ICOS Symposium on the North Atlantic Carbon Cycle 19th March 2019

Agenda

08.30 -welcome

9.00 - Andy Watson (University of Exeter)- Overview - The sink for atmospheric carbon dioxide in the northern hemisphere oceans - a strong observational carbon cycle constraint

9.20 - Harry Lankreijer (Lund University) and Ben Pfeil (University of Bergen) - SOCAT and ICOS Carbon Portal

9.40 - Vas Kitidis (Plymouth Marine Laboratory)- (Talk via VC) Winter weather controls net influx of atmospheric CO_2 on the north-west European shelf

10.00 - Vlad Macovei (NOC) - Temporal variations in the carbonate system of the mid-latitude North Atlantic

10.20 - Clare Ostle (MBA) - Changes in productivity influence the variability of the North Atlantic carbon sink

10.40- Meike Becker (University of Bergen)- Trends in coastal fCO_2 and pH

11 – Refreshment Break

11.30- Wilhelm Petersen (Helmholtz-Zentrum Geesthacht (HZG) - Carbonate system measurements with FerryBox systems in Europe: current state and recent advancements

11.50 - Kath Seelmann (GEOMAR Helmholtz Centre for Ocean Research Kiel) - Characterization and long-term deployment of the first commercial autonomous analyzer for total alkalinity (TA) in seawater

12.10 - Richard Lampitt (NOC)- Downward particle flux of carbon at 3000m depth over 24 years in the Northeast Atlantic: What are the driving forces?

12.30 - Are Olson (University of Bergen)- Effects of deep mixing on subpolar North Atlantic carbon

13.00 - Lunch

14:00- Lidia Carracedo (NOC) - Overturning circulation regulates the North Atlantic nutrient pool and biological pump efficiency

14.20- Pete Brown (NOC) - Feedbacks between the Meridional Overturning Circulation and the accumulation of carbon in the North Atlantic

14.40- Aimee Coggins (University of Exeter) - An autonomous view of the carbon system

15.00 Refreshment Break

15.30 - David Ford (Met Office -UK) - Assimilating synthetic Biogeochemical-Argo observations into a global ocean model

15.50 - Socratis Loucaides (NOC) Development of Lab-On-Chip sensors for autonomous high-resolution carbonate chemistry and ocean acidification observations

16.10 - Richard S (NOC) to wrap up meeting

Abstracts

The sink for atmospheric carbon dioxide in the northern hemisphere oceans - a strong observational carbon cycle constraint

Andy Watson Ute Schuster, Peter Landschutzer, Jamie Shutler, Parvadha Suntharalingham

We examine how robustly the surface CO_2 observations in SOCAT can be used to specify the flux of atmospheric carbon dioxide into the oceans. For the north and tropical Atlantic and Pacific oceans and for the period since the early 90s to the present day, different methods of interpolation and averaging of the observations closely agree. This results in robust estimates of the ocean sink, that can be used with atmospheric inversions to give robust estimates of the northern hemisphere terrestrial sink also. In the southern hemisphere the sparseness of the data results in much less robust estimates, particularly for the decade of the 1990s.

SOCAT and ICOS Carbon Portal.

Harry Lankreijer (Lund University) and Ben Pfeil

Winter weather controls net influx of atmospheric CO_2 on the north-west European shelf

V. Kitidis, J.D. Shutler, I. Ashton, M. Warren, I. Brown, H. Findlay, S.E. Hartman, R. Sanders, M. Humphreys, C. Kivimäe, N. Greenwood, T. Hull, D. Pearce, T. McGrath, B.M. Stewart, P. Walsham, E. McGovern, Y. Bozec, J-P. Gac, S. van Heuven , M. Hoppema, U. Schuster, T. Johannessen, A. Omar, S.K. Lauvset, I. Skjelvan, A. Olsen, T. Steinhoff, A. Körtzinger, M. Becker, N. Lefevre, D. Diverrès, T. Gkritzalis, A. Catrijsse, W. Petersen, Y. Voynova, B. Chapron, A. Grouazel, P. E. Land, J. Sharples, P.D. Nightingale.

Shelf seas play an important role in the global carbon cycle, absorbing atmospheric carbon dioxide (CO_2) and exporting carbon (C) to the open ocean and sediments. However, the magnitude of these processes is not well constrained, not least because observations are interpolated in space and over multiple years. Here, we used 298500 observations of CO_2 fugacity (fCO_2) from a single year (2015), to estimate the net influx of atmospheric CO2 as 26.2 ± 4.7 Tg C yr-1 over the open NW European shelf (within the 200 m isobaths). We found that CO_2 influx from the atmosphere was dominated by influx during winter as a consequence of high winds, despite a smaller sea-air CO_2 gradient compared to summer. We further synthesized C-fluxes across the NW European shelf. C-burial was estimated as 1.3 ± 3.1 Tg C yr-1 from benthic process rates in the Celtic Sea. CO_2 efflux from estuaries to the atmosphere (24.4 ± 10.4 Tg C yr-1), practically removes river C-inputs (21.6 Tg C yr-1). In

contrast, the input from the Baltic Sea (12.6 ± 2.7 Tg C yr-1) likely contributes to export from the shelf. Inorganic-C accumulation was estimated as 1.0 ± 0.5 Tg C yr-1. C-export via the continental shelf pump and advection was 34.4 ± 6.0 Tg C yr-1. These results suggest that land-management policies which might alter the delivery of C to the NW European shelf would only have a modest effect on the open-shelf climate regulation service (net CO_2 influx from the atmosphere).

Temporal variations in the carbonate system of the mid-latitude North Atlantic

Vlad Macovei, Susan Hartman, Ute Schuster, Sinhue Torres-Valdes, Mark Moore, Richard Sanders

The ocean is a significant net sink for anthropogenically remobilised CO_2, taking up around 24% of CO_2 emissions. Without this sink climate change would proceed much faster. Thus, the status of this sink is a matter of considerable societal interest. The net uptake is a small element of a large natural carbon sink, hence evaluating net uptake is a complex problem. The North Atlantic Drift Region (NADR), a large area of the mid-latitude North Atlantic Ocean, is an important CO_2 sink.We calculated an average area integrated carbon flux of 0.064 Pg yr-1 into the ocean in the NADR, similar to past estimates. The North Atlantic circulation and surface water properties are changing, hence it seems likely that this sink and its various components may change. Here we use a high temporal resolution observational dataset from underway p CO_2 instruments on ships of opportunity, part of the ICOS observing network, to investigate changes in the surface ocean carbonate system of the NADR, as well as the relative contribution of physical and biological processes to these changes. In spite of the increase in atmospheric carbon dioxide partial pressure (pCO_2), seawater p CO_2 only shows higher variability rather than a statistically significant increasing trend.The larger delta p CO_2 leads to an estimated increase in CO_2 flux into the ocean of 10.8 ± 1.8 µmol m-2 hr-1 per year across the entire time series. This is 6% of the long term average of 183.9 µmol m-2 hr-1, making the NADR a stronger carbon sink. The seawater p CO_2 variability is mostly influenced by temperature and dissolved inorganic carbon (DIC) changes. In our study, 77% of the annual seawater p CO_2 changes are explained by these two terms. DIC is in turn influenced by gas exchange, biological production and vertical mixing. In an average year, the DIC drawdown by biological production, determined from nitrate uptake, is higher than the DIC increase due to atmospheric CO_2 dissolution in the surface ocean. The biological production influence on DIC and implicitly on seawater p CO_2 offsets most of the increase caused by gas exchange, more so in years with a high nutrient input or when the spring bloom starts earlier in the year. Using the rate of change of DIC and nitrate, we observed carbon overconsumption during the spring bloom at a C:N ratio of 9.6 ± 1.50. This study uses ship of opportunity data to demonstrate that the NADR has continued to absorb atmospheric CO_2 in recent years and has the potential to keep doing so, partly due to the influence of new biological production on the surface carbon budget. In addition, it allows direct intercomparison between two ICOS platforms: the UK-Caribbean line and the Porcupine Abyssal Plain fixed point observatory.

Changes in productivity influence the variability of the North Atlantic carbon sink

Clare Ostle, Peter Landschützer, Martin Edwards, Martin Johnson, Sunke Schmidtko, Ute Schuster, Andrew J. Watson, and Carol Robinson

The North Atlantic Ocean is a globally important sink of carbon dioxide (CO_2). However, the strength of the sink varies temporally and regionally. This study uses a neural network method to map the surface ocean $_p CO_2$ (partial pressure of CO_2 and flux of CO_2 from the atmosphere to the ocean alongside measurements of plankton abundance collected from the Continuous Plankton Recorder (CPR) survey to determine the relationship between regional changes in phytoplankton community structure and regional differences in carbon flux. The use of volunteer ships to concurrently collect these datasets demonstrates the potential to investigate relationships between plankton community structure and carbon flux in a cost-effective way. These results not only have implications for plankton-dynamic biogeochemical models, but also likely influence carbon export, as different phytoplankton communities have different carbon export efficiencies. Extending and maintaining such datasets is critical to improving our understanding of and monitoring carbon cycling in the surface ocean and improving climate model accuracy.

Trends in coastal fCO_2 and pH

Meike Becker, Are Olsen, Peter Landschützer, Abdirhaman Omar, Christian Rödenbeck, and Ingunn Skjelvan

For estimating air-sea fluxes of CO_2 in coastal regions the special characteristics of each region need to be considered when interpolating existing observations into maps of fCO_2. We developed a simple method to refine the existing open ocean maps towards different coastal seas. Using a multi linear regression based on the open ocean CO_2 map, bathymetry, satellite and reanalysis data such as chlorophyll a, mixed layer depth, ice concentration, sea surface temperature and salinity we produced monthly maps of 5 surface ocean f CO_2 in the northern European coastal seas (North Sea, Baltic Sea, Norwegian Coast and in the Barents Sea) covering a time period from 1997 to 2016. These maps were used to estimate trends in surface ocean fCO_2 and pH.

Carbonate system measurements with FerryBox systems in Europe: current state and recent advancements

Wilhelm Petersen, Yoana G. Voynova, Andrew King, Kai Sørensen

The European FerryBox community is operating several FerryBoxes in the seas around Europe. Besides measuring numerous essential ocean variables, like temperature, salinity, oxygen and chlorophyll fluorescence, investigations of the carbon cycle became a special focus in the Baltic Sea, North Sea and North Atlantic in the last few years. The North Atlantic is a key region of carbon uptake, enhancing ocean acidification, particularly in polar regions. From the temperate North Sea to the polar regions, FerryBoxes equipped with various state-of-the-art sensors are collecting different carbonate system parameters at high-frequency and spatial coverage, including pH and total alkalinity. This presentation gives an overview about ongoing FerryBox activities regarding the marine carbonate system and coupled biogeochemical processes. We focus on two examples, one examining a more than 6 years long time series of p CO_2 in the North Sea, and a second showing the first successful application of automated total alkalinity measurements along a transect in the Southern North Sea. Both of these demonstrate the benefit of making continuous measurements of carbonate system parameters with FerryBox systems.

Characterization and long-term deployment of the first commercial autonomous analyzer for total alkalinity (TA) in seawater

Katharina Seelmann, Steffen Aßmann, Tobias Steinhoff, Arne Körtzinger

Total alkalinity (TA) is one of the four key parameters of the marine CO_2 system and obligatory for the understanding of important biogeochemical processes in the ocean. Accordingly, the measurement of this variable is essential for ocean carbon observations. For high-resolution TA measurements with minimal personnel and instrumental effort, Kongsberg Maritime Contros GmbH (Kiel, Germany) develops a commercially available, rapid, automated underway analyzer based on a single-point open-cell titration principle with spectrophotometric pH detection. Our work deals with an intensive performance testing of this analyzer both in the laboratory and at sea, and finally, an automated long-term deployment of this system in the open ocean. The main outcome of the performance tests is, that the analyzer reaches the

high quality standards for TA measurements required within the oceanographic community with a precision of ± 1.1 µmol kg-1 and an accuracy of (-0.3 ± 2.8) µmol kg-1. Although a linear drift to higher TA values belongs to the normal behaviour of the system, this can be corrected by regular reference measurements giving consistent measurement results.
Furthermore, all test results and experiences are summarized in fundamental guidelines for long-term deployments of this analyzer. Finally, these guidelines are the bases for our autonomous long-term installation of the system on a North Atlantic VOS (voluntary observing ship) line to improve our observational capabilities for the marine CO_2 system in this area. First results of these deployments verify the good long-term performance of the analyzer.

Downward particle flux of carbon at 3000m depth over 24 years in the Northeast Atlantic: What are the driving forces?

Lampitt R.S., Pebody C.A, Yool A.

Organic carbon and associated compounds reaching the deep ocean as a result of gravitational settling can be considered as sequestered for prolonged periods of time. In the temperate Northeast Atlantic, the long-term variability in downward flux at 3000m depth occurs with a seasonal and interannual characteristic. In a general sense, this variability is to be expected. However the forcing factors which determine this have not to date been elucidated. We present the trends in flux over the past 24 years and the characteristics of the sinking material. We then use other contemporaneous data from the PAP sustained observatory, ARGO floats and from satellite remote sensing to explore the factors which may be responsible for this variability. Using a 1/12th degree resolution ecosystem model we outline which factors may affect this variability and long-term trend.

Effects of deep mixing on subpolar North Atlantic carbon

Are Olsen, Friederike Fröb, Meike Becker, Emil Jeansson, Abdirahman Omar et al.

The Irminger Sea in the subpolar North Atlantic is a region where deep mixing occurs. After a period of rather shallow mixing in the early 2000s, deep mixing has occurred regularly since 2008 as a consequence of frequent positive states of the NAO. Our observational records from this region now show that this affects both ocean inventories of carbon and surface ocean p CO_2. For example, during winters of deep mixing the region becomes a source of CO_2 to the atmosphere, and at the same time the inventory of anthropogenic carbon increases. These results will be presented, paradoxes highlighted and attempted reconciled, and need for more understanding outlined.

Overturning circulation regulates the North Atlantic nutrient

L. I. Carracedo, E. McDonagh, R. Sanders, C.M. Moore, P. Brown, S. Torres-Valdés, M. Baringer, D. Smeed, G. Rosón

The Meridional Overturning Circulation (MOC) plays a major role in the carbon cycle by meridional redistribution of organic and inorganic carbon and nutrients. Biological productivity and associated carbon uptake by the Biological Carbon Pump (BCP) in the Atlantic Ocean is supported by northward nutrient transport in the upper limb of the MOC. Changes in MOC strength might thus be expected to alter regional nutrient cycles and the strength and efficiency of the BCP. We combine observations from the RAPID, Argo and GO-SHIP International Programs in the North Atlantic, with time-varying inorganic nutrient (silicate, nitrate and phosphate) fields obtained through a Multilinear regression (MLR) method, to generate continuous time series of the basin-wide meridional nutrient transport for the 2004–2012 period. Repeat hydrographic observations at the 24.5°N section is used for additional in situ estimates of basin-wide nutrient transports during the period in order to evaluate the validity of this approach. We provide evidence for non-steady state behaviour of this system through 8.5 years of observations across 26.5°N which indicate significant (50%) nutrient transport variability and persistent net southward nutrient transport that exceeds external nutrient sources. Calculated transports of remineralised and preformed nutrient components across the section confirm a net negative BCP for the Atlantic region north of 26.5°N, reflecting transformation of northward transported remineralised nutrients into a southward transported preformed pool. Variability of these transports over the time series further indicates a decreasing preformed:remineralised ratio denoting an increasing BCP efficiency. Overturning circulation strength dominates these nutrient transports on all time scales (MOC explaining ~90% of the variance), suggesting that the observed non-steady state behaviour is a likely consequence of transient responses to circulation changes.

Feedbacks between the Meridional Overturning Circulation and the accumulation of carbon in the North Atlantic

Peter Brown, Elaine McDonagh, Richard Sanders, Brian King, Mark Moore, Andrew Yool, Andrew Watson, Peter Landschützer, Damien Desbruyères, Ute Schuster, Vlad Macovei

The ocean carbon sink currently mitigates the continuing build-up of carbon dioxide in the atmosphere by absorbing approximately 30% of all additional CO_2 derived from human activities. Within the Atlantic, the overturning circulation plays a key role, driving the carbon uptake associated with biological productivity (transporting nutrients to productive regions) and the physical carbon pump (heat fluxes changing CO_2 solubility of surface waters). It also transports surface waters replete with high levels of anthropogenic carbon to depth on climatically important timescales. While decadal variation in the overturning circulation has recently been linked to changing global carbon uptake patterns, knowledge about their correspondence over shorter timescales is in its infancy. Here we investigate what current observations show us about how the biological and carbon systems respond to circulation variability over multiple timescales, how models currently perform in replicating this, and what the future holds.

An autonomous view of the carbon system

Aimee Coggins, Andy Watson, Ute Schuster, Paul Halloran, Brian King, Richard Saunders, Pete Brown, Elaine McDonough, Vassilis Kitidis

The ocean is an important sink of anthropogenic CO_2 from the atmosphere, however, oceanic uptake is not homogeneous in time or space. Despite scientists' good overall understanding of the ocean carbon cycle, remaining uncertainties of the variability in oceanic CO_2 uptake has limited our ability to estimate the oceans capacity to buffer atmospheric CO_2 in present day and in the future. This is partially due in the Southern Ocean where the harsh weather and sea conditions prevents year-round conventional sampling campaigns, resulting in data sparsity of key parameters in a region so important for CO_2 exchange between the ocean and the atmosphere. In recent years, the use of biogeochemical Argo floats have given us year round access to measurements in remote regions that are severely under sampled. Here, I focus on a month long experimental period in which we have attempted to validate Argo float measurements in the Southern Ocean.

Assimilating synthetic Biogeochemical-Argo observations into a global ocean model

David Ford

Argo has revolutionised our understanding of ocean physics, and Biogeochemical-Argo (BGC-Argo) is now extending the concept to biogeochemistry. There are currently around 300 operational floats measuring one or more biogeochemical variables, and over the coming years an array of BGC-Argo floats will be established to provide regular profiles of pH, oxygen, nitrate, chlorophyll, suspended particles and downwelling irradiance. In preparation for this, and to inform decision-making around future deployments, a set of observing system simulation experiments (OSSEs) has been performed as part of the AtlantOS project. To perform the OSSEs, the MEDUSA biogeochemical model has been coupled with the global FOAM reanalysis system, and the capability developed to assimilate 3D profiles of pH, oxygen, nitrate, and chlorophyll, as well as surface chlorophyll from ocean colour. The OSSEs test the impact on the system of assimilating simulated BGC-Argo observations for two potential scenarios: having BGC sensors on the full current Argo array (~4000 floats), and having BGC sensors on ¼ of the current Argo array (~1000 floats). The results demonstrate the potential of BGC-Argo data to constrain biogeochemical reanalyses, including fields of sea surface p CO_2.

Development of Lab-On-Chip sensors for autonomous high-resolution carbonate chemistry and ocean acidification observations

S. Loucaides, A. Schaap, S. Monk, M. Arundell, S.Papadimitriou and M. Mowlem

Since the beginning of the industrial revolution the ocean has become more acidic due to uptake of atmospheric CO_2, a process that is projected to continue under current scenarios. Monitoring ocean acidification through ship-based measurements cannot address the urgent need for high spatiotemporal resolution characterization of the marine CO_2 system. Swarms of small, intelligent and low-cost autonomous robotic vehicles could address this challenge as soon as small, fast, low power, sensors have reached high technology readiness. Over the last five years, the National Oceanography Centre in the U.K. along with industry partners have been committed to the development of in-situ carbonate chemistry sensors for autonomous ocean observations on stationary and fast moving platforms. In this talk I will present recent developments in autonomous marine carbonate sensor technology including initial validation data from Lab-On-a-Chip based pH, Total Alkalinity

(TA) and Dissolved Inorganic Carbon (DIC) sensors developed at the National Oceanography Centre. I will discuss current capability, limitations and technology development roadmap and considerations for deployment on different