase in long-term reliability. During the next decade, the transition of nutrient sensors from research to commercial devices is likely to continue. It will be, in particular, based on the fast growing microsystem technology (MST). MST application to in situ oceanographic sensing is in its infancy, but survival and operation at depth has been demonstrated (Adornato et al. 2010).

2.2.3. Plankton or particulate functional types

Biogeochemical models have specific requirements with respect to the key plankton or particle functional types that should be measured (Lequéré et al., 2010). Monitoring plankton or particle functional types is challenging and requires high resolution imaging systems together with dedicated data analysis systems. Presently, the degree of maturation of these developments is variable according to the particle or plankton size class that is sensed by this emerging instrumentation (Sieracki et al., 2010).

For plankton or particles greater than 20 µm various systems have been developed. The rapid advances in electro-optical technology have resulted in new and better ways of illuminating, detecting and imaging plankton in situ. Prototypes or commercially available high resolution imaging systems now allow plankton and particles to be detected across a wide range of size (up to the cm scale for some instruments). While the hardware part of these systems is now maturing, some additional miniaturization efforts are still required for these sensors to become fully adaptable on autonomous platforms (e.g. floats and gliders,). A good example for such miniaturization is the Laser optical plankton counter which enumerates and sizes particles and plankton in the 100 µm - 1 cm range and has been successfully deployed for several days on profiling floats (Checkley et al., 2008). Similarly, although recognition of phytoplankton (e.g., Sosik and Olson 2007) and zooplankton (Grosjean et al., 2004; Hu and Davis, 2006) begin to be currently possible, data analysis and software systems still need some additional maturation (Sieracki et al., 2010).

Plankton organisms smaller than about 20 µm (pico- and nano-size range), which includes prokaryots and protists, have generally simple shapes (round, oblong) not useful for taxonomic discrimination. In such cases, the use of flow cytometry appears to be the only way to automatically access taxonomic information in this size range. In situ flow cytometers thus represent a promising avenue with this respect, although their size and energy consumption prevent them, for the moment, to be part of operational open ocean observation systems. With respect to coccolithophorids, the use of birefringence properties of their carbonate shells might be a way to discriminate them from the background of nano-sized phytoplankton cells (Gay and Bishop, 2002; Sieracki et al., 2010).

2.2.4. Mid-trophic Automatic Acoustic Sampler for meso-zooplancton and micronecton

Hydroacoustic sensors offer unique possibilities for remote sensing of marine life on various scales, extending from basin scale observations at low frequencies (100s of Hz) (Makris et al, 2006) to small scale-high-frequency (mHz) acoustics for detailed observations (mm scale), often coupled by optical sensors (Holliday et al, 2009).

The ecosystem approach to fisheries management has shifted the focus from traditional single species management to an overall evaluation of the ecosystem (FAO, 2005), including the effects of climate change. As a response, modeling approaches that couple traditional population-, biogeochemical-, and ocean-circulation-models are emerging (e.g. Lehodey et al. 2008). These models have identified the mid-trophic level as a critical gap that needs to be addressed.

Hydroacoustic has matured to a standard tool for quantifying marine life (e.g. MacLennan and Simmons, 2005), and is well suited to observe the mid-trophic levels (Handegard et al., 2010). Presently applied systems (e.g. Trevorrow, 2005) are large and expensive, need connection to shore and/or routinely tend or have short operational times. Low cost low power transducers are currently available, and mounting them to floats is today a realistic option.

3. THE VARIOUS PLATFORMS IN SUPPORT OF AN OBSERVATION SYSTEM.

In complement to ocean color satellite observation of the ocean surface, there are five main sampling platforms on which a future observation system dedicated to ocean biogeochemistry and ecosystem could be anchored. These emerging or already existing platforms are hereafter detailed. For each of them, a brief summary is given with respect to its main spatio-temporal range of application and specific potential as well as constraints. When possible, suggestions regarding a future implementation plan, corresponding to the whishes of the community, are also tentatively given.

3.1. A "bio" profiling float array.

Thanks to the miniaturization of sensors, biological and biogeochemical oceanographers are beginning to follow the way of physical oceanography with Argo floats and undertake a similar technological leap by developing and deploying "biogeochemical floats". The proof-of-concept of these floats has been demonstrated for several types of applications. Floats with oxygen sensors have been used to document ventilation processes in the Labrador Sea (Körtzinger et al., 2004) while time series performed by similar floats in the Pacific subtropical gyres have allowed the quantification of Net Community Production over several seasonal cycles (Riser and Johnson, 2008). Optical sensors have been implemented on profiling floats allowing addressing key processes (e.g. production, export) of carbon biogeochemical cycle (e.g. Bishop and Wood, 2009). A 3-year time series of Chlorophyll a and backscattering (a proxy for POC) was acquired in the North Atlantic using a profiling float equipped with optical sensors (Boss et al., 2008). Nitrate sensors are currently deployed on floats and operated successfully for > 500 days (Johnson et al., 2009). It therefore appears that the technology is now mature and has a great potential for envisaging the development of an array of biogeochemical floats. The rationale for the development / deployment of such floats is to provide the biogeochemical community with an unprecedented amount of vertical profiles of (real-time) key biogeochemical quantities. At present, the variables that begin to be routinely acquired by profiling floats (and identified as core variables, see above) are O_2 (see Gruber et al., 2010), bio-optical variables (Chlorophyll *a* as well as optically resolved POC; see Claustre et al., 2010) and NO_3 (Johnson et al., 2009) (Fig 1). All these variables are essential in the understanding and modeling of biogeochemical cycles and ecosystems dynamics (e.g. Lequéré et al., 2010).

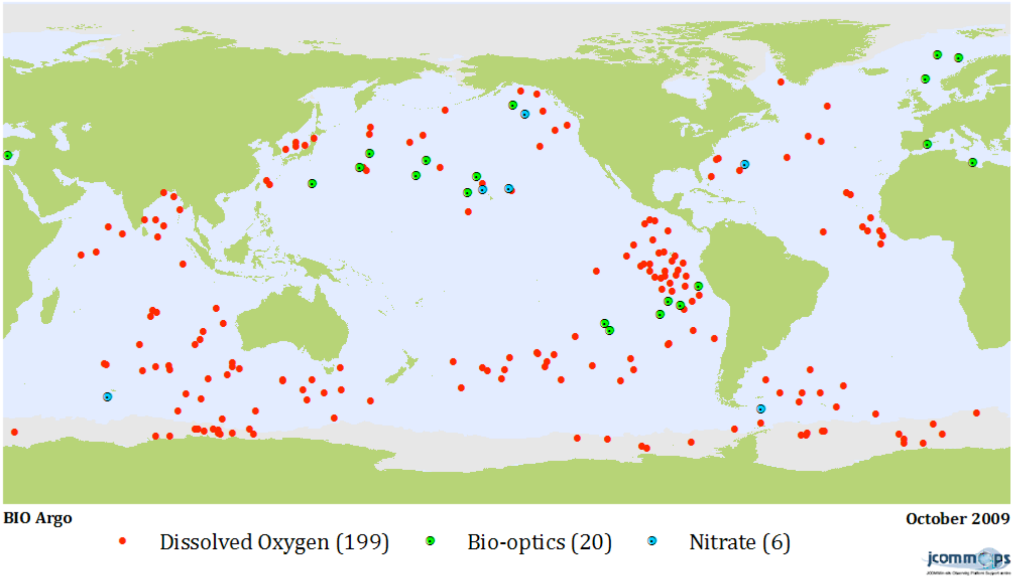

Figure 1: Status of profiling floats with biogeochemical and / or bio-optical sensors in October 2009.

In conjunction to this technological development, the community of potential users is beginning to coordinate itself. A community user group "the friend of oxygen on ARGO" has written a white paper (Gruber et al., 2007), which gives the foundations for an oxygen float array development. IOCCG (International Ocean Color Coordinating Group) is funding the Bio-Argo working group which provides recommendation for the development of a bio-optical float array as a synergistic complement in the ocean interior of remotely sensed bio-optical variables (e.g. Claustre et al., 2010). Similarly some recommendations have been formulated as a follow-up of an US Ocean Carbon and Biogeochemistry meeting on profiling floats (and gliders) (Johnson et al., 2009). The community is presently relying on these various coordination efforts to envisage the implementation of a biogeochemical float array. The profiling float technology being the most cost-effective one to acquire biogeochemical data at global scale, the final and natural objective is to progressively implement a global biogeochemical float array. Nevertheless before to reach this ambitious target, the feasibility of such system has to be demonstrated at a reasonable scale. Thus, the community of potential users plans to implement one or two pilot projects on targeted areas of biogeochemical relevance and where some key issues of the system operation could be tested, namely (1) that sensor accuracy and stability are sufficient for stated scientific objectives and (2) that the community implement real-time and delayed mode quality control capabilities.

3.2. A "bio" glider network

Gliders can be steered and maintained in particular areas providing the spatial structure for all parameters measured by the sensors on-board, at relatively slow speed (30 km day^{-1} horizontally). Only ten years ago, underwater gliders were making history with their maiden deployments, lasting only hours to several days, and initially measuring only temperature and salinity. In the past decade, the sensors have been specifically designed to meet gliders' stringent specifications for low power consumption and small size. The litany of successful missions, lasting months in duration with operations in remote and hostile environments, continues to grow. Gliders are now technologically mature, ready to be incorporated into sustained ocean observing programs, as well as continue experimental process studies (Testor et al., 2010).

As for "bio" floats, the same basic and core variables are now potentially measurable from gliders *i.e.* O2, Chl*a*, optically resolved POC (Davis et al., 2008; Niewiadomska et al., 2008; Perry et al., 2008) and soon, very likely, NO_3 (Johnson, unpublished). Acoustic backscattering measurements have also been used to provide bulk information on zooplankton biomass (Davis et al., 2008). "Bio" Gliders' in ocean observing would complement that of the "Bio" floats, providing more flexibility in applications where the ability to navigate is essential. Several key areas or processes could be targeted by "bio"-glider deployment as part of a sustained network.

"Bio-gliders" are very suitable platforms for any sustained observational system aiming at monitoring bio-physical coupling at the coastal interface between shelf and open ocean. This interface is essential for the understanding of biogeochemical cycles and biological resources dynamics. It is also a place where harmful algae blooms may develop. There is a strong societal demand on these issues (forecast, mitigation), which requires increasing biophysical monitoring capabilities in these a priori sensitive areas.

They appear particularly essential for investigating

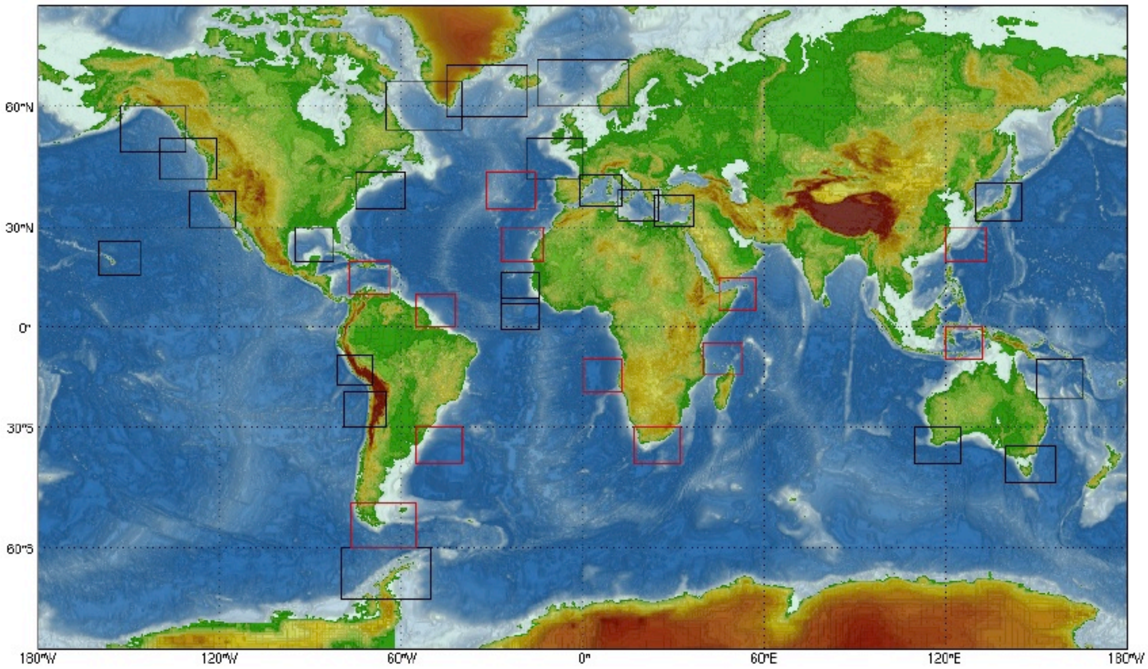

Figure 2: *Map showing the geographical coverage of a future glider network (possibly including a biogeochemical payload). Black boxes correspond to regions where gliders have been already deployed. Red boxes identify additional sites of interest for future deployments. The size of the boxes are 1000km x 1000km. After Testor et al. (2010).*

eastern boundary currents. These systems are the place of the most productive large marine ecosystems in the world (20% of the global fisheries) due to upwelling phenomena. They are also the place of oxygen minimum zones, which, despite representing less than 0.1% of the global ocean volume are of recognized global biogeochemical and climatic importance. The expansion of these OMZ and associated feedback (on biogeochemistry and biodiversity) is of great concern. The intensification of observations is critical and "bio"-gliders appear as key platforms in setting observational capabilities for these critical areas which are very difficult to monitor in a sustained way since floats drift away with currents from these divergence systems.

Finally, "Bio"-gliders are ideal platforms for bio-physical investigations at sub-meso / meso scale (1 km-100 km) which are critical for biogeochemical cycle and ecosystem studies. Indeed, physical processes at these scales might significantly influence nutrient injection in the upper layers, and hence phytoplankton new production and the subsequent export of newly formed material at depth. Our present understanding of the bio-physical coupling at these scales, however, mostly derives from numerical experimentations (e.g. Lévy et al., 2009) highlighting the stimulation of production by submesocsale physical processes. There are few validation observations of these finding and "bio"-glider studies would be perfectly adapted to this important research area.

Contrarily to a float, which can be lost (but sometimes recovered thanks to two way communication) a glider should always be recovered and this is obviously useful not only for the glider sensors calibration but also, for cross-calibration since one could think of gliders steered to meet other biogeochemical platforms (floats, animals, ...) and allowing comparison situations.

The maturation of glider technology was accompanied by the emergence of glider ports or centers. These logistical centers, very often in the proximity of a lab, are and will be the key locations from which endurance lines between coastal waters and open ocean as well as the monitoring of eastern boundary currents can and will be implemented. The development of a "global" "bio"-glider network in the near-future will have to rely on a cluster of these local, national or international (e.g. Everyone's Gliding Observatories) centers (Fig 2). The endurance (~4 months) and range (2000 km) of gliders constrain the location of sustained deployments (requiring repetitive deployments) but already allow coverage of large parts of the global ocean. In a longer term and with the continuing improvement of technology (e.g. increasing endurance and range), transoceanic bio-physical repeated transect will likely become possible from glider port to glider port.

3.3. "bio" animals in polar latitudes.

Animal-borne systems nicely complement gliders and floats at polar latitudes. Recently animal-borne instruments have indeed been designed and implemented that provide *in situ* hydrographic data from parts of the oceans where little or no other data are currently available, e.g. even from beneath the ice in polar regions (Charrassin et al., 2008; Nicholls et al., 2008). Their spatial range depends on the chosen animal species, but they can deliver broad- and small-scale observations.

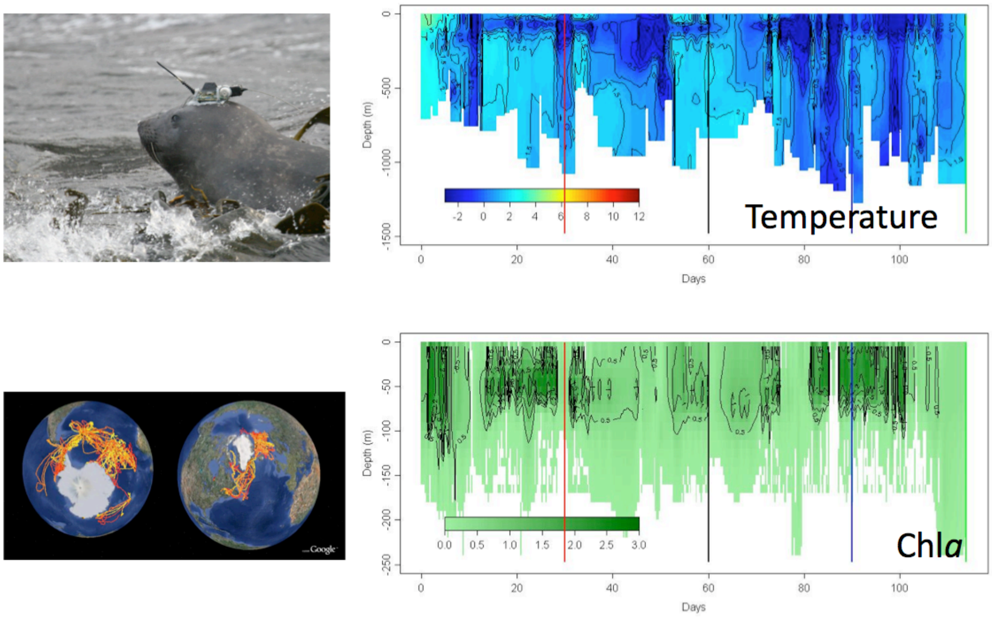

Figure 3: Sea mammals instrumented with Chla fluorescence, temperature and salinity sensors begin to operate in polar areas. As an example, the right panel displays a ~120 day temperature (from 0 to 1500m) and Chla (from 0 to 250m) transect between kerguelen plateau and Antarctic Peninsula (back and forth). The bottom left panel (courtesy of Clint Blight-SMRU) display the track of seals instrumented with argos CTD tags as part of the SEaOS and the MEOP projects (2004-2009).

Specific biogeochemical sensors are being developed. Some studies use instruments equipped with single wavelength light sensors to derive chlorophyll a concentrations using a bio-optical model (Teo et al., 2009). Other new sensors are being developed specifically for animal applications and the first pilot study started in 2008 using a CTD sensor and a chlorophyll *a* fluorometer integrated into a small package, which was deployed on Southern elephant seals at Kerguelen islands (Charrassin et al., 2010) (Fig 3). These data are not only used by oceanographers, but also represent a unique combined biological and physical dataset, which is used by marine biologists who study these animal behaviors. As a direct consequence of this developing field, for example the number of profiles collected by elephant seals for the southern ocean now represents more than 95 % of the CTD and chlorophyll *a* profiles collected south of 60°S. Animal-platform technology is thus emerging from its infancy. It is now providing valuable standard oceanographic measurements in remote regions and also starts to generate biogeochemical datasets.

There are a number of constraints that must be overcome to realize the full potential of animal-borne oceanographic sampling devices. Some are specific to oceanographic sampling from animals, essentially keeping instrument size to a minimum. As an example, miniature O_2 optodes are specifically developed to be implemented on animals. Other issues are linked to the efficiency of data transfer, which will be very likely improved in a near future with the update of the Argos system (allowing for two way communications). Finally ensuring data quality is an especially critical issue as animal-borne instruments are calibrated before deployment, but retrieval of instruments is not always possible (like for floats).

The animal-platform community is in its infancy and no continuous deployments are in place. However, efforts are made to integrate this technology into GOOS as a permanent contributor of ocean data. Animal-borne instruments last typically for one year and provide generally 300-400 T/S/fluorescence profiles by deployment until the animals molt again. A minimum number of CTD instruments for GOOS would be about 100 instruments per year to observe both Polar Regions, based on experiences made in SEaOS, SAVEX and MEOP. A reasonable target would be to equip 40% of them with fluorometers. When O_2 optode sensor will be mature, the implementation of such sensor will have to be planed too.

3.4. Ship-based hydrographic investigations and "bio" measurements.

Repeated hydrographic sections were established by the WOCE program and were mainly driven by physical oceanography and the global carbon survey of JGOFS. Formal organization of the hydrography community has nevertheless been lacking since the end of WOCE (1998), although hydrographic investigations were maintained as part of CLIVAR. This lack of clear international agreement and associated planning has resulted in an inefficient implementation of hydrographic sections with respect to section optimization and data-sharing policies. Following this analysis, the repeat hydrography community is planning a long-term coordination effort to ensure a sustained hydrographic observational activity as a follow-on to CLIVAR (Hood et al., 2010). This activity would be organized according to two types of surveys (Fig 4): (1) Decadal surveys, requiring full basin synopticity would be conducted over less than 3 years. (2) Sub-sets of these decadal survey lines would be re-investigated every 2-3 years.

For the biological and biogeochemical communities, an important outcome of this reorganization is that, following recommendations of IOCCP, more biogeochemical variables are planned to be added into this "redesigned" and more cost-effective observation system.

A first goal of these coordinated ship-based hydrographic investigations is the understanding of the controls and distribution of natural and anthropogenic carbon and biogeochemistry in the ocean interior. Intensification of biogeochemical data acquisition is indeed mandatory in this respect, in particular for a better evaluation of global biogeochemical models, which critically lack data. While the variables of the CO_2 system as well as those required to monitor ocean acidification (Feely et al. 2010) are already considered as core variables of hydrographic sections, the new recommendations emphasize the need for additional biogeochemically-relevant measurements. This includes, notably, some core variables (defined in section 2) like O_2, nutrients, pigments and bio-optical measurements (e.g. Chl*a* fluorescence, transmissiometry). Some of these measurements are relevant to Cal-Val activities of OCR (ground-truthing), while others are phytoplankton functional type (PFT) proxies required for the evaluation of corresponding models.

It is worth recalling that most (if not all) of these "new" measurements are also systematically undertaken as part of SOLAS or IMBER-relevant cruises. Additionally, the GEOTRACES program has identified some of these biogeochemical variables (e.g. HPLC pigments) as core variables to be measured in complement to the trace elements and isotopes measurements. It is thus obvious that, in the future, ship-based hydrography as well as more process-study oriented cruises will share a set of common measurements. Planning and coordination to guarantee the best practice in data acquisition and availability is highly desirable. With respect to

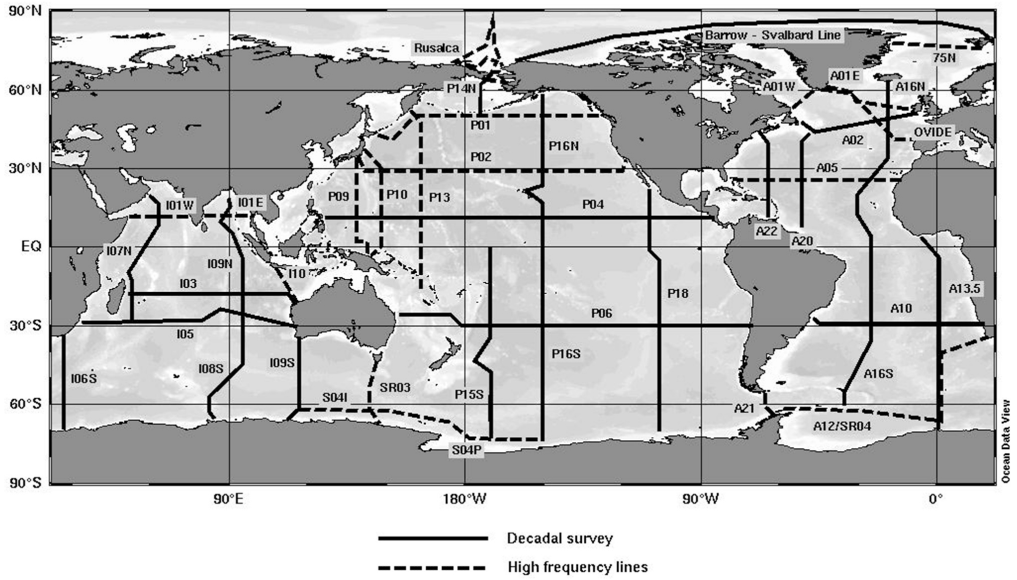

Figure 4: Repeated hydrography cruise plans for the next decade. These cruises will measure some core biogeochemical and bio-optical variables.

strengthening and valorizing the coordination effort for hydrographic data acquisition, the GO-SHIP community is thus considering data management of Argo and OceanSITES program as an example to follow in the future.

Some of the core biogeochemical and bio-optical measurements acquired on these cruises are those also acquired by sensors on autonomous platforms, especially floats. These cruises thus appear as ideal for supporting "bio" float deployments because of the systematic availability of measurements required for sensor evaluation at the time of launch. A close coordination should thus be envisaged with hydrographic section cruises (as well as other cruises) for an optimal planning of float deployments which will, very likely, increase in the near-future.

3.5. Fixed point (Eulerian) Time series and "bio" measurements.

The international OceanSITES program integrates a global array of sustained multidisciplinary eulerian observatories (Send et al., 2010). Although this diverse array does not yet have an agreed set of core measurements, this is currently in progress particularly with regard to the biogeochemical variables. The two main drivers for these observations are to monitor changes in the environment on the annual to decadal scale and secondly to provide insights into system function. This second driver demands a multidisciplinary approach and particularly addresses episodic events which may have a disproportional effect on system function. The OceanSITES infrastructure is common to both of these objectives with high frequency observations (e.g. several times per day), the intention of real time data delivery, an open data policy and data management protocols which are agreed.

The intention is that the present array continues as it is with some additions of sites in specific locations, which have critical attributes and where data are particularly sparse. In addition, a minimal list of state variables is being developed which cover the key properties of each site and which provide a basis for both ocean monitoring and intercomparison between sites. This will probably involve meteorological measurements (heat, wind etc), physical water column properties (current speed at 15m depth, profiles of temperature and salinity) and a small number of core biogeochemical variables such as pCO_2, oxygen, nutrients and optical measurements of phytoplankton biomass (see section 2). The biogeochemical and ecological properties, which can be reliably measured autonomously, is increasing at a high rate. It is therefore expected that other significant variables will join this minimal list in the next few years. Some of the Ocean Time series have the capability to deploy large and power-hungry instruments allowing detailed investigations of some biological or ecological properties (*in situ* flow cytometer). Nevertheless and in spite of the enhancements which are anticipated with respect to access to "new" autonomous variables, calibration, biofouling (e.g. Byrne et al., 2010) and sensor drift still remain significant issues that deserve appropriate investigations for such long term measurements.

For many biogeochemical and ecological properties, the state variables mentioned above is only the first part of the process and the ultimate objective is often to derive rate variables. For example phytoplankton productivity is frequently estimated by a measurement of water fluorescence leading to an estimate of biomass and from that productivity is calculated. The measurement of variables at high frequency is also a way to derivate rates of changes. All steps in the process have large uncertainties and a major challenge which is currently a focus of research and development is to reduce these uncertainties.

At present, 10 to 15 sites in representative biogeochemical provinces are being selected for the progressive implementation of biogeochemical measurements. (Fig 5).

With respect to protocols for measurements, data quality control and distribution, OceanSITES follows the philosophy and principles established by the Argo program.

decennial variability (Antoine et al., 2005). By implementing bio-optical models fed with satellite Chla fields, rates of primary production (Antoine et al., 1996; Berhenfeld and Falkowski, 1997) as well as phytoplankton loss rates (Zhai et al., 2008) can be determined. Other fundamental biogeochemical quantities have recently begun to be derived from space, such as the particulate organic carbon concentration (POC) (e.g. Stramski et al., 2008), the colored detrital material (Siegel et al., 2002; Brown et al., 2008), indices of particle size (Loisel, et al., 2006) or the phytoplankton community composition (Alvain et al., 2005; Uitz et al., 2006, Nair et al., 2008). This is opening new perspectives for the understanding of biogeochemical cycling at regional and global scales.

Before the end of the present decade, the OCR community could have access to data acquired from geostationary platforms, starting with the GOCI instrument aboard the Korean COMS-1 satellite. These high-frequency (~hourly) observations represent an avenue for the OCR community for the exploration of daily-scale processes including the possible quantification of primary production rates, at least at regional scale.

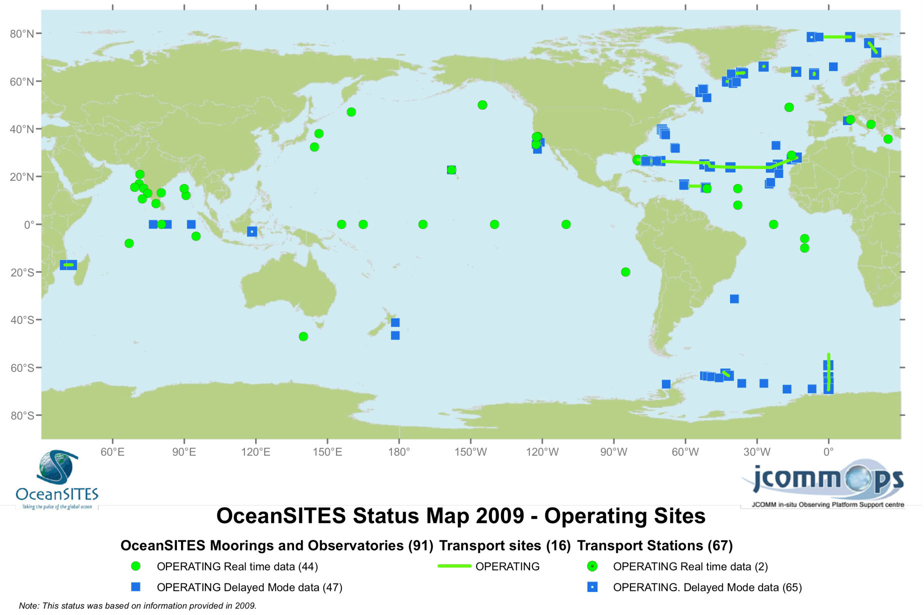

Figure 5: Current status of OceanSITES based on a census of sites/operators that are willing to participate in the project and make their data publicly available to the OceanSITES data system.

3.6. The Ocean Color Radiometry satellite component

In the past two decades, and particularly since the beginning of the SeaWiFS era in 1998, remote sensing of ocean color has become a unique tool by which biologists and biogeochemists have access to global and quasi-synoptic measurements of the surface Chl*a* concentration. The use of ocean color remote sensing made it possible to investigate processes ranging from meso-scale (e.g. Doney et al., 2003) to inter-annual and

The production of long-term climate-quality data records (CQDRs) is an essential requirement for the OCR community. Associated to this are two important prerequisites. The first one is an uninterrupted OCR data stream, which is presently of great concern. For the near-future, while the continuity of the SeaWiFS, MODIS and MERIS observations is possibly ensured thanks to the ESA Sentinel-3 and the ISRO OceanSat-2 missions, there are some concerns with potential critical delays in subsequent missions (e.g., NPP and NPOESS). The second essential condition is the consistency of the dataset of various sensors (e.g. Antoine et al., 2005). The climate-related signals that we need to measure are tiny and even the smallest differences in satellite calibration or data processing procedures can obfuscate these trends. Notably, this production of continuous and coherent OCR datasets is tightly dependant on the continuous availability of in situ calibration / validation datasets.

It is strongly advised that additional bands are added to future OCR satellites to better resolve in-water constituents (e.g. CDM and Chlorophyll, Siegel et al, 2005), improve atmospheric correction and improve our ability to obtain information on community composition. Additionally inclusion of other spaceborn sensors (e.g. polarimeters and LIDAR) could provide more discrimination of particles (e.g. Loisel et al., 2008; Chami, 2007) and their vertical distribution.

The merging of OCR products from various sensors is also a way to increase the spatial / temporal coverage of observations (Fig 6) and is potentially useful for operational applications. The NASA-reason has merged SeaWiFS and MODIS-Aqua data into a single time series. The GlobColour Project has similarly merged MERIS, SeaWiFS and MODIS-Aqua data. Such merging efforts should be continued in the future.

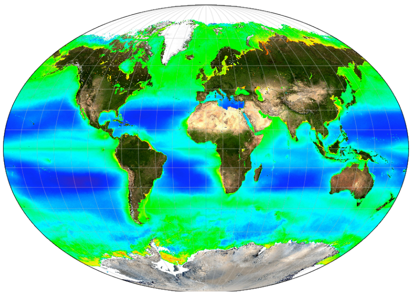

Figure 6: Example of an annual mean merged SeaWiFS-MODIS MERIS product from a 1997-2006 climatology. From the GlobColour project.

4. THE KEY OF THE SUCCESS: AGREED PROCEDURES, DATA MANAGEMENT AND DISTRIBUTION

4.1. In situ data acquired by autonomous platforms

The technology for observing key oceanic biogeochemistry and ecosystem variables has progressively matured to the point where it is now amenable to a global dissemination. Additionally, data sources will be much more diverse than today, going essentially from ship-based data acquisition to an increased contribution of data acquired through remotely operated platforms. Within a few years, our community will thus acquire tremendous amounts of "bio" data. An integrated observation system will be operationally useful and scientifically relevant if and only if this huge data acquisition effort is supported by an efficient data management system able to meet both basic scientific and operational goals. Indeed the success in implementing these new cost effective technologies in our observation strategy will heavily rely on our capacity to make all data easily available.

Nevertheless, such a data management system remains to be designed and implemented. The important criteria that preclude this implementation are, notably, availability of real-time quality-controlled (QC) data for operational applications, production of delayed-mode QC data required for climate-related studies. In some ways, these perquisites are orthogonal to the historic habits or constraint with respect to bio data management. First of all, with the exception of satellite data, our community has not been used to the management of very large datasets because most biological data acquisition has been essentially based on discrete measurements performed from ship-based platforms. Secondly, there are generally some hurdles to make "bio"-data publically available. While on-going efforts in this direction are underway (Lequéré and Pesant, 2009), much remains to be done. Finally, and in corollary to the preceding point, our community is even less used to the constraints involved in the production and distribution of data in near-to-real-time.

A revolution is thus required in the way we manage data This likely represents the most challenging issue for our community, at least as challenging than the required technological developments themselves. Some good examples of rather efficient (although not optimal) data management can be taken from nearby communities, for example, the OCR satellite community, the Argo community and the Ocean Biogeographic Information System which are pioneered the organization and management of data on the distribution of marine species. The management of data within these communities is organized through common principles. (1) Operational data are delivered in near to real-time with associated quality control. (2) Delayed mode, interactive quality-controlled data are delivered with raw data reprocessing undertaken, if required. These data are of scientific value, and compatible with the extraction of climatic trends. (3) Some derived products are produced and distributed by the data centers. (4) Raw data are publically available as well as the codes for their processing into products.

The system developed for Argo QC and management should thus serve as the basis for beginning the implementation of bio-data management. A good example is the OceanSITES program that has an integrated core "bio" variable and which relies on the same Global Data Assembly Center (GDAC) as Argo for archiving (Send et al., 2010), QC and distribution of data. GO-SHIP (Hood et al., 2010) is also taking these programs as an example for organizing future ship-based hydrographic investigations. More generally Argo and OceanSITES should be the example followed for the management of data acquired by other types platforms especially floats, gliders and animals.

Even if Argo (or satellite OCR) data management can serve as the backbone of a future bio-data management system, we have nevertheless to acknowledge that the specificity of "bio" data makes their management a much more complicated task than for physical variables (e.g. T, S from Argo), especially because of the diversity of ways for measuring variables. An example is Chla, the "universal" proxy of phytoplankton, which can be measured through several ways. Firstly it can be measured from space through reflectance ratios or fluorescence measurements. It can also be non-intrusively measured from in situ sensors (in vivo fluorescence, absorption) or through laboratory analysis (HPLC, spectrophotometry, fluorometry, spectrofluorometry) on filtered water samples. All together the concentration of Chl*a* should represent the target "bio" product regardless the method of acquisition. Presently this is not the case and it is obvious that modelers can be lost when they try to access this fundamental variable from available databases. It is therefore mandatory to develop a unified format and language for "bio"-data, which is an essential prerequisite for efficiently streamline and interfacing datasets.

Furthermore and upstream of data management it is worth recalling the necessity of conducting essential actions to guarantee the quality of the acquired data. First of all it is essential to develop best-practice manuals in support of practical training and capacity building. The development of reference material for sensor calibration prior to platform deployment, as well as the support of regular international inter-comparison exercises is crucial. Ideally some internationally agreed calibrations centers for bio-sensors should be also implemented.

4.2. Satellite data

The minimum requirement here is a free, easy and permanent access to satellite-derived products. This statement might be read as an obvious one, whereas the present situation in terms of data availability is actually not optimal.

The rapid growth of the use of satellite ocean-color products in various fields of biogeochemical oceanography has been possible in the past decade because data have been made available efficiently to the overall science community, in particular from the NASA SeaWiFS and MODIS instruments. Data from other missions are still not so intensively used because of inappropriate data policies and distribution procedures, although the situation admittedly improved in the recent years. There is not a single satellite mission that can provide all needed information at all required temporal and spatial resolutions, however. This is due in particular to the specifics of orbits, swath widths and other mission characteristics, and also to the finite and finally short lifetime of satellite missions with respect to the time scale of the phenomena of interest. The key here is the merging of data from multiple missions.

The first requirement is, therefore, that liberal data policies be adopted by space Agencies, so that data from multiple sensors are available for being used, exchanged, compared and eventually merged. An appropriate data policy can be overwhelmed, however, by deficient ground segment capabilities for data distribution. Therefore, the mandatory corollary of an open data policy is a well-dimensioned online data distribution system.

The second requirement is that all needed information are made available, in parallel to the final geophysical products, which includes information and data on instruments characterization, calibration techniques, data processing algorithms etc...This is mandatory to achieve a meaningful data merging. The corollary of such a requirement is the need for a "place" where information is gathered, centralized and made available, so the final objective of building climate quality data records is realized. This can be either an organization, a project or whatever body, which doesn't exist today.

5. TOWARDS INTEGRATION

When referring to integration of the various elements (in situ measurements, satellite measurements, models) into a sustained observation system, the development of synergy immediately arises: how to set up the integrated system in such a way that its usefulness for science and operational activities is superior to that of the various elements taken individually. Several lines of integration can be envisaged in this context.

5.1 Bio-physical integration

In the late eighties-early nineties, when the JGOFS program started, two rather distinct communities were coexisting, the biological and the geochemical ones. It took more than one decade for both communities to learn modalities of working together, resulting in the development of a real biogeochemical community. This community is now mature and has begun to develop observational tools with a spatial or temporal resolution similar to that used for the observation of physical fields.

Integration of a biological component into an already existing physical observational system, however, is not just adding “bio”-sensors to this system. Because “bio”-processes strongly depend on physical forcing at all scales, a “bio”-program of observation (“bio”-Argo, “bio”-Glider, “bio”-Time series…) should not be a side program, independent of the corresponding physical program. Optimally, it should be clearly defined and then implemented in close association with physical oceanographers. However, while ocean biology depends on physics the reverse is not (generally) true and hence biogeochemical topics are perhaps in some instances, not sufficiently attractive for physical oceanographers. Nevertheless, the possibility to acquire biogeochemical data at high frequency might change this a priori weak interest: common scientific objectives have to be identified by both communities as a natural way to develop true integrated bio-physical observational approaches which can take the best benefit of the emerging technologies.

The operational maturity of gliders developed more or less simultaneous with the operational maturity of biogeochemical / bio-optical sensors. Furthermore, the spatial domain covered by gliders encompasses the sub-meso and mesoscale, which are critical for biogeochemistry and physics; the development of real bio-physical synergetic approaches based on the use of gliders is naturally on the way. The same applies for animals with physical and bio-sensors.

For time series and ship-based hydrography, following the initial inclusion of variables of the CO_2 system, new biological and biogeochemical core variables are now implemented into the physical observation system (Hood et al., 2010; Send et al., 2010). Thus, new studies at the interface of physics and biogeochemistry can be undertaken for a better understanding of the driving mechanisms of biologically mediated carbon fluxes, from the diel to the decennial scales (time series) or at a regional/basin scale (ship-based repeated transects).

Developing coupled approaches between physical and biogeochemical oceanographers based on the use of float technology appears *a priori* less obvious. The Argo program is well organized and mature, while the “bio”-counterpart is in infancy. Adding “bio”-variables to the overall system might be seen as technically challenging, costly, and generating issues related to the law of the sea. However there are mutual advantages both communities working together. The addition of bio-variables will require Iridium transmission. The additional bandwidth provides the ability to collect addition data, for example, the ability to resolve meter-scales in the vertical, essential when accurate mixed layer estimation is a target. Similarly phytoplankton content in upper layers affects their heating rates (one rare if not the sole feedback of biology on physics!). Topics related to biological response to mixed layer dynamics (from the event to the seasonal and inter-annual time scale) represent an interdisciplinary topic for synergy between both communities.

5.2 Synergy between *in situ* “bio” data and OCR satellite data.

Building an observing system with a global scope inevitably requires the inclusion of satellite remote sensing observations. Modern ocean observing networks will be built as an aggregate of ship-based observations plus observations from mooring sites and from various autonomous platforms, such as floats and gliders. Remote-sensing observations are the appropriate element needed to integrate inherently localized information into a basin-scale context, and to embed them into the long-term view progressively built from past, present and future satellite archives.

Remote sensing doesn't stand alone, however. All remote sensing techniques, such as infrared radiometry for the determination of SST or visible and near infrared spectral radiometry (VSR) for the determination of ocean color, require in situ data for calibration of the radiometric observations recorded at the top of the atmosphere, and for validation of the final « geophysical products » derived from these observations (reflectances, chlorophyll concentration, SST etc..). In addition, remote sensing techniques are far from being frozen, which means that algorithms used to derive the geophysical products of interest need permanent improvements. This is mandatory to improve the quality of existing products and to derive new, advanced, products in order to maximize the benefits from the satellite information. Again, *in situ* data play a central role here. This is the first stage of complementarity between in situ and satellite observations.

The second aspect is when field observations are available in areas that are hardly observable by remote sensing because of clouds and low sun angles. The third aspect is linked to the nature of the satellite OCR observations, which allow retrieval of biogeochemical quantities within the upper oceanic layer. This layer is typically the 4/5 of the so-called euphotic layer, which itself varies from a few meters in eutrophic areas to ~ 160m in the clearest waters (Morel et al., 2007).

Therefore *in situ* data are essential to complement fields of satellite data and to extend them into the ocean interior (Sathyendranath et al., 2010).

This complementarity will allow the development of 3D / 4D views of key biogeochemical variables in the world ocean. These aggregated datasets will serve to evaluate the performance of coupled physical-biogeochemical models at various scales, and to identify and quantify seasonal, inter-annual and multi-decadal variability and trends. Additionally, these 3D fields will also constitute the "initial climatologies" that will serve as baseline to establish delayed-mode data quality control for biogeochemical data (e.g. Chl*a*, POC) acquired by bio-sensors on autonomous platforms.

In a more general sense, the rapidly evolving field of data assimilation holds great promise to integrate operational models and a wide variety of data sources. Most of this work has taken place within meteorology, and more recently physical oceanography, but recent successes with assimilation of biogeochemical data are evident (see Brasseur et al. 2009).

Therefore, there is a permanent exchange between satellite remote sensing, field oceanography, and numerical modeling with mutual benefits. Long-term global ocean observing systems are the crucible within which this tight coupling between fundamental research in marine optics and bio-optics, ocean color remote sensing science and applications, and biogeochemical oceanography can develop.

5.3 A step towards global integration: conducting process studies at « super-sites ».

At the moment, the "bio" community is deeply engaged in maturing the various platforms of the observation system. Developing a synergetic interplay of these various "bio-platforms" into a sustainable integrated observation system will only be successful if the system is designed to respond to well-addressed scientific questions. The sizing of the system (density of bio-gliders, bio-floats, bio-animals…) and the synergistic integration of these various elements will become more natural and easy to implement as soon as these questions and associated relevant spatio-temporal scales are clearly identified.

An example of an integrated approach of the open ocean biogeochemistry and ecosystems can be represented by the JGOFS era. The main question of the JGOFS program was to understand and quantify the so-called oceanic biological pump. To achieve this goal, several key oceanic provinces were selected and "process study" cruises conducted where relationships between autotrophic biomass, carbon fixation and export could be established and quantified. These relationships provide a basis on which to establish parametrization of global biogeochemical models. In its ultimate phase (synthesis and modeling activities), the main goal of JGOFS was to use these models to estimate carbon export flux from observations of the upper ocean Chl*a* and POC, the only variables accessible at the global scale. Unfortunately, JGOFS process studies were mostly conducted after the end of CZCS (1983) and before the beginning of the SeaWiFS (1997) era. Additionally, no autonomous platforms were available at that time. Nevertheless, the JGOFS program remains the main coordinated and integrated observational effort to date to observe and understand marine biogeochemical cycles.

While the global ocean would appear the natural target to set up a long-term and sustained observation system, the implementation of pilot studies on regional "hot-spot(s)" or super-sites, based on the example of international coordination developed during JGOFS, appears as the first and most reasonable step towards integration. There are indeed regional "hot-spots" that are natural laboratories for addressing key scientific questions of global relevance, and which would benefit from being tackled in a highly integrated way. Two examples can be highlighted of such "super-sites".

Eastern boundary currents are highly dynamic locations with enhanced biological and biogeochemical activity. These generally extremely eddy-rich areas exhibit active upwelling and consequently intense fishery activities. Additionally the intermediate layers in these areas are characterized by the presence of oxygen minimum zones (OMZs) which impact the carbon and nitrogen cycles. The size of the OMZs is presently increasing (ocean deoxygenation) as a consequence of ocean warming and increased stratification. This reduction in oxygen level may have dramatic consequences for bio-diversity and coastal economies. It is therefore timely and very opportune to take benefit from the new multiscale and multivariate capabilities of the various platforms to design a long term integrated observation system of an eastern boundary current system and its associated OMZ.

A second example is the North Atlantic. Despite representing only 1.4% of the ocean's area, the North Atlantic (northward of 50°N) accounts for about 20% of the global ocean carbon sink (Takahashi et al., 2009) and is the site of the largest spring / summer phytoplankton bloom in the global ocean. The magnitude of the CO_2 sink presents strong inter-annual variability (e.g. Corbière et al., 2007) and recent studies have documented its decrease (Schuster and Watson, 2007). To what degree this decrease results from natural oscillation (e.g. North Atlantic Oscillation, NAO, Thomas et al., 2008) in the rates of wintertime mixing and ventilation, or from the response of biological activity to global warming and associated progressive stratification remains to be assessed. The design of a multiplatform observational approach sustained over the long-term is the only adequate response to resolve this key question.

6. FINAL RECOMMENDATIONS

There are several key elements that are perquisite for guaranteeing the success of a future integrated system. Here, we briefly summarize them.

The implementation and the sustainability of the observation system rely on the critical choice of the "bio" variables. The community first has to begin with few variables, chosen for their scientific relevance as well as the technological maturity of their autonomous measurements. Thereafter, the observation system could be progressively elaborated with the addition of new variables satisfying both criteria.

This in situ system should be fully designed and implemented in tight synergy with satellite ocean color radiometry as well as advanced numerical models of biogeochemical cycles and ecosystems.

The sustainability of the entire system will depend on the capability of our community to implement a dedicated data management system. Open access data and quality control in real-time as well as in delayed-mode are the keywords of this challenging and ambitious task.

The possibility to measure biological and biogeochemical fields with the same spatio-temporal resolution than the physical ones pleads for the development of truly integrated bio-physical scientific approaches that can be developed for the first time. This is highly desirable because biological and biogeochemical fields are forced and driven, to first order, by physics.

Finally the community should begin "simple" and consider the observation of "super sites" in key areas of global relevance as a first step towards global integration.

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