Project	AtlantOS – 633211
Deliverable number	5.3
Deliverable title	Indices associated with Primary productivity and carbon export
Description	Analysis of nutrient cycling, primary productivity and particulate carbon export flux in the subpolar North Atlantic and the subtropical South Atlantic.
Work Package number	5
Work Package title	Integrated regional observing systems
Lead beneficiary	UPMC
Lead authors	Hervé Claustre (UPMC), Henry Bittig (UPMC), Johannes Karstensen (GEOMAR)
Contributors	
Submission data	
Due date	March 2018 (PM 36)
Comments	[in case the deliverable is late please explain why]

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Stakeholder engagement relating to this task*

WHO are your most important stakeholders?	■ Private company If yes, is it an SME ■ or a large company ☐? ■ National governmental body: space agency: ESA, NASA (export program) ■ International organization (Copernicus, Mercator) ☐ NGO ☐ others Please give the name(s) of the stakeholder(s): …scientific community
WHERE is/are the company(ies) or organization(s) from?	■ Your own country ■ Another country in the EU ■ Another country outside the EU (possibly) Please name the country(ies):
Is this deliverable a success story? If yes, why? **If not, why?**	■ Yes, because here we show new sets of ecosystem relevant indices that are based on a combination of observational data (satellites, in-situ) and merged with reanalysis data (e.g. atmosphere). Access to data with a sufficient spatial and temporal resolution to address biogeochemical processes that it was not possible to tackle before because of critical observational gaps. It constitutes a perquisite in view of developing baseline references aiming at better tracking, in the near-future, the possible evolutions in these key processes as a result of climate change impact on biogeochemical cycles. ☐ No, because …..
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	■ Yes this pilot-indices list may serve as a proposal for the generation of indices in an operational mode e.g by the EEA or Copernicus climate change service (climate.copernicus.eu). See concluding remarks section in this deliverable. ☐ No, because …..

Executive summary

Primary productivity is the process where on phytoplankton use chlorophyll to capture light for photosynthesis, in which carbon dioxide and water are combined to produce organic matter and oxygen. The organic material produced by phytoplankton serves as food for larger organisms at sea, sustaining the mesopelagic communities and fish resources as well as contributing to carbon sequestration when sinking by-products of phytoplankton production are exported below the permanent pycnocline.

Indices for primary productivity (PP) and carbon export are key state indicators of the marine ecosystem and the oceans capacity to take up carbon dioxide (biological pump). Routine estimation of primary productivity at basin and even global scale, started at the end of the 1990 with the SeaWIFS ocean color satellite mission. Satellite based estimates are subject to a number of simplifications and augmenting the satellite data with profile data from other ocean observing platforms is of critical importance to estimate PP with sufficient accuracy to eventually detect long term trends.

AtlantOS was implemented at a time where autonomous measurements of the ocean biogeochemical status were in the transition phase from research project-based to more operational networks. This was the case for the Atlantic Ocean and especially for the North Atlantic Subpolar Gyre (NASPG) and the South Atlantic subtropical gyre (SASTG). Both zones present specific scientific interest. The NASPG is one of the key places of the global ocean for CO2 drawdown in particular through the most intense spring phytoplankton bloom and subsequent export of organic matter in the mesopelagic (100-1000 m) realm. The SASTG is one of the most oligotrophic zone of the open ocean (together with its South Pacific counterpart) and hence a key experimental zone in the context of increasing stratification and associated extension of oligotrophic areas. In both areas, a growing fleet of biogeochemical profiling floats had been deployed and was potentially sustained, thanks through additional deployment planned as part of AtlantOS-WP3. These emerging profiling float activities were totally in line with the nascent international BGC-Argo program. Moreover, long time series stations at regions considered representative for a larger area (biophysical provinces) are used to derive indices as well as to test index performance.

The data used here is gathered by autonomous instrumentation (robotic Argo fleet recording vertical profiles of Chlorophyll a, backscattering coefficient (proxy for Particulate Organic Carbon), irradiance, nitrate and oxygen and by moored instrumentation (nutrient analyser, Chlorophyll a, Turbidity, backscatter target strength profiles) in biophysical provinces) and analysed in a synergetic way with complementary data collected by other observing networks (e.g. hydrographic Argo program, satellite remote sensing), atmospheric reanalysis. **These analyses gave a unique opportunity to address, for the first time, key biogeochemical processes at unprecedented spatial and temporal resolutions.**

This deliverable provides a summary of R&D on key processes in PP and carbon export that will found the base for the operational generation of related indices which in turn will help to assess the ecosystem state. Three main research lines, namely phytoplankton dynamic, export of phytoplankton products or by-products and nutrient cycling are followed. **The studies conducted emphasize the complementarity of the data sources in order to quantify processes and identify the main drivers of their occurrence. These first analyses are in particular important through the definition or use of already existing various indices / metrics of these processes (e.g. magnitude, occurrence, timing), which could be used in the future to address their evolution in a potentially changing ocean.**

The presentation of this deliverable is done according to the main results obtained with

respect to zones (NASPG, SASTG, whole Atlantic basin) and processes (phytoplankton dynamics, export, nutrient cycling). A specific emphasis is put on NASPG given its fundamental role in anthropogenic carbon sequestration through the biological carbon pump largely associated to spring phytoplankton blooms. A summary table of the diverse indices and metrics and their potential usefulness is subsequently proposed. The AtlantOS references (peer-reviewed papers and communication at meetings) related to this deliverable are presented and concluding remarks are provided at the end of this document.

1. North Atlantic Sub-polar Gyre

1.1 Phytoplankton dynamics and productivity

In the NASPG the massive spring bloom is a key event that has strong impact on the carbon export and hence of sustaining the mesopelagic communities and fish resources as well as contributing to carbon sequestration when sinking by-products of phytoplankton production are exported below the permanent pycnocline. Addressing the bio-physical drivers of these production and export processes and defining metrics and indices of their occurrence is becoming essential. It constitutes a perquisite in view of developing baseline references aiming at better tracking, in the near-future, the possible evolutions in these key processes as a result of climate change impact on biogeochemical cycles. Here, phytoplankton dynamics and productivity are addressed through several complementary studies which made used of the complementarity of in situ data (Argo, BGC-Argo) with satellite data (ocean color), atmospheric data and models/modelling (bio-optical model of primary production*).*

1.1.1 Determinism of the phytoplankton bloom in the Labrador Sea

; *Main data source*: *Argo TS, Ocean Color.* Main reference related to this study: Lacour et al., 2015. An analysis combining climatological data of Ocean color (MODIS) together with a T & S climatology (Argo) has allowed addressing the phenology of phytoplankton blooms in various zones of the NASPG, and to understand in particular the specificities of the Labrador Sea, on each side of 60° N. North of 60° N, the bloom paradoxically occurs one month in advance compared to the Southern part (Figure 1); this unexpected pattern is essentially driven by water column stability in winter, which is higher in the North (due to strong haline stratification) than in the southernmost part. **The mixed layer is always shallower in the North, which, even if surface light intensity is lower, makes spring bloom occurring earlier** (Figure 2). The average light within the mixed layer thus appears as a first useful metrics of the physical environment characteristic of the beginning of the bloom. In the Labrador Sea, this irradiance threshold is estimated to be of 2.5mol photon m^{-2} d^{-1} over the mixed layer

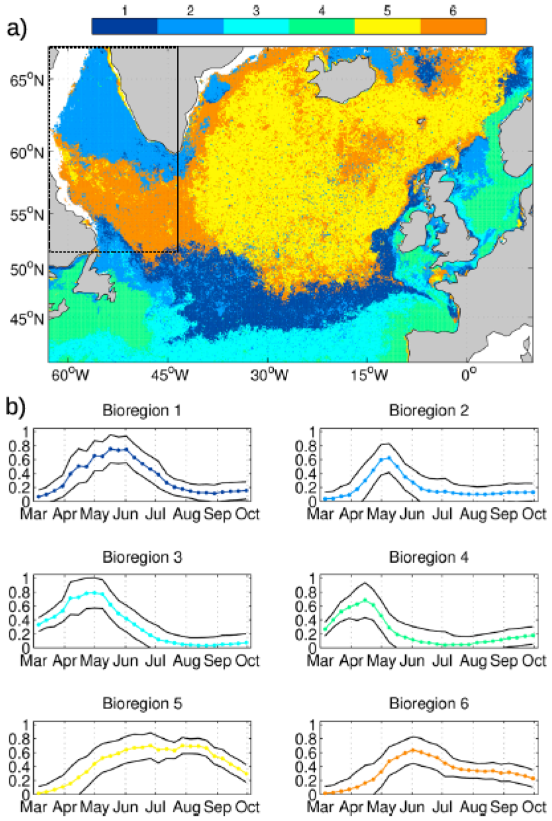

Figure 1. (a) Spatial distribution of the clusters obtained from a K-means analysis of satellite climatologic Chla (b) mean normalized Chl a annual cycles in each cluster ±1 standard deviation. Each cluster is considered as a bioregion with a spatiotemporal coherence with respect to phytoplankton biomass cycles. The dashed black box delineates the area of interest.

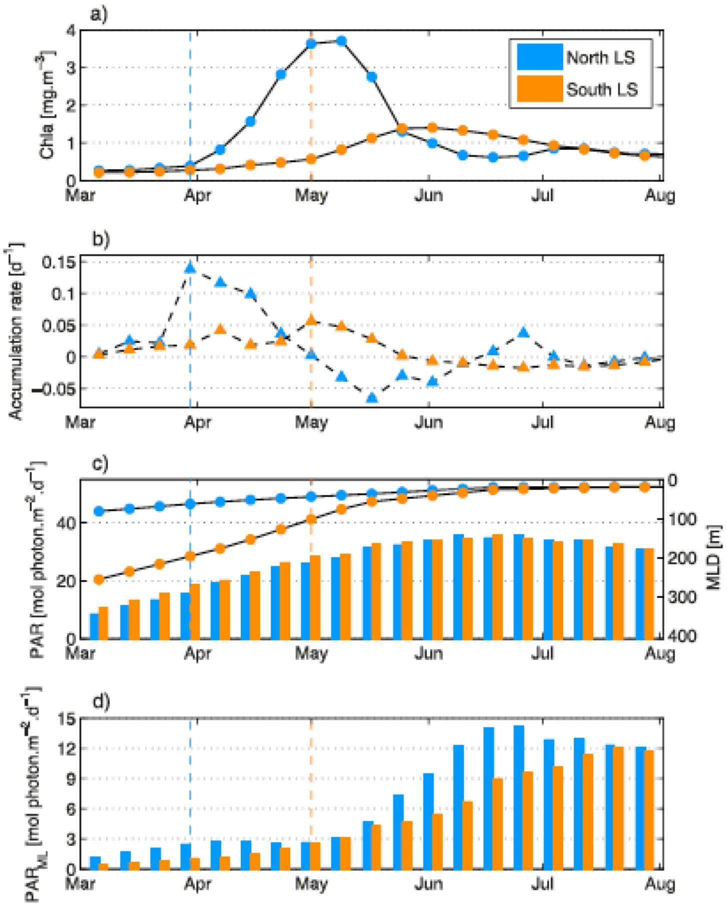

Figure 2. (a) Climatological cycle of area-averaged surface Chl a. Accumulation rate (see equation (1)) of the (b) surface Chl a, (c) surface PAR (bars) and MLD (lines), and (d) mean PAR over the MLD. Vertical dashed lines denote the bloom initiation deduced in Figure 4b. Blue correspond to the North LS and red to the South LS. Note the scale inversion for MLD in Figure 4c. The time axis, from 1 March to 31 July, is centered on the bloom period.

1.1.2 Annual cycle of phytoplankton in biomass in the NASPG; *data source*: *BGC-Argo, ship survey data for calibration and deployment sensors, heat flux, wind, bio-optical model of primary production*.

Main reference related to this study: Mignot et al., 2018

The first (1.1.2) study was dealing only with Argo floats and Ocean color remote sensing data. Yet the vertical distribution of biological and biogeochemical properties, including phytoplankton biomass, could be solely assessed assuming the satellite (Chla) signal to be homogeneous within the mixed layer. The next step was to develop an in-depth understanding of the biological and the environmental mechanisms that allow for the development of phytoplankton bloom in the whole productive layer. The numerous annual time series collected by BGC-Argo floats in the NAPSG, thanks to the ERC project remOcean, provide the framework for this analysis. Mignot et al (2018) identifies two phases in the seasonal growth of phytoplankton. The first phase, so-called weak winter accumulation phase (Figure 3), starts in early winter when the mixed layer is still deepening. This winter growth period extends up to the time of heat flux reversal and associated beginning in mixed layer shoaling (Figure 3a) which is the starting point of the bloom characterized by strong increase in the net population growth rates (Figure 3b). The period of positive net growth in winter, when the phytoplankton division rates are still decreasing (Figure 3c) suggests that loss terms (possibly grazing) are decreasing even faster. **We confirm here the dominant role of the spring bloom, as compared to slight biomass increase in winter, in organic carbon synthesis, hence bringing clear observational argument to a decade-long debate on the north Atlantic bloom initiation.** Furthermore a temporal scale metrics is proposed (the x axis of Figure) which allow aggregating various phytoplankton time series along a coherent biological and environmental forcing referential (see Figure 3 caption for details).

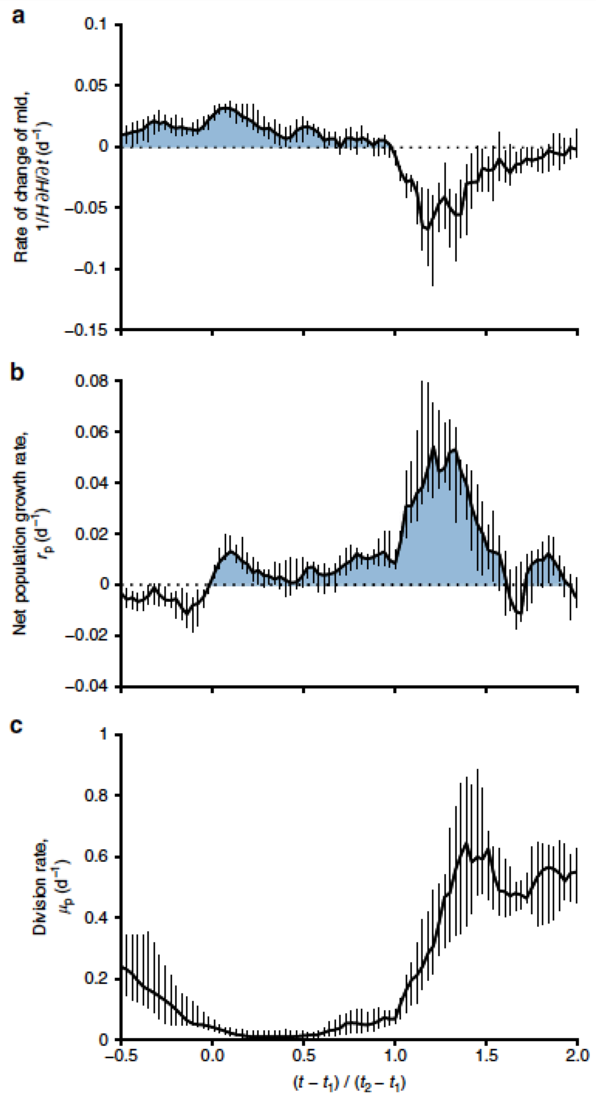

Figure 3. Rate of change of physical and biological variables during annual phytoplankton cycle in the NASPG. Median (solid thick line) and interquartile range (vertical bars) of the rate of change of mixed layer depth (a, 1H **∂**H **∂**t), the net phytoplankton population growth rate (b, rp), and phytoplankton division rates (c, **μ**p), estimated from the 12 time series collected by the floats. The time axis is rescaled by the onset times of the weak winter accumulation phase (t1) and the spring bloom (t2) introducing **τ** . (t -t1) /(t2-t1). **τ** = 0 corresponds to the initiation of the weak winter accumulation phase and **τ** = 1 corresponds to the initiation of the spring bloom when the mixed layer is starting shoaling when there is a shift from atmospheric cooling to heating, at least for a few hours during the dayThe time span between τ = 0 and τ = 1 corresponds to the duration of the weak winter accumulation phase and it is ~120 days long.

1.1.3. The winter phytoplankton accumulation in the NASPG. *data*: *BGC-Argo, ship survey data for calibration and deployment sensors, atmospheric data*. Main reference related to this study: Lacour et al., 2017

The slight phytoplankton accumulation rate during winter-time (1.1.2), at a period that a priori does not favor phytoplankton growth, let the questions of what the drivers of these accumulations were. Thanks to the same BGC-Argo float used previously (1.13), we have presented observational evidences for widespread winter phytoplankton blooms in a large part of the North Atlantic subpolar gyre. These blooms were triggered by intermittent restratification of the mixed layer when mixed-layer eddies led to a horizontal transport of lighter water over denser layers. Combining a bio-optical index (Chla/backscattering coefficient) with complementary chemotaxonomic and modeling approaches, we show that these restratification events increase phytoplankton residence time in the sunlight zone, resulting in greater light interception and the emergence of winter blooms. Restratification also caused a phytoplankton community shift from pico- and nanophytoplankton to phototrophic diatoms. **We conclude that transient winter blooms can maintain active diatom populations throughout the winter months, directly seeding the spring bloom and potentially making a significant contribution to over-winter carbon export.**

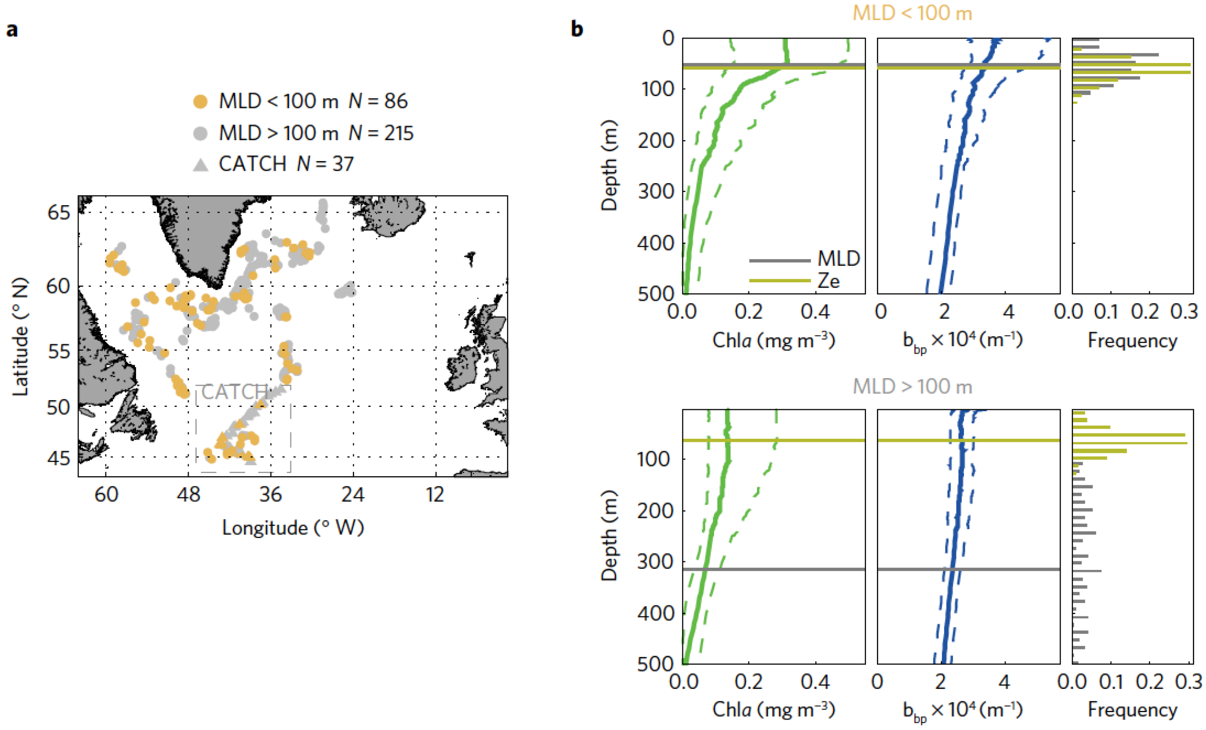

Figure 4: **Winter phytoplankton blooms in the North Atlantic subpolar gyre. a**, Location of the 301 BGC-Argo float profiles (dots, January–March 2014–2015). Orange symbols indicate stratified profiles (MLD < 100 m, 35% of the profiles, including CATCH profiles) and grey symbols indicate deep mixed profiles (MLD > 100 m). **b**, Median profile and quartiles of chlorophyll a (chla) and backscattering (b_{bp}) from BGC-Argo floats shown in a, for MLD < 100m (top) and MLD > 100m (bottom). The two sets of data (MLD < 100m and MLD > 100 m) are statistically different in terms of both surface chla and b_{bp} (Wilcoxon test, p-value < 0.01). Every single chla and bbp profile is shown in Supplementary Fig. 9. Horizontal grey and yellow lines indicate the median MLD and euphotic depth (Ze) respectively. Ze is defined as the depth of the 0.1 mol photons m^{-2} daily isolume (Supplementary Methods 1.8). Panels on the right show the frequency distribution of MLD (grey) and euphotic depth (yellow).

1.2 Particle export

1.2.1 Mixed layer pump (MLP). The mixed-layer pump is the physical mechanism by which particulate organic carbon from the upper layers is fuelled into the mesopelagic zone. It is driven by mixing events that « dilute » particles from the surface into the mesopelagic zone before the subsequent stratification isolates it with its enhanced carbon content from the contact with the upper layer. The MLP was addressed through two approaches linked to specific scale of its occurrence.

1.2.1.1 Global analysis of the MLP at the seasonal scale. *data*: *Argo TS, ship survey data for calibration and deployment sensors, remote sensing of backscattering coefficient*. Main reference related to this study: Dall'Olmo et al., 2016.

Time series of the POC content within the mixed layer were established combining mixed layer estimation derived from Argo profiles with the backscattering coefficient (a proxy for Particulate organic carbon) derived from ocean color. The analysis of these time series between the period of the deepest mixing up to the period of established stratification allows the estimation of the amount of POC which is seasonally isolated from the surface through the MLP. These estimations were further used to establish a relationship linking MLP and the depth of deepest mixed layer and finally to quantify the regional impact of MLP in carbon export budgets. These results demonstrate that, in North Atlantic subpolar gyre (one of the place with the deepest mixed-layer of the global ocean), the MLP supplies a major flux of organic carbon to the mesopelagic zone. **It reveals that mixed layer pump in the NASPG is extremely efficient and might sometimes overpass the biological carbon pump (direct sinking of particulate material) in fueling deep layers with carbon.**

1.2.1.2 Detailed investigations of the MLP at intra-seasonal scale in the NASPG. *data: BGC-Argo, atmospheric data, ship survey data for calibration and deployment sensors..* Main reference related to this study: Lacour et al., (submitted)

While the previous study (1.1.2.1) had addressed the MLP at the seasonal and regional scale, the dynamics of the MLP at intra-seasonal scales remains poorly known, mainly because the lack of observational tools suited to studying such dynamics. Using the dense network of BGC-Argo floats, we have revealed frequent and widespread MLP-driven export events, during the winter and early spring period, in a large part of the subpolar North Atlantic Ocean. This intra-seasonal dynamic of the ML pump exports fresh organic material to depth (75 mg C m-2 d-1 on average), providing a significant source of energy to the mesopelagic food web before the spring bloom period. **This mechanism may sustain the seasonal development of overwintering organisms such as copepods with potential impact on the characteristics of the forthcoming spring phytoplankton bloom through predator-prey interactions.**

1.2.2 Events of large particle export. *data: BGC-Argo, ship survey data for calibration and deployment sensors*. Main reference related to this study: Briggs et al., (in prep)

A specific analysis of post-bloom particulate export, through an original approach developed by Briggs et al. (2011)[1] has been initiated. Basically, this approach makes use of the so-called spikes in the backscattering and fluorescence deep (100m-1000m) signal that are recorded when the bloom collapses. These spikes corresponds either to phytoplankton aggregates or to fecal pellets that sink into the mesopelagic layer. In the NASPG, more than 20 bloom

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[1] Briggs, N., M.J. Perry, I. Cetinic, C. Lee, E. D'Asaro, A.M. Gray, et al. (2011). High-resolution observations of aggregate flux during a sub-polar North Atlantic spring bloom. Deep-Sea Research Part I-Oceanographic Research Papers. 58(10):1031-9.

terminations are presently addressed using highly resolved (1-m on the vertical scale, 2 day temporal resolution) 0-1000m vertical Biogeochemical-Argo profiles. **These analyses allow identifying possible general patterns in the transfer of this fast-sinking ($\sim$100 md^{-1}) particulate material at depth and associated disaggregation during this transfer. Ultimately the characterization of these mesopelagic deep processes will be related to surface layer signature (e.g. satellite Ocean color) with the aim to upscale the process studies undertaken by floats in a more general context of carbon export in the NASPG.**

1.2.3 From export to mesopelagic remineralisation.

data: BGC-Argo. Main reference related to this study: Bittig et al., (in prep)

The analysis of post-bloom particulate export is complemented by a biogeochemical analysis of mesopelagic respiration. Organic particles exported after the phytoplankton blooms are partially remineralized as they sink through the mesopelagic layer (100m-1000m). The carbon remineralization consumes stoichiometric amounts of oxygen. Using three Biogeochemical-Argo floats with O_2 sensors, which stayed near-stationary in the Labrador Sea, we began to analyze the mesopelagic carbon flux attenuation and the difference between export flux and sequestration flux. The relation between remineralization (O_2 and carbon budgets), particle export (1.2.2.), and MLP (1.2.1), including both their respective magnitude and timing, provides valuable insight into the biological carbon pump from complementary perspectives.

1.3 Nutrient cycling

data: Moored Nitrate, Chl-a & TS sensors, ship survey data for calibration of data and exchange of moored sensors, surface buoyancy flux data. Main reference related to this study: Karstensen et al., (in prep)

The correlation between surface nitrate and temperature have been attractive to estimate productivity from space and hence to establish a PP index. The analysis of nitrate and temperature time series data from the central Irminger Sea is used to explore phases where and why the correlation between nitrate and temperature exits. The nitrate to temperature relation is more complex than previously thought and a model, separating five phases of physical as well as biogeochemical processes, is developed. By scaling nitrate with the locally observed mixed layer depth productivity during the low light winter season is derived. It is found that before the onset of the spring bloom by mid April about the same amount of carbon is already fixed. Intermittent stratification events can trigger intense pre-bloom events but only over very shallow depth.

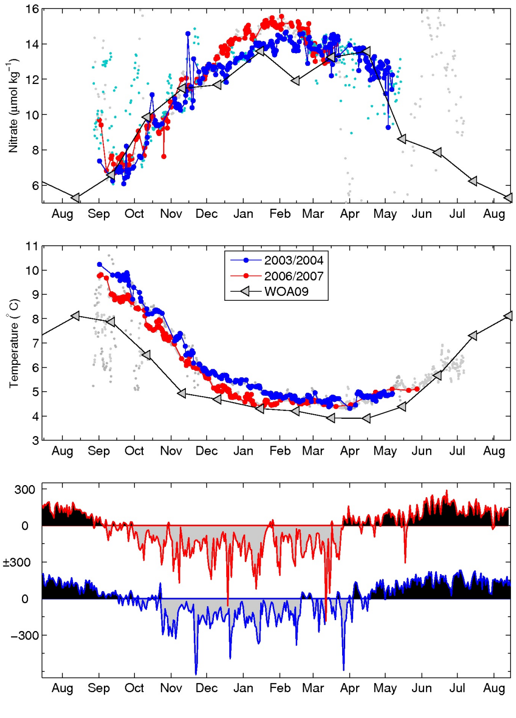

Figure 5: Time series of nitrate, temperature and net heat flux for two deployment periods that cover two mixed layer deepening/shallowing periods. The 2006/2007 winter was marked by a stronger heat flux and deeper mixed layer depth and hence a higher nitrate replenishment of the mixed layer in January/ February.

1.4 Chlorophyll-a: in-situ versus satellite from moored time series,

data: moored chlorophyll and TS sensor, surface buoyancy fluxes (atmospheric reanalysis), Main reference related to this study: Bunsen 2016/(in prep)

The Critical-Depth-Hypothesis, formulated in 1953, was traditionally hold liable to explain phytoplankton dynamics in winter and spring. According to it, the phytoplankton population is incorporated in the mixed layer convection. The key factor determining its growth is the light availability within the mixed layer. However, the Critical-Depth-Hypothesis has more recently been challenged by several authors proposing a number of alternative criteria for the onset of the phytoplankton spring bloom. Particularly in the North Atlantic, the Critical-Depth-Hypothesis is not sufficient to explain all spring blooms. A key parameter to estimate the algal biomass in seawater is the chlorophyll-a concentration. It can be determined by analysis of the ocean colour as observed by satellites. Meanwhile at high latitudes, data from remote sensing is not available during the poorly lit winter months. In addition observations in key areas, representative for a larger region may help to overcome the winter “blindness” of satellites. Making use of moored Chlorophyll sensors from the period 2004 to 2007 from the Central Irminger Sea, a comparison has been done. The results of two years of measurements suggest qualitatively fair agreement between satellite and in-situ data. In autumn (October and November), all measurements are found to confirm the Critical- Depth-Hypothesis, where phytoplankton losses occur with the diminishment of light and the increase of mixed layer depth. The onset of positive net growth, found in December, can be explained by weakened grazing pressure according to Behrenfeld’s [2010] Dilution-Recoupling-Hypothesis. In spring, rapidly enhanced growth is triggered and leads to a peak in chlorophyll concentration. Its timing matches with the occurrence of the mixed layer depth maximum and the onset of mixed layer shoaling.

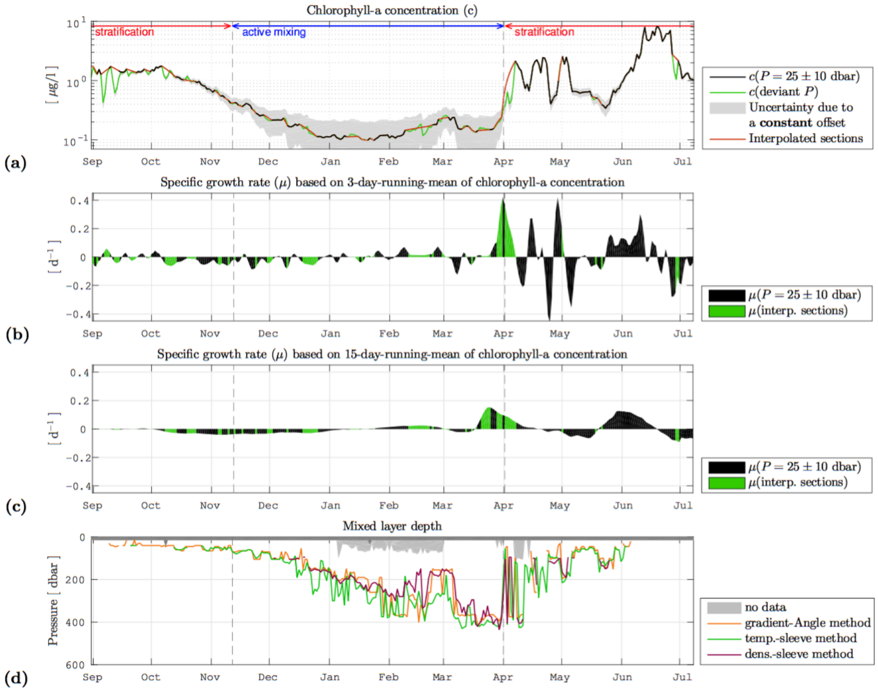

Figure 6: Parameters deduced from mooring data CIS 6 (yearly cycle 2006/2007) are shown. The initiation of the active mixing phase is set approx. at the point when the deepening mixed layer has engulfed the moored chlorophyll sensor. Its end is assigned to the point when the MLD reaches its maximum. P is the pressure at sensor depth of the moored fluorometer.

2. South Atlantic Sub-tropical Gyre

data: BGC-Argo, remote sensing of altimetry, atmospheric data, bio-optical model of primary production.
Main reference related to this study: Bittig et al., (in prep)
The SASTG is one of the most oligotrophic zone of the open ocean (together with its South Pacific counterpart) and hence a key experimental zone in the context of increasing stratification and associated extension of oligotrophic areas.

As an example, a 5.5 year time series from the same BGC-Argo float is available and under consideration as part of this study (Figure 5). The work of Bittig (2014)[2] already looked at the balance between nutrient utilization/production and O_2 production/utilization as well as their biogeochemical depth structure and seasonal evolution. In addition, net community production was quantified for the open ocean South Atlantic, remote from any time series stations that are usually essential. During AtlantOS, this work is being expanded and emphasis put on the link with bio-optical proxies in the water column. **They provide a proxy of phytoplankton abundance and phenology, allowing differentiation between Deep-Chlorophyll Maxima and Deep-Biomass Maxima and their variation, as well as estimation of primary productivity. In addition, the study addresses the role of mesoscale features on nutrient supply and productivity in the strongly stratified subtropical gyres with the aim to arrive at a better understanding of the mechanisms and how production is fueled in the subtropical Atlantic Ocean.**

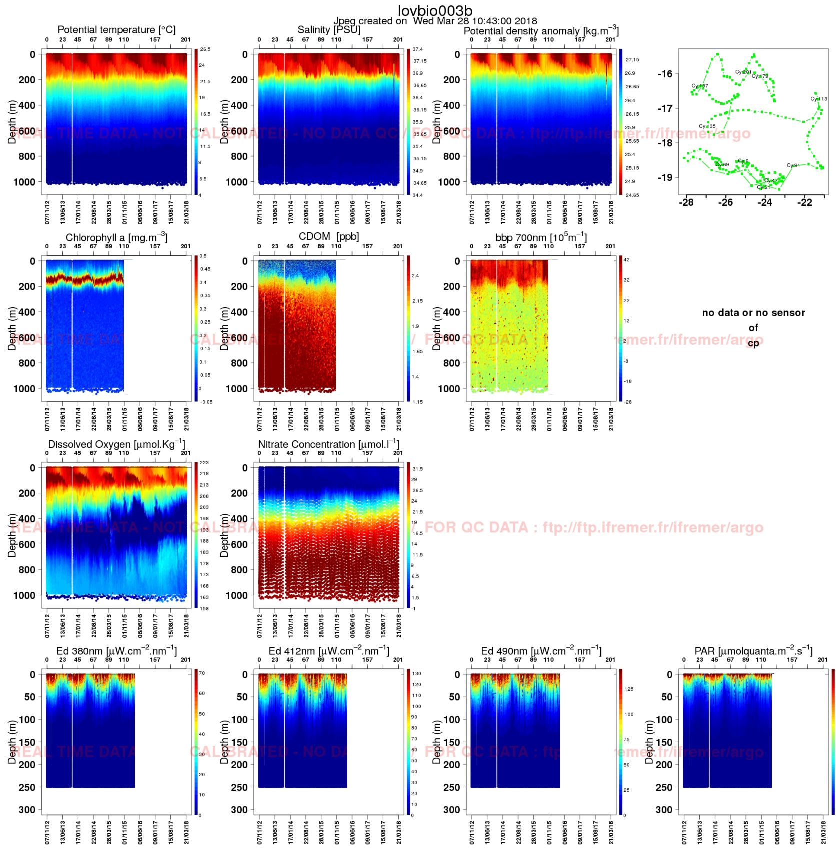

Figure 7: South Atlantic sub-topical gyre. Time-series of a BGC-Argo float measuring, over the 0-1000m water column and at a 10-day interval, various physical, chemical and optical variables. The time-serie here presented is still on-going after a deployment in October 2012. It is completed by analysis of Ocean coulor, mesoscale structures identified through satellite altimetry and bio-optical modelling of primary production to evaluate a possible closure of the C, N and O budget in this ultra-oligotrophic area.

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[2] Bittig, H.C. (2014). Towards a Quantum Leap in Oceanic Oxygen Observation – From Oxygen Optode Characterization to Autonomous Observation of Gas Exchange and Net Community Production. PhD thesis, 215 p., http://oceanrep.geomar.de/id/eprint/26558

3. Whole Atlantic basin

- From large dataset (Organelli et al., 2017a) collected in various biogeochemical provinces of the Atlantic, we have begun to undertake comparative analysis of regional bio-optical and biogeochemical specificities, including NASPG, NASTG & SATSTG. In particular, it was shown that high latitude environments, when compared to low latitude ones, present marked differences in bio-optical signatures (possibly linked to balance between phytoplankton biomass and colored dissolved organic matter). These differences are responsible for “bio-optical” anomalies, which could possibly impact on the accuracy of ocean color product retrieval using generic (established for the global scale) algorithms (Organelli et al., 2017b).
- From the large BGC-Argo data base analysis, a specific focus has been carried on the presence of Deep-Chlorophyll Maxima in stratified environment and their potential role as a nutrient trap and hence in organic carbon synthesis. These phytoplankton features are indeed missed by ocean remote sensing, resulting in an observational and hence knowledge gap. It results (Cornec et al., in prep) that the presence of DCM in subtropical environment (both NASTG and SASTG) appears essentially as the consequence of phytoplankton photo-acclimation (more Chlorophyll synthetized at low light). By contrast, in sub-equatorial waters like the Guinea Dome the permanent DCM is always associated to a permanent maximum in particulate organic carbon (revealed by the backscattering coefficient measured by floats). This reveals the potential key role of such feature in regulating carbon cycle and deep ecosystem fueling in such environments.
- From the large GLODAPv2 data-base of ship-based observations, Sauzède et al. (2017) developed neural network-based parameterizations to estimate macronutrient concentrations and the inorganic carbon system variables from easily observed input variables of T, S, and O_2. These parameterizations were improved and the carbon system estimates refined by verifying their consistency with carbonate chemistry, which provides carbon system estimates *with realistic, local uncertainties* (Bittig et al., in revision). This technique was applied to surface underway observations across the whole Atlantic basin and compares favorably to concurrent surface $p\mathrm{CO}_2$ measurements, which illustrates its potential to interconnect data from different parts of the global observing system (ship-based hydrography, Argo-O_2, underway).

4. Summary of indices and metrics for production and export

Table 1: Summary of indices and metrics for production and export. In complement to the specific AtlantOS activities related to the development and test of indices and metrics for production and export, the present table also summarizes outcomes of (recent) works with respect to the processes here under consideration. The chosen criteria for their selection was that relevant processes have been (or could be in the near-future) addressed by remotely operated techniques either satellite (ocean color, altimetry) or in situ autonomous platforms / (floats, gliders, moorings) and complemented by meteorological data analysis / reanalysis. Underlined references are outcomes of AtlantOS research activities and referenced in section 5 of the document while other references are listed at the end of this Table 1.

Biogeochemical process investigated	Metrics or indices for	Data and approach	Potential use and impact	References
Production	Phenology of phytoplankton biomass and production	Bioregionalisation of phytoplankton biomass through clustering of normalized time serie of satellite Chla	Unique and synoptical way to delineate coherent bioregions through identification pixel with similar Chla seasonal cycle. Baseline for regional biogeochemical (and ecosystem) studies addressing potential phenological changes due to climate change-driven physical forcing	D'Ortenzio & D'alcala, 2009; Lacour et al., 2015
Production	Spring bloom initiation	Satellite time series: Biomass threshold-based method	Address potential phenological changes due to climate change-driven physical forcing	Siegel et al., 2002; Brody et al., 2013
Production	Spring bloom initiation	Satellite time series: rate of biomass change method	Address potential phenological changes due to climate change-driven physical forcing	Brody et al., 2013;
Production	Spring bloom initiation	Satellite time series: rate of biomass change method + average light in the mixed layer threshold	Address potential phenological changes due to climate change-driven physical forcing	Lacour et al., 2015
Production	Spring bloom initiation	Satellite time series: method based on	Address potential phenological changes due to climate change-driven physical forcing	Brody et al., 2013

		cumulative serie of Chla		
Production	Spring bloom initiation	Argo TS data: time of mixed layer shoaling	Address potential phenological changes due to climate change-driven physical forcing	Mignot et al., 2018
Production	Presence of transient winter blooms	BGC-Argo data: average Chla and b_{bp} within the mixed layer	Address potential phenological changes due to climate change-driven physical forcing	Lacour et al., 2017
Production	Nature of phytoplankton populations	Gliders or BGC-Argo floats bio-optical indices (Chla/bbp) acquire in the mixed layer	Balance between large (e.g. diatoms) and small (nano- and pico) during phytoplankton successions (associated to blooms);	Cetinic et al., 2015 Lacour et al. 2017
Export	Large aggregate sinking	Analysis of spikes in vertically highly resolved bio-optical 0-1000m profiles (Chla, b_{bp}) acquired by gliders or BGC-Argo floats	Quantifying the carbon flux delivered to the mesopelagic layer by large particles and their fragmentation during post-bloom periods in the North Atlantic subpolar Gyre	Briggs et al., 2011 Briggs et al. in prep
Export	Mixed layer pump	Argo TS data combined with remotely sensed estimation of backscatterrering coefficient, proxy for Particulate Carbon	Identifying the period and the magnitude of the carbon flux delivered to the mesopelagic layer associated with alternation of mixed layer shoaling and deepening during the winter spring transition (regional/ global scale)	Dall'Olmo et al., 2016;
Export	Mixed layer pump	Analysis of gliders and BGC-Argo floats b_{bp} time series in the mesopelagic layer.	Identifying the period and the magnitude of the carbon flux delivered to the mesopelagic layer associated with alternation of mixed layer shoaling and deepening during the winter spring transition (regional/ local scale)	Lacour et al. (submitted)
Export	Eddy-frontal pump	Deep anomalies in hydrological, bio-optical proxies and oxygen acquired gliders or BGC-Argo floats	Identifying (local/regional) signature of particle injection at depth due to sub-mesoscale subduction processes	Omand et al. ,2015 Llort et al., 2018

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5. Concluding remarks

The indices baseline assessments presented in this deliverable and derived by AtlantOS R&D in the context of WP5 may convert in the future into operational products. The work presented in this deliverable was only possible through the coordinated activities in different AtlantOS workpackages: in particular, it benefited from the enhancement of the observing capabilities of ship based (WP2 and its subtasks) and autonomous observing networks (WP3 and its subtasks) and the enhancement of data access (WP7). Moreover, and maybe even more important from an AtlantOS legacy perspective, it benefited from what AtlantOS as a whole contributed in a substantial way: an improved operational service of established ocean observing networks (JCOMM) and (meta-)data management facilities (Coriolis, EMODnet) and linked to a data integration facility, most importantly the Copernicus marine environmental Monitoring Service providing for example satellite data, reanalysis data.

A future routine generation of these indices should closely link with the Copernicus climate change service (climate.copernicus.eu) and the European Environment Agency (www.eea.europa.eu/data-and-maps/indicators). At these levels the link with other climate indices can be created (e.g. WP5 deliverable D5.3: Climate Indices). Such linkages have been shown to be very successful in supporting and guiding advice strategies (see e.g. EU reports such as “Climate Change and European Fisheries” https://publications.europa.eu/s/go3l) for example in the context of specific services such as ecosystem services for fisheries by ICES.

SCIENTIFIC VALORISATION OF THE ANALYSIS

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