SEVENTH FRAMEWORK PROGRAMME THEME 7 Environment

Collaborative project (Large-scale Integrating Project)

Project no: 246 933

Project Acronym: EURO-BASIN

Project title: European Basin-scale Analysis, Synthesis and Integration

Deliverable 2.9 Final report incorporating scientific papers: detailing progress in field of particle aggregation and consumption

Contributors: A. MARTIN (NOC), C. DE LA ROCHA (CNRS-UBO), R. BELLERBY (UNI RESEARCH; NIWA), M. KOSKI (DTU), B. SALIHOGLU (IMS-METU), A. VISSER (DTU)

Due date of deliverable: Nov 2014
Actual submission date: Nov 2014
Organisation name of the lead contractor of this deliverable: NOC

Start date of project: 31.12.2010   Duration: 48 months
Project Coordinator: Michael St John, DTU Aqua

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission)	
RE	Restricted to a group specified by the consortium (including the Commission)	
CO	Confidential, only for members of the consortium (including the Commission)	

Deliverable 2.9 "Final report incorporating scientific papers: detailing progress in field of particle aggregation and consumption, made in grant" is a contribution to all Tasks in WP2.

Responsible: Adrian Martin (NOC)
Start month 1, end month 48

Executive Summary:
This report provides a summary of the work done under WP2 to advance our knowledge of the biological carbon pump. More specifically, we highlight the work that spans from the collation and analysis of extant data, through focussed field, lab and mesocosm work on the characteristics and dynamics of marine aggregates through to recommendations and examples of how these processes can be represented in models.

Relevance to the project & potential policy impact:
This deliverable will have an indirect effect on policy through WP6 by assisting in the refinement of how the key process of the biological carbon pump is represented in models.

Access to Data and/or model code (where relevant):
Data from field campaigns and mesocosms are currently being archived in www.PANGAEA.de with full public access. All related data from field and lab work will be submitted December 2014.

Full EURO-BASIN DataSet Compilation at www.pangaea.de > EURO-BASIN

Report:
This report presents highlights of the research done under WP2, specifically under the headings of

- Synthesising measurements of the biological carbon pump (BCP)
- The influence of zooplankton on the BCP
- Temporal variability in the BCP and associated biogeochemistry
- Characterisation of the sinking flux constituting the BCP
- The interplay of zooplankton and minerals in influencing the BCP
- Development of new algorithms to represent the BCP
- Modelling the BCP

Synthesising measurements of the biological carbon pump (BCP) (NOC lead)

Although a deliverable for WP1, WP2 researchers were responsible for compiling two valuable new and complementary datasets for studying and parameterising the biological carbon pump. The first (le Moigne et al., 2013b; data published on PANGAEA as doi:10.1594/PANGAEA.809717), synthesised all current estimates of export using the Thorium technique. The second (Torres et al., 2013; data published in PANGAEA as doi.pangaea.de/10.1594/PANGAEA.807946) brought together ~5000 direct observations of the sinking flux at all depths and times of year across the Atlantic, from Arctic to Antarctic. The two ESSD papers describing the data have been viewed 1,574 and 648 times respectively. The data have been used to develop a parameterisation for sinking flux which has already been used by other workpackages to validate models (WP6) and value the biological carbon pump (WP7).

The influence of zooplankton on the BCP (DTU Aqua lead)

The work focused on three questions:

1) *Which species / geneses in the zooplankton community contribute to particle degradation (decreasing the efficiency of the biological pump) and which will perform vertical migration and enhance active carbon transport (increasing the efficiency of the biological pump)?*

Our results from the Trondheim mesocosm experiment showed that calanoid copepods are typically only able to feed on small suspended particles and will therefore not contribute to degradation of sinking aggregates, but will instead enhance vertical transport by re-packaging their food to fast-sinking fecal pellets. In contrast, harpacticoid copepods and *Oncaea* spp. are only able to feed on aggregates, and will therefore mainly contribute to degradation of sinking particles (Fig. 1).

2) *Which activities of these two groups (copepods contributing to flux degradation vs. copepods enhancing the vertical transport) have a potential to induce most variability to the efficiency of the biological pump?*

Our results from Meteor M87 cruise show that while calanoid respiration and egg production or harpacticoid feeding on marine snow vary 2-3 times depending on station and time (respiration and egg production) or depending on the quality of marine snow (harpacticoids), fecal pellet production of calanoids can vary up to 6 times between locations and time. To be able to predict the effect of different zooplankton on the efficiency of biological pump we would therefore need to understand the environmental dependency of all of these processes, though with a particular focus on fecal pellet production.
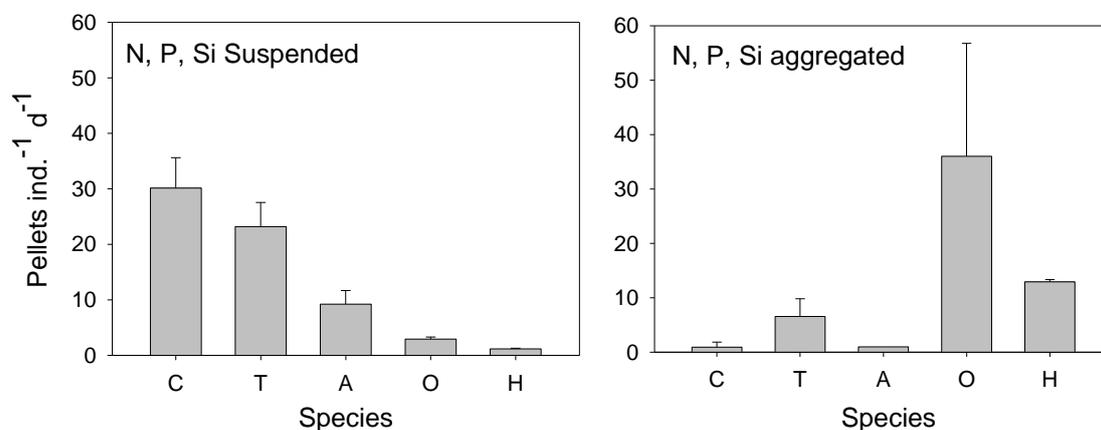
Fig. 1. Pellet production of different copepod species feeding on suspended vs. aggregated food in a mesocosm dominated by diatoms (enriched with N, P, Si; mean $\pm$ SD). The figure shows that calanoid copepods Centropages spp. (C), Temora longicornis (T) and Acartia sp. (A) mainly feed on suspended food, while harpacticoids (H) and Oncaea spp. only feed on aggregated food.

3) *Are the changes in zooplankton community structure (flux degraders vs. flux enhancers) reflected in the observations of vertical flux?*

Our results from Meteor and James Cook cruises as well as from Greenland work show fast and large fluctuations in the abundance and community composition of zooplankton,

often with a dominance of particle-colonising copepods. Based on the experimental results, it appears clear that a community dominated by particle-degraders can consume most of the sinking particles before they leave the euphotic layer (Table1), although that is not directly obvious based on the preliminary results from the PAP site.

Table 1. Total minimum carbon consumption of the zooplankton community (mg C m^{-2} d^{-1}) during the different visits to the three stations sampled during the Meteor cruise. The number in parenthesis shows the percentage (%) of the contribution of small particle-colonizing copepods. As most of the carbon ingested by particle-colonising copepods will be respired in or close to the euphotic layer, at times and stations of high dominance of these species (e.g., station 1 in late April) vertical flux should be reduced.

| Visit #	Station 1	Station 2	Station 3
1. (start April)	0.25 (3.4)	0.78 (2.4)	3.54 (1.1)
2. (mid April)	0.14 (10)	1.04 (1.9)	
3. (end April)	1.21 (71)		

Temporal variability in the BCP and associated biogeochemistry (Uni Research lead)

1) *Stoichiometry*: Analyses have been conducted on data from three time-series stations in the Nordic Seas and the North Atlantic: the Iceland Sea time-series station (68.00°N, 12.68°W), Station M, Norwegian Sea (66.00°N, 2.0°E), and the PAP site in the North Atlantic (49°N, 16.5°W), with the main objective to estimate NCP, new production and stoichiometric relationships, based on climatology. The PAP analysis found seasonal new production of 0.37±0.14 mol N m-2, and seasonal NCP of 4.57±0.27 mol C m-2, and an export ratio of 15%. Further north, the mean annual NCP and new production in the Iceland Sea was estimated to 6.1±0.9 mol C m-2 and 0.23±0.18 mol N m-2, respectively, while the mean annual NCP and new production in the Norwegian Sea was estimated to 5.8 mol C m-2 and 0.36 mol N m-2, respectively. All three regions show C:N ratios for biological production clearly higher than Redfield (6.6). Frigstad et al. (2014) found a clear temporal and regional variability in seston C:N in Arctic and sub-Arctic regions, and generally higher than Redfield. This challenges the use of fixed stoichiometry in these regions.

2) *Impacts of climate change and acidification on BCP*: New understanding of ecosystem-biogeochemical coupling under a changing climate have been developed following a mesocosm study on the effects of ocean acidification on ecosystem function, biogeochemical cycling and pelagic-benthic exchange. Under high CO2, a shift from E. Huxleyii dominated plankton communities following reductions in competitive fitness resulted in reduced calcification and less export through a decrease in the ballast effect. This has dramatic consequences for the partitioning of CNPOSi between the pelagic and exported material which when scaled to the Basin scale would perturb carbon and energy flow to intermediate depths.

3) *Carbon chemistry during a bloom:* New data from the EUROBASIN Meteor M87 cruise to the North Atlantic on the dynamics of spring bloom carbon biogeochemistry show that there was only a moderate net seasonal perturbation of the euphotic zone carbonate chemistry. Productivity drew down the pCO2 but gas exchange was

efficient to counter the excesses of any biological signal. Nevertheless, the biological drawdown of carbon was significant. For the first time in this region, the CO2 system was accurately over-determined with the addition of a new pH approach, which has provided an excellent baseline for future studies of ocean acidification.

Characterisation of the sinking flux constituting the BCP (NOC lead)

Potential changes in ocean stratification and associated changes in sinking particle characteristics (composition, size, sinking speed) and export (magnitude and remineralization rate) are key to understanding the mechanisms leading to the initiation of a spring bloom. During the cruise Meteor M87 in the Iceland Basin and Norwegian Basin, small and large sinking particles between 50-650 m were studied using the Marine Snow Catcher (MSC). The measured pre-bloom fluxes were of similar magnitude to bloom and post-bloom export and largely comprised of small particles (<0.5mm). Our data provides evidence that small particles are being exported to > 500 m (Fig. 2) via 'detrainment', which occurred during a period of intermittent destabilization of the water column. Yet, loss through detrainment was likely balanced by phytoplankton carbon fixation, rendering the two sites at near steady state. Our findings contradict the traditional view that pre-spring bloom export is negligible and that small particles do not contribute significantly to export to the lower mesopelagic (500-1000 m). Moreover, pre-bloom export via detrainment may be an important source of carbon for the mesopelagic biota, potentially alerting the ecosystem to the forthcoming spring bloom, and may further contribute significantly to the annual carbon fixation and storage at depth.
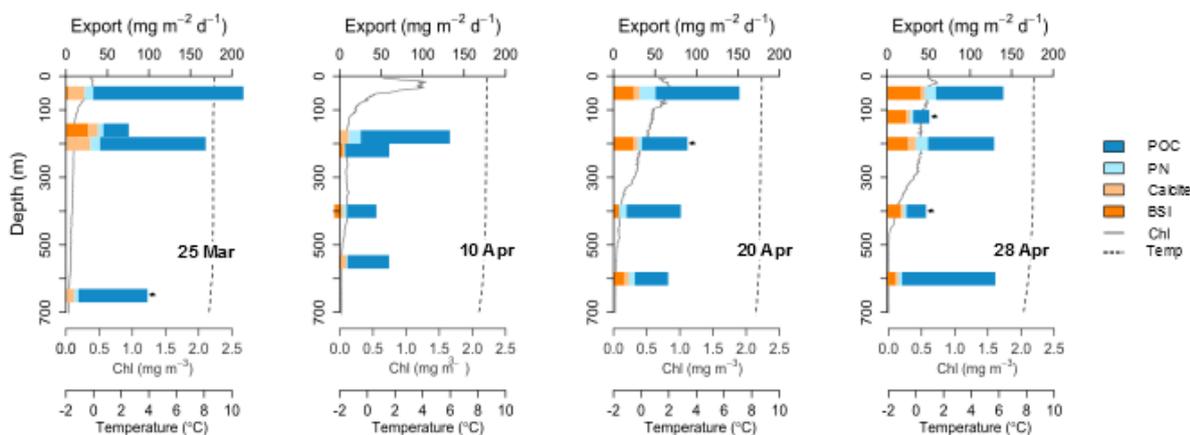
Figure 2. Flux profiles of small sinking particles in the Iceland Basin during Meteor M87. Fluxes of particulate organic carbon (deep blue), particulate nitrogen (light blue), calcite (light orange) and biogenic silica (deep orange) were measured during four visits between 25 Mar – 28 Apr 2012. Average chlorophyll and temperature during each visit based on CTD profiles are shown by grey solid line and black dashed line, respectively.

The interplay of zooplankton and minerals in influencing the BCP (Brest lead)

We focussed on the influence of micro- or mesozooplankton on a population of phytoplankton in the process of aggregation, with or without extra ballast minerals present.

The four main results of use in models are:

1) The presence of ballast minerals can inhibit grazing by small zooplankton as measured via rates of ammonium excretion per zooplankter. The minerals either serve as an obstacle to ingestion of food or, if the zooplankton are non-selective

feeders, by decreasing the amount of organic matter ingested per volume of mass ingested per individual per time. This may have consequences explorable via modeling- reducing the phytoplankton mortality rate, slowing the transfer of primary production into other parts of the food web, increasing the amount of primary production that gets exported as opposed to retained in upper ocean food webs, etc.

2) Although ballast minerals can trigger aggregation, they do NOT result in "more" aggregation (in a closed system), than would occur over a longer period of time at a given TEP concentration and abundance of phytoplankton cells. It would be of interest to look at this in a model to see the end result on export efficiency under different conditions (e.g., respiration rates and zooplankton grazing pressures).

3) In the mesocosm studies, the sinking POC flux in each bag was strongly correlated to net dissolved silicon uptake in the bag over the course of the experiment and to the sinking flux of biogenic silica in each bag. Interestingly, the sinking flux had a higher Si/C ratio than the biomass that remained suspended in the mesocosms, suggesting that "dead" silica and/or silica-containing cells were being preferentially exported over non-ballasted organic matter. All of the above was true regardless of whether or not there were copepods in the mesocosms and whether or not silicate was included in the daily nutrient additions. In addition, standing stocks were highest in mesocosms with copepods (the recycled ammonium seemed to keep the phytoplankton happy) but high standing stocks of POC did not translate into higher sinking fluxes (the only correlation was with the biogenic silica).

4) Calcite in the form of coccoliths results in smaller, denser, more rapidly sinking aggregates. The same amount of calcite in the form of foraminiferan tests can manage to accumulate a little clinging clump of organic matter as they sink > 800 meters per day, but any aggregate it collides with is fragmented into smaller, more slowly sinking (or even non-sinking) aggregates. How common would this be in the real world remains a question to be addressed. Using coccolith ballasting to increase sinking speeds in a model would not be difficult, though, related to both density addition and the estimated decrease in porosity of the aggregates with compaction. We don't have the equivalent numbers for silica ballasting, though, and for clay minerals the story is even less clear (the effect is less pronounced).

Development of new algorithms to represent the BCP (joint lead)
The algorithm development and recommendations produced under WP2 have previously been described fully in report D2.7 to where the reader is referred.

Modelling the BCP (lead IMS-METU)
Within the scope of EUROBASIN project, the development and implementation of the biological carbon pump processes into a 1D model comprised 3 major parts:

1)   Implementation of the 1D lower trophic pelagic ecosystem model (NAGEM) to 3 time-series stations in the North Atlantic (Figure-1a). The aim was to capture different environments with distinct physical and ecosystem characteristics, so that in the algorithm implementation phase, we could evaluate the success of the algorithms to mimic their generic capabilities. This item has also connections with historical data mining provided by WP1 & WP2 (Figure 1b&c). Our initial results were compared with the dataset provided.

2)   Implementation of algorithms that were previously used by other models and had distinct functionalities in reference to the structure of carbon flow through the water column. Our main focus was the 3 models used in WP6 basinwide runs (ERSEM, MEDUSA and PISCES). These models had their own unique equation sets defining terms like multiple plankton functional types (PFT's), aggregation of organic matter and ballasting effect due to the presence of mineral structures (Figure- 1c). Similar algorithms and definitions from other models in literature were also considered when defining the algorithm sets to be tested in WP2 Task2.4.

3)   In parallel to already used algorithms by other models, experimental results, and theoretical inputs from various partners of EUROBASIN were also considered in an algorithm testing phase in order to provide the state-of-the-art information to be included. These algorithms include zooplankton dynamics like "flux feeding mechanism and diel vertical migration" received from WP4, and comments and observational input regarding aggregation and ballasting effect from other tasks of WP2. In addition to those, we have also manipulated the mineralization mechanisms of the ecosystem compartments in the 1D model to provide further information to global runs provided in WP6.

4)   The final stage of our work was to assess algorithms to be used in WP6 global runs. Our 1D modelling gave us the ability and insight to redefine key elements in ecosystem structure of the models and flow of matter within compartments were modified. On our advice, key suggestions include a) addition of a zooplankton flux feeding mechanism b) a detailed aggregation routine to be used in future studies c) a mechanism to represent ballast effect d) suggestions on applying a range of mineralization rates to be tested in 3D.

Figure 3: Locations of the time-series stations in the North Atlantic , POC export at BATS station (original model implementation) and implemented algorithms at PAP station. Red line represents ballasting and aggregation input. Blue line represents original.
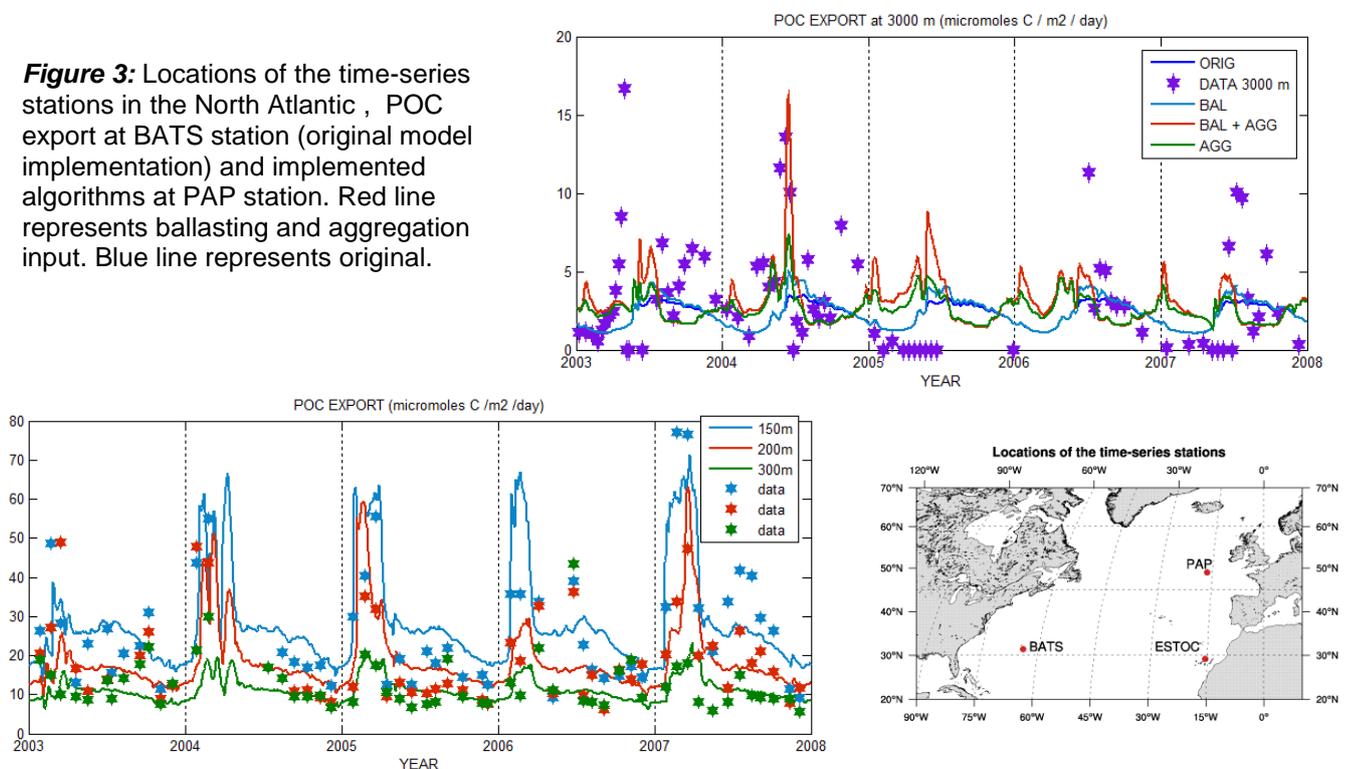
These suggestions initially were implemented in GOTM-ERSEM 1D model to create a link between WP2 and WP6. 3D results will be provided within the scope of WP6. The main challenge of this item was to provide enough information to represent effects present in nature, and at the same time, the recommendation had to feasible for inclusion in 3D models. At the end, our theoretical studies were designed in a way that the applicability was highest. The suggestions included information that were parallel to the theoretical and practical structure of the models in WP6.

Scientific peer-reviewed publications:
Published (and Open Access available via FP7 OpenAIRE):

Koski Marja, Swalethorp Rasmus, Kjellerup Sanne, Nielsen Torkel Gissel (2014). **The mystery of Microsetella: combination of sac- and broadcast-spawning in an Arctic fjord**. *Journal Of Plankton Research*, 36(1), 259-264. http://dx.doi.org/10.1093/plankt/fbt117

Torres-Valdes, S et al. (2013): Compilation of downward flux observations from sediment trap deployments in the Atlantic Ocean - Contribution to EURO-BASIN's Data integration. doi:10.1594/PANGAEA.807946, *Supplement to:*

Torres-Valdes, Sinhue; Painter, Stuart; Martin, Adrian; Sanders, Richard J; Felden, Janine (2013): Fluxes of sedimenting material from sediment traps in the Atlantic Ocean. *Earth System Science Data Discussion*, 6, 541-595

Le Moigne, F. A. C., Gallinari, M., Laurenceau, E., and De La Rocha, C. L.: Enhanced rates of particulate organic matter remineralization by microzooplankton are diminished by added ballast minerals, Biogeosciences, 10, 5755-5765, doi:10.5194/bg-10-5755-2013

Silyakova, A. et al. 2013. Pelagic community production and carbon-nutrient stoichiometry under variable ocean acidification in an Arctic fjord, Biogeosciences, 10, 4847–4859

Frigstad, H., T. Andersen, D. O. Hessen, E. Jeansson, M. Skogen, L.Naustvoll, M. Miles, T. Johannessen, R. Bellerby 2013. Long-term trends in carbon, nutrients and stoichiometry in Norwegian coastal waters: Evidence of a regime shift, Progress in Oceanography, Vol 111, p. 113–124 http://dx.doi.org/10.1016/j.pocean.2013.01.006

L. Resplandy, A.P. Martin, F. Le Moigne, P. Martin, A. Aquilina, L. Mémery, M. Lévy, R. Sanders, 2012. How does dynamical spatial variability impact 234Th-derived estimates of organic export? Deep Sea Research Part I: Vol 68, October 2012, Pages 24–45

Jeansson, E., A. Olsen, T. Eldevik, I. Skjelvan, A. M. Omar, S. K. Lauvset, J. E. Ø. Nilsen, R. G. J. Bellerby, T. Johannessen, and E. Falck (2011), The Nordic Seas carbon budget: Sources, sinks, and uncertainties, Global Biogeochem. Cycles, 25, GB4010, doi:10.1029/2010GB003961.

Frigstad, H., Andersen, T., Hessen, D. O., Naustvoll, L.-J., Johnsen, T. M., and Bellerby, R. G. J. 2011. Seasonal variation in marine C:N:P stoichiometry: can the composition of seston explain stable Redfield ratios?, Biogeosciences, 8, 2917-2933, doi:10.5194/bg-8-2917-2011

Frigstad, H., T. Andersen, R. G. J. Bellerby, A. Silyakova, and D. O. Hessen (2014), Variation in the seston C:N ratio of the Arctic Ocean and pan-Arctic shelves, *Journal of Marine Systems, 129*(0), 214-223.

Giering, S. L. C., Richard Sanders, Richard S. Lampitt, Thomas R. Anderson, Christian Tamburini, Mehdi Boutrif, Mikhail V. Zubkov, Chris M. Marsay, Stephanie A. Henson, Kevin Saw, Kathryn Cook & Daniel J. Mayor (2014) Reconciliation of the carbon budget in the ocean's twilight zone. Nature, 507, 480–483, doi:10.1038/nature13123

Le Moigne, F. A. C., Henson, S. A., Sanders, R. J., and Madsen, E. (2013b) Global database of surface ocean particulate organic carbon export fluxes diagnosed from the 234Th technique, Earth Syst. Sci. Data, 5, 295-304, doi:10.5194/essd-5-295-2013

Sanders, R., Stephanie A. Henson, Marja Koski, Christina L. De La Rocha, Stuart C. Painter, Alex J. Poulton, Jennifer Riley, Baris Salihoglu, Andre Visser, Andrew Yool, Richard Bellerby, Adrian P. Martin. 2014. The Biological Carbon Pump in the North Atlantic *Progress in Oceanography, In Press,*

K Schmidt, CL De La Rocha, M Gallinari, G Cortese (2014) Not all calcite ballast is created equal: differing effects of foraminiferan and coccolith calcite on the formation and sinking of aggregates. Biogeosciences 11 (1), 135-145

Submitted:
- Daniels, C. J., A. J. Poulton, M. Esposito, M. Lund Paulsen, R. Bellerby, M. St John and A. P. Martin.Phytoplankton dynamics in contrasting early stage North Atlantic spring blooms: composition, succession, and potential drivers, in prep
- Giering, S., R. Sanders , A. Martin , C. Lindemann , D. J. Mayor , M. St. John. High export via small particles before the onset of the North Atlantic spring bloom. Submitted to Global Biogeochemical Cycles.
- Reggiani E., Bellerby R.G.J. and Sørensen K., Scaling down ocean acidification monitoring, *submitted IEEE Journal of Oceanic Engineering*

In preparation:
- Skjelvan, I., Jeansson, E. Rey, F, and Falck, E. , Mixed layer transport of carbon, nutrients, and oxygen in the Norwegian Sea and its related stoichiometry based on time series measurements. Manuscript in prep.
- K. G. Schulz, R. G. J. Bellerby, R. Bermudez, J. Budenbender, T. Boxhammer, J. Czerny, A. Engel, S. Febiri, S. Lischka, A. Ludwig, M. Meyerho¨fer, A. Larsen, A. Paul, M. Sswat , and U. Riebesell. Temperate phytoplankton blooms at increasing levels of atmospheric carbon dioxide: insights from mesocosm studies, in prep.
- Ulf Riebesell, Lennart Bach, Richard Bellerby, Rafael Bermudez, Tim Boxhammer, Jan Czerny, Aud Larsen, Andrea Ludwig, Kai Schulz. Ocean acidification impairs competitive fitness of predominant calcifying species, in prep
- Frigstad, H., S.A. Henson, S.E. Hartman, H. Cole, A.M. Omar, E. Jeansson, C. Pebody, and R.S. Lampitt, Links between surface productivity and deep ocean particle flux at the Porcupine Abyssal Plain (PAP) sustained observatory. Manuscript in prep.
- Bellerby R.G.J., Jeansson E., Nondal G., Daniels C.J., Esposito M., Skjelvan I., Reichelt T., Evolution of the marine carbonate system during the winter to spring transition in the North Atlantic, in prep