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Integrated Data Sets of the EU FP5 Research Project

ORFOIS: Origin and fate of biogenic particle fluxes in the ocean and their interactions with the atmospheric CO_2 concentration as well as the marine sediment (Vol. 1)

Nicolas Dittert, Dorothee Bakker, Jørgen Bendtsen, Lydie Corrin, Marion Gehlen, Christoph Heinze, Ernst Maier-Reimer, Panagiotis Michalopoulos, Karline E.R. Soetaert, Richard J.S. Tol

WORLD DATA CENTER FOR MARINE ENVIRONMENTAL SCIENCES

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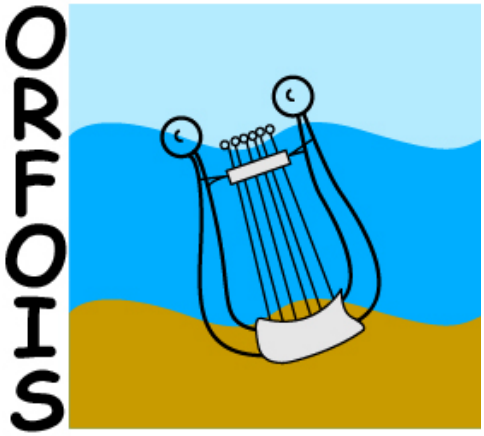
In ancient times there was a King of Thrace by the name of Oeagrus who fell in love with the Muse Calliope. She found him to her taste, and of their union was born a boy, whom they named Orpheus (French: *Orphée*). Calliope had the divine gift of song, and she taught her son well.

Orpheus became the greatest of all musicians. He sang a wide variety of songs. Sometimes he sang high-pitched songs about the mystical creation of the universe. Other times he played low notes on his lyre as he sang of the battles of Zeus ad the Olympians gods who clashed against the Titans. Orpheus even had songs about people who were changed into flowers or birds.

But whatever he sang, the rich clear words and the silvery notes from his harp were so enchanting that they always had a magical effect on everything around him. His songs could charm even rocks and rivers as well as humans and animals. Once when Orpheus was playing his splendid music in the forest, the oak trees pulled up their roots. They followed him down the mountainside and planted themselves by the seashore where Orpheus ended his song.

Orphic poetry was recited in mystery-rites and purification rituals. Those who were especially devoted to these rituals and poems came to be known as those committing the *Orphikos bios* , or "**Orphic way of life**"…

…and that's what ORFOIS is about.



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„**OR**igin and **F**ate of biogenic particle fluxes in the **O**cean and their **I**nteractions with the atmospheric CO_2 concentration as well as the marine **S**ediment" (ORFOIS)

(Contract No. EVK2-CT2001-00100 [2001-2004] with the European Commission)

1.1 Problems to be solved

The simulation of thoroughly backed up surface ocean pCO_2 distributions has narrowed the uncertainties of carbon redistribution estimates within the earth system. This knowledge has direct economic consequences because it enables early political measures to react on and prevent undesired climate change evolutions. Likewise, this knowledge enables a well planned procedure for fulfilling the Kyoto Protocol obligations of member states. Early planning on the basis of solid research results within this context has been shown to be of extreme economic value. The calculation of the fate of particles became the foundation for valid estimates of removal and storage of hazardous substances within the ocean (coming from land based sources through river runoff and atmospheric transport as well as from direct marine disposal). The consideration of near shore and shelf systems within a global BOGCM (Biogeochemical Ocean General Circulation Model) has provided a first global estimate of shelf/open ocean interaction and related water exchange time scales based on mechanistic modelling. The particle flux and sediment „community models" has provided a basis for future operational biogeochemical forecasting of environmental key variables. Thus these models help to prevent marine areas around EU member states from environmental damage and foster sustainable use of these oceanic areas for fisheries.

1.2 Scientific objectives and approach

The main scientific objectives of ORFOIS were (1) to identify and quantify globally the mechanisms underlying the transformation of biogenic particles to dissolved substances within the ocean water column in order to predict correctly surface ocean carbon dioxide sources and sinks; (2) to develop a refined particle flux model for operational use in ocean general circulation models which realistically describes particle dynamics in the water column, deposition of material to the sediment, and the interaction with the carbon dioxide partial pressure (pCO_2); (3) to provide a global closed carbon and nutrient budget for modern (pre-industrial) conditions including the water column sediment interaction; (4) and to estimate the changes in CO_2 sea surface source/sink patterns and vertical redistributions of carbon as well as nutrients for future global change, climate change as well as carbon sequestration scenarios including the associated potential economic impacts.

ORFOIS' main technological objectives were (1) to establish publicly available community models for particle flux dynamics in the water column and early sediment diagenesis which are suited for use in general circulation ocean climate models and (2) to establish data bases for marine carbon and nutrient cycling which will be easily publicly available.

The methodology to achieve these goals was based on a combination of a comprehensive observational data base on marine carbon cycling to be collated with two BOGCMs.

2. Scientific Summary and Innovation Initiated

2.1 Scientific summary

Next to water vapour, carbon dioxide is the second most important greenhouse gas. The airborne fraction of carbon dioxide is determined by anthropogenic emissions and natural carbon redistribution processes between several reservoirs (atmosphere, land biosphere, ocean water, marine as well as lacustrine sediments, soils, and lithosphere). The world ocean (inorganic marine carbon cycle) and the terrestrial biosphere are the most important sink reservoirs for anthropogenic CO_2.

Compared to the atmosphere, the ocean contains a much larger standing stock of carbon (inorganically and organically dissolved as well as in particulate form). Turnover times of the marine carbon reservoir are shorter than those of the soil carbon pool. Therefore, small perturbations of the marine carbon cycle can induce significant alterations of the atmospheric CO_2 concentration. The CO_2 partial pressure in the ocean depends on the concentration of dissolved inorganic carbon and alkalinity (or pH value). The structure of dissolved inorganic carbon and alkalinity in ocean water is determined through ocean circulation and biogeochemical processes. These biogeochemical processes are mainly transfers of carbon from dissolved to particulate form and vice versa. These transfers are governed by biota (uptake of carbon, remineralisation by bacteria) and inorganic processes (dissolution) and are coupled to the nutrient cycles.

In large scale physical/biogeochemical models, the transformation from new biomass at the ocean surface back to redissolved forms in deeper waters up to now is performed through highly simplified quasi-exponential flux redistribution profiles. It has been shown in previous model experiments, that the oceanic CO_2 uptake or outgassing as well as the vertical nutrient distribution depend critically on the choice of these profiles (Najjar et al., 1992; Archer and Maier-Reimer, 1994; Heinze et al., 1999). In the real world, more complex particle dynamics processes are at work. These processes depend on factors such as wind stress, atmospheric dust loads, primary production, plankton composition, particle structure, trace substance composition, degree of saturation of seawater (for the respective substance), and oxygen availability.

For a reliable simulation of the time and space dependent CO_2 redistribution between ocean and atmosphere an appropriate time dependent simulation of particle dynamics processes is essential but has not been carried out so far. The major difficulties were the lack of suitable modules for particle dynamics and early diagenesis (in order to close the carbon and nutrient budget) in ocean general circulation models, and the lack of an understanding of biogeochemical processes, such as the partial dissolution of calcareous particles in oversaturated water.

The main target of ORFOIS was to fill in this gap in our knowledge and prediction capability infrastructure. This goal has been achieved step by step. At first comprehensive data bases (already existing data) of observations of relevance for the three major types of biogenic particles, organic carbon (POC), calcium carbonate ($CaCO_3$), and biogenic silica (BSi or opal), as well as for refractory particles of terrestrial origin were collated and made publicly available.

From these data base and process studies, model formulations and parameterisations for simulations of particle dynamics and particle degradation were developed and formulated. These model formulations were implemented in already existing „extended NPZD-models" of ocean circulation and ecology (NPZD="nutrient phytoplankton zooplankton detritus", „extended NPZD-models" = further developments of standard NPZD-models, to also include the silicon cycle, $CaCO_3$ production, and co-limitations of nitrate, phosphate, light, temperature, trace substances such as iron, and further factors). Specifically the following mechanisms were addressed: Coagulation and disaggregation of particles, seasonality of particle production, settling velocity of particles, particle solubilities and redissolution kinetics dependent on particle structure and composition, change of particle size and settling velocity with wind mixing and aeolian particle deposition. The particle dynamics module were applied in two different high end BOGCMs (Biogeochemical Ocean General Circulation Models). Both BOGCMs, I and II, include a full ocean physics component based on the Primitive Equations.

A closed nutrient and carbon budget was established through equilibrium climate simulations for the pre-industrial situation. This simulation includes a quantitatively correct simulation of the carbon and nutrient fluxes between the sediment and the water column. The simulation was verified with the comprehensive data base developed before. The model set up includes „community models" of particle dynamics and sediment biogeochemisty (early diagenesis) which can be implemented in operationally running ocean climate models („community models" = well documented and tested source codes of model components which can be shared by the entire scientific community). The surface ocean CO_2 source/sink pattern for the pre-industrial ocean was established.

External forcing as derived from global climate change scenarios was then applied to the biogeochemical ocean circulation models. Aeolian dust flux and changes in atmospheric CO_2 content were prescribed. The reaction of the water column processes and the resulting change in the surface ocean CO_2 partial pressure field were established. Regions of highest variability (pre-anthropogenic/anthropogenically disturbed status) were diagnosed. Changes in the intensity of particle fluxes and redistributions of matter within the ocean water column were analysed. These biogeochemical redistributions have also implications for the fertility of the ocean and respective sizes of fish stocks. Finally, also the effects of marine carbon sequestration activities on the marine particle flux and pCO_2 were investigated and potential economic impacts were estimated.

2.2 Innovation initiated

The major principles of the geochemical cycles governing the global carbon and nutrient fluxes were known (e.g., Delaney, 1998; Falkowski, 1997; Tréguer et al., 1995; Moore and Bolin, 1986/87; Degens et al., 1987) and could be described by models. For the ocean, comprehensive BOGCMs (Biogeochemical Ocean General Circulation Models) based on DOGCMs (Dynamical Ocean General Circulation Models providing velocity, sea ice, and thermohaline fields) were available (e.g., Palmer and Totterdell, 2001; Fasham and Evans, 2000; Aumont et al., 2002, 1998; Heinze et al., 1999; Sarmiento et al., 1998; Drange, 1996; Maier-Reimer, 1993). These models predict global or basin wide distributions of carbon tracers and nutrients, as well as air sea carbon fluxes. The models include biological modules of different complexity. The models were applied for studies concerning the regulation of the atmospheric CO_2 content in the present (e.g. Palmer and Totterdell, 2001; Aumont et al., 1998; Drange, 1996; Maier-Reimer, 1993), past (Heinze et al., 1999; Archer and Maier-Reimer, 1994; Heinze et al., 1991), and future (e.g., Bopp et al., 2001; Sarmiento et al., 1998; Archer et al., 1997; Sarmiento and Le Quéré, 1996; Maier-Reimer et al., 1996) by marine processes.

All these models are based on strongly simplifying parameterisations of the real processes with biological primary production being a partial mirror image of the wind stress curl and the mixed layer depth - with high production rates in upwelling regimes and oligotrophic conditions in downwelling regimes. The respective space time pattern of simulated surface ocean carbon dioxide partial pressure (pCO_2) reflects the patterns of the biological carbon uptake by biota, the fate of the particles during their sinking through the water column, the vertical transport of carbon into the surface ocean (mainly through *Ekman* pumping), and surface hydrography (with enhanced marine storage of carbon in saline and cold waters). Surface ocean pCO_2 patterns can be reproduced qualitatively (a comparison of various biotic and abiotic models is under way using fixed ocean velocity fields in the OCMIP-2 study, http://www.ipsl.jussieu.fr/OCMIP/phase2/#simulations). However,

A rigorous comparison of BOGCM results with data sets of observed pCO_2 using time dependent model forcing also for the model physics, was carried out for the first time by ORFOIS.

The marine particle production was represented mostly through Michaelis-Menten kinetics. NPZD-models and more detailed extensions of them (e.g., Fasham et al., 1993; Six and Maier-Reimer, 1996) included besides phytoplankton and zooplankton also the microbial loop through detritus consuming organisms. For a parameterisation of the particle flux through the water column, all BOGCMs so far published employ exponential or quasi-exponential flux redistribution profiles. These profiles combine the two processes redissolution rate constant and particle settling velocity in one parameter (in exponential decay formulations in a number called „e-folding depth", the depth level at which the actual particle flux is reduced to 1/e of the export flux out of the euphotic zone). Fixed values for each of the three particle species POC, $CaCO_3$, and BSi are used (Volk and Hoffert, 1985; Najjar et al., 1992; Maier-Reimer, 1993; Heinze et al., 1999). Increasingly deep depth levels were chosen from POC to $CaCO_3$ to BSi (corresponding to higher settling velocities or lower redissolution rate constants). Besides the exponential profile, for POC, also the formulations of Suess (1980) (1/z-law) and Martin et al. (1987) (x^{-z}-law) were applied in BOGCMs (Najjar et al., 1992; Maier-Reimer, 1993; Heinze et al., 1999). It turned out that the vertical carbon and nutrient structure and hence the biological surface production and surface pCO_2 depend critically on the choice of these parameterisations. Moreover, it is shown from inverse modelling studies using adjoint modelling techniques, that spatially varying penetration constants had to be applied in order to match observations from the water column closely everywhere (Schlitzer, 2000).

Being a key process for regulating the pCO_2, a more realistic detailed particle flux simulation was attempted in BOGCMs for the first time by ORFOIS.

The Martin et al. (1987) formulation for the POC flux through the water column is based on a best fit to sediment trap data and has been considered as the best guess for depth dependent POC degradation by many scientists. However it should be noted that the deep carbon flux is only poorly constrained by this curve because the lowest depth level of the traps used in Martin et al. (1987) is at 2000 m, far above the average ocean floor. The existing POC deposition map of Jahnke (1996) is not regarded as conclusive because it reveals a too strong coupling to bottom topography.

Even the order of magnitude of the deposition rate of biogenic material onto the ocean floor was not quantified and was only crudely estimated globally from budget considerations, but was determined locally in a synoptic approach for the first time by ORFOIS.

2.3 Advancement of state of the art by ORFOIS

Time dependent global maps of surface ocean CO_2 partial pressure were provided from improved BOGCMs which more appropriately describe the biogeochemical processes governing the marine carbon cycle. A detailed comparison between simulated and observed pCO_2 values were carried out. Surface, sub-surface and ocean floor processes were considered in a closed budget approach. State of the art „ecological models" and gas exchange formulations were employed („ecological models" = large scale ocean models of the NPZD type, but with extensions to include the marine biogenic silicon cycle and co-limitations of biological production by several factors such as nitrogen and phosphorous availability, radiation, temperature, and trace substance availability). The resulting pCO_2 maps yielded additional constraints for inverse atmospheric computations in order to reliably predict terrestrial as well as marine carbon sources and sinks. The improved BOGCMs were run under time dependent forcing (including the physical forcing for computing respective time dependent ocean velocity fields) in order to establish inter-annually varying CO_2 fluxes between atmosphere and ocean. The verified model was used under global warming future climate forcing in order to predict the change of carbon uptake/release areas in the world ocean.

In ORFOIS, a more advanced particle dynamics module on the based on the work of Kriest and Evans (1999) was employed in global BOGCM computations for the first time in order to more correctly simulate the degradation of biogenic particles in the water column and to establish realistic settling velocity values. Coagulation and disaggreation of particles in the water column were simulated. New (still unpublished) findings from in situ and laboratory experiments were used to establish significantly improved values for dissolution rate constants of biogenic matter (dissolution kinetics) and (apparent) solubilities. New geochemical findings concerning the degradation of $CaCO_3$ in oversaturated waters were included in the model formulations. Dynamical changes of biogeochemical parameters due to microenvironments and organic/inorganic coatings of particle aggregates was accounted for. The new particle flux model contributed to a much more detailed prediction of the carbon redistribution in the water column and the surface ocean and now enables a mechanistic (and not empirical) prediction of biogenic pCO_2 regulation superior to former state of the art capabilities. In addition, it provided more quantitatively correct boundary conditions for the sediment early diagenesis model.

The model approach included for the first time in global BOGCMs a time dependent realistic module of organic carbon degradation in the bioturbated sediment. Together with the early diagenesis modelling of $CaCO_3$ (inorganic carbon) and BSi, this simulation enables to present a closed budget for nutrients and carbon in the total model ocean system.

Within the global ocean approach, also the continental shelf regions were considered. A first step of including shelf seas in a global BOGCM study was tried through a crude parameterisation of retention of river load carbon and nutrients in shallow waters, shelf/open ocean carbon and nutrient exchange, as well as shallow water sedimentation (including a first order representation of anaerobic pore water chemistry). A correct representation of shallow water sedimentation processes was desirable in order to correctly quantify the amount of carbon and nutrients entering the open ocean from continental runoff loads. A correct simulation of sedimentary processes was vital for a correct prediction of local deposition rates and hence for a rigorous verification of the new particle dynamics module to be implemented. While particle flux measurements with sediment traps in the water column are extremely difficult, expensive, and associated with enormous systematic errors (though the traps give invaluable information concerning the timing of particulate fluxes), sediment pore water and solid sediment component data are more reliably and more widespread. A satisfying simulation of sediment processes in the bioturbated zone was the clue for a verification of the particle dynamics model and the simulated deposition rates to the ocean floor. The improved sediment module furthermore was the tool for evaluating the local and global impact of direct deep ocean sequestration of anthropogenic CO_2. To estimate the impact of deep release of CO_2, an appropriate simulation of the associated $CaCO_3$ dissolution dynamics from the ocean floor was essential for a thorough estimate of the consequences for deep ocean ecology and the efficiency of the sequestering procedure.

3. Project Working Plan

The working plan was structured into 10 main packages: Work Packages 1-6 (fundamental science batch) included fundamental science work and technological development of the project's logistical infrastructure placing special emphasis on common use of data sets and computer programme source codes. Work Packages 7-9 (application batch) applied the deliverables to societal issues and disseminate the deliverables to the public. Coordination was an additional Work Package (WP 10) to ensure smooth flow of the entire project.

Time-work flow-chart

Work-package no.	Workpackage name	year 1	year 2	year 3
1	Data base compilation of observations	X X X X	X X	
2	Process parameterisations	X X X X	X	
3	Community model development	X X X X	X	
4	Compilation of model forcing fields	X X		

5	BOGCM implementation			X	X	X	X								
6	Optimisation of the prognostic system					X	X	X	X	X	X	X	X		
7	Model application and demonstration							X	X	X	X	X	X		
8	Economic evaluation							X	X	X	X	X	X		
9	Dissemination											X	X	X	
10	Coordination	X	X	X	X	X	X	X	X	X	X	X	X	X	

4. Contribution to Objectives of Programme/Call

The project contributed directly to Key Action 2 (Global Change, Climate and Biodiversity) of the Work Programme for Part A (Environment and Sustainable Development) of the Energy, Environment and Sustainable Development Programme for RTD under the 5th Framework. Through the model development, ORFOIS provided tools for the study of global and regional environmental issues (marine CO_2 source/sink distribution and its spatial as well as temporal change, carbon nutrient redistribution in the water column and the sediment, atmospheric CO_2 partial pressure, see p. 16 of the Work Programme EESD, Part A).

A correct knowledge and prediction of the CO_2 source/sink pattern is essential for a check of the Kyoto protocol targets. At that time atmospheric transport models were employed in inverse mode by several research groups in order to deduce carbon sources and sinks at the land and ocean surface. Especially the resulting terrestrial source/sink pattern was under heavy debate (e.g., Fan et al., 1998). ORFOIS produced a proper quantification of surface ocean pCO_2 distributions which can be used to efficiently constrain these inverse models for a firm estimate of terrestrial carbon sources and sinks. The observational data bases as well as the community models for particle flux dynamics and early diagenesis are available at

http://orfois.wdc-mare.org

making use of up to date e-science technologies for data exchange as encouraged in the Work Programme (see p. 16 of the Work Programme EESD, Part A).

The project's targets were tied to item 2.2 (Actions to foster better understanding of terrestrial and marine ecosystems and their interactions) of the Work Programme, and addressed the central issues of RTD priority action 2.2.2. (Interactions between ecosystems and the carbon and nitrogen cycles): ORFOIS directly provided an improved quantification of the marine biospheric sources, sinks, and fluxes of carbon and nutrients (N, P, Si), which was one of the targets as stated in the Work Programme (see p. 18 of the Work Programme EESD, Part A). The temporal and spatial changes for carbon and nutrient redistributions within the ocean as well as between ocean and atmosphere under anthropogenically perturbed conditions were established.

Moreover, the project was linked to topic 2.1 (Actions to understand, detect, assess, and predict global change processes) of the Work Programme. ORFOIS contributed to RTD priority action 2.1.1. (Atmospheric composition change). ORFOIS provided best guesses for the pre-industrial as well as future marine source/sink distribution for CO_2 at the sea surface and the associated fluxes of CO_2 out of and into the atmosphere. Likewise, ORFOIS linked to RTD priority action 2.1.3. (Climate change and prediction scenarios). The project helped to reduce uncertainties of future evolution of the atmospheric CO_2 concentration through identifying which marine regions are amplified sources/sinks in a warmer climate in relation to biogeochemical processes in the water column and the bioturbated sediment.

5. Community Added Value and Contribution to EU Policies

The subject addressed in ORFOIS is of wide European interest and strategic importance. The work carried out directly relates to obligations of the Member States to international treaties on environmental protection issues. These treaties are for the atmosphere the *Kyoto Protocol* (KP) on climate change, and for the ocean the *London Convention* (LC) (1972, plus protocol from 1996) on the prevention of marine pollution, the 1992 *OSPAR Convention* (OC) (replacing the earlier Paris and Oslo Conventions) for the protection of the marine environment of the North-East Atlantic, and also the 1992 *Helsinki Convention* (HC) on the protection of the marine environment of the Baltic Sea Area.

The establishment of reliable marine CO_2 source/sink distributions and their temporal and spatial prediction as well as research on carbon sequestration is part of the obligations of the Member States within KP (Articles 2.1.a.i., 2.1.a.ii, 3.3, 5.1, 9.1, 10.a, 10.b, 10.b.ii, 10.d, and 10.e). Exchange of information as well as cooperation on scientific and technical research on climate and carbon cycle issues are encouraged explicitly through KP Articles 10.c, 10.d, and 13.c.

Quantifying correctly marine particle flux dynamics and fluxes is necessary to predict reliably the fate of hazardous substances in the marine realm. These substances are, e.g., heavy metals such as lead and radio nuclides which are scavenged from dissolution to particles and finally are enriched within the sediment. The work in ORFOIS enabled corresponding quantifications. ORFOIS contributed to the objectives of LC (Articles I, II, and XII), of OC (Articles 1a,b), and of HC (Article 3). All three marine conventions demand joint collaborative research on environmental issues in order to protect natural resources (LC, Article IX; OC, Article 8; HC, Article 24).

The joint modelling of marine carbon sources and sinks is of strategic importance for Europe. This additional constraint for atmospheric CO_2 transport inverse calculations exclude biased sink propositions such as a highly unlikely North American carbon sink as suggested by Fan et al. (1998).

However, the establishment of precise temporal spatial surface ocean pCO_2 arrays and their prediction is too ambitious to be carried out on a national level alone. It is necessary to share experiences from the measuring, data analysing, and modelling community throughout Europe in order to make common use of expensive infrastructure (super computer resources, data bases and information systems).

6. Contribution to Community Social Objectives

ORFOIS contributed significantly to social objectives of EU Member States:

- The calculation of the fate of particles became the foundation for valid estimates of removal and storage of hazardous substances within the ocean (coming from land based sources through river runoff and atmospheric transport as well as from direct marine disposal). The consideration of near shore and shelf systems within a global BOGCM provided a first global estimate of shelf/open ocean interaction and related water exchange time scales based on mechanistic modelling. The particle flux and sediment „community models“ provided a basis for future operational biogeochemical forecasting of environmental key variables. Thus these models will help to prevent marine areas around EU member states from environmental damage and foster sustainable use of these oceanic areas for fisheries.

- The simulation of thoroughly backed up surface ocean pCO_2 distributions narrowed the uncertainties of carbon redistribution estimates within the Earth system. This knowledge has direct economic consequences because it enables early political measures to react on and prevent undesired climate change evolutions. This knowledge enables a well planned procedure for fulfilling the Kyoto Protocol obligations of member states. Early planning on the basis of solid research results within this context has been shown to be of extreme economic value (Nordhaus and Popp, 1997; Peck and Teisberg, 1993).

- In ORFOIS young scientists were trained for understanding and forecasting environmental systems. This qualification is contributing to recruit highly skilled personnel for the climate and global change tasks in the future (monitoring the environment, fulfilment of Kyoto Protocol obligations). Within the European science network these well educated people are the most valuable human resource to guarantee a world leading position concerning scientific staff and ensure to keep Europe as a centre of excellence concerning earth system science.

Furthermore, the specialists that worked together in ORFOIS have particular expertise on their fields which is not available at each national level in the same quality, e.g., some groups have the capability of carrying out BOGCM runs on high end supercomputers, while other groups have special expertise on selected marine processes

and access to up to date observations. The results of the project became „community models“ of ocean particle flux dynamics and sediment modules which were standardised for use in different model frame works. Comparable model components are not available from other places, providing a technological and scientific leading edge position for the EU.

7. Economic Development and S&T Prospects

7.1 Dissemination of results for the consortium as a whole

The data sets were compiled and made available to the public through the World Data Center for Marine Environmental Sciences (WDC-MARE, Germany) online in electronic form (see http://orfois.wdc-mare.org/) and as CD-ROM/DVD as part of two WDC-MARE reports that document the history of data sets, quality issues, and how to retrieve data for individual user's purposes. The access to the ORFOIS data collection is facilitated through publication of access modes on the project's homepage.

The community models for particle flux dynamics and early sediment diagenesis, as well as the updated BOGCMs I and II (the HOPE-C and the IPSL-OGCM) are archived with all necessary files to run the models at the World Data Center for Climate (WDCC, Hamburg, Germany). Access to all these codes is possible through Internet (http://www.mad.zmaw.de/wdcc/). User manuals for all models/model components are published online as well as technical report in the MPG-IMET/DKRZ Technical Report Series ISSN 0940-9327. BOGCM II is additionally archived and maintained for further use at LSCE. BOGCM I is additionally archived for further use at NERI.

Model results (especially the surface ocean pCO_2 data sets, but also three-dimensional and time dependent data sets of further variables) are stored at WDCC for further exploitation in natural and economic sciences. Meta information about these data sets are available to other European and overseas data centres including the CDIAC (Carbon Dioxide Information and Analsysis Center, Oak Ridge, Tennessee, USA).

7.2 Exploitation of results for individual participants

Individual users are applying ORFOIS results as foundation for their further work: The data collections allow for further evaluation of biogeochemical data and for further statistical analysis as well as for identification of major gaps in data coverage to be closed in future research cruises and for cross correlation of data of different variables in order to derive new advanced models of oceanic cycling of matter. Organisations running 3-D models are using the data collections for further rigorous tuning of their models. Likewise, the data collections provided the backbone for systematic data assimilation into the BOGCMs with adjoint model codes.

The model codes are exploited for analysis of research cruises, single stations, and time series deployments of sediment traps and other devices (1-D mode) and are used to address global and regional issues of climate change and environmental protection (BOGCM versions in their quasi-operationally running 3-D model systems). The particle flux dynamics module (within the 3-D model framework) is used to study the export of hazardous substances out of the water column into the sediment and allows a more sophisticated representation of shelf seas within global marine budget computations.

7.3 Strategic impact of ORFOIS

ORFOIS joined researchers from very different disciplines on a common platform to address questions of vital interest to both the society and the scientific community. In ORFOIS high end data sets and high end model systems on the marine biogeochemistry were developed and thoroughly archived for further exploitation. This exploitation is ensured by use of up to date e-technologies for (a) the data management (observations, model results) and (b) the model development and archiving (by use of the source code control system ClearCase). Observed and modelled data can be exchanged easily via the Internet through the use of WDC-MARE and WDCC, respectively. The same is true for the models. In fact, easy exchange of model codes between 1-D „process modellers“ and 3-D „simulation modellers“ is guaranteed through WDCC. This ensures fast and smooth information flow on a European platform between scientists working on different scales and provides further improvement of scientific-technical leadership.

8. Consortium and Advisory Board

The consortium consisted of 9 participating organisations from 6 different European countries:

	Name of organisation	Country
UIB	University of Bergen (Co-ordinators place), Bergen	Norway
1 - NERI	National Environmental Research Institute, Roskilde	Denmark
2 - LSCE	Laboratoire des Sciences du Climat et de l'Environnement, Gif-^{s}/-Yvette	France
3 - UBO	Institut Universitaire Européen de la Mer, Brest	France
4 - MPG-IMET	Max Planck Institute of Meteorology, Hamburg	Germany
(MARUM)	(Center for Marine Environmental Sciences, Bremen, subcontractor of MPG-IMET)	(Germany)
5 - Uni-HH	University of Hamburg, research unit	Germany

	Sustainability and Global Change, Hamburg	
6 - NCMR	(National) Hellenic Centre for Marine Research, Athens	Greece
7 - NIOO	Nederlands Instituut voor Oecologisch Onderzoek - Centrum voor Estuariene en Mariene Oecologie, Yerseke	The Netherlands
8 - UEA	University of East Anglia, School of Environmental Sciences, Norwich	United Kingdom

Advisory Board - List of Consultants

The following persons agreed to act as consultants of the project. Their input was invaluable to improve the quality of the results.

Consultant's name	Special interest	Organisation
Prof. Dr. Karin Lochte	Pelagic-benthic coupling, benthos biogeochemistry	Institut für Meereskunde, Universität Kiel (D)
Dr. Axel Michaelowa	Socio-economic impacts of climate and of climate research	Hamburger Weltwirt-schaftsarchiv HWWA (D)
Dr. Olivier Aumont	Large scale ocean modelling of physics and biogeochemistry	LODYC, Paris (F)
Dr. Isabelle Dadou	Oceanic biogeochemistry, satellite data, data assimilation methods	LEGOS, Toulouse (F)
Prof. Dr. Ulf Riebesell Dr. Markus Pahlow	Biological oceanography, micro-scale processes, marine ecology	AWI, Bremerhaven (D)
Prof. Dr. Gary Shaffer	Biogeochemistry of organic carbon remineralisation	DCESS, Copenhagen (DK)

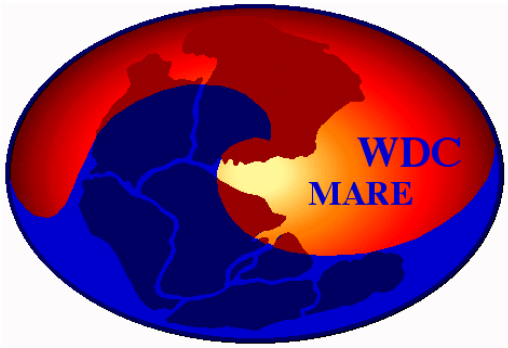
9. Introduction

With the ORFOIS data collection we establish a comprehensive database that contains all existing and published data that refer scientifically to this project. At the beginning of the project it had already become evident that so-called multi-tracer stations or sites would be a priority in order to properly serve the modellers requirement for model validation. Thus the data management approach was modified and 14 sites have been extensively investigated regarding:

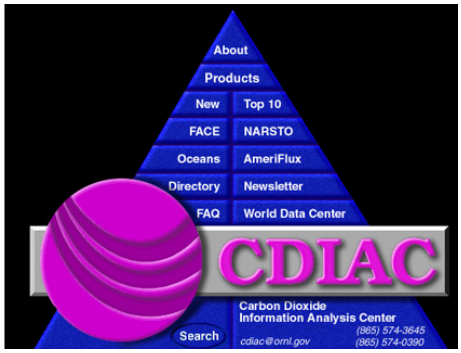
1. Biogenic matter production rates;
2. Concentrations in the water column and in the sediment pore-waters;
3. Particle fluxes from sediment traps;
4. Solid sediment concentrations.

Suggestions for the multi-tracer sites comprise those well-known BATS, BENGAL, BIGSET, EqPac, ESTOC, Eumeli, HOT, NABE, OMEX, PAP, PAPA, and Southern Ocean (Atlantic, Pacific, Indian sectors) sites or transects, respectively.
However, 3-D modellers required global data sets equally, too. Thus, in parallel, new data sets were compiled to produce global collections of oceanic production, concentration, flux, and sediment data.

ORFOIS data were produced, collected, and compiled during the whole project funding period from December 1, 2001 to November 30, 2004. The entire data collection, i.e. published and unpublished data, is archived at the World Data Center for Marine Environmental Sciences, WDC-MARE (http://orfois.wdc-mare.org/) or at the Carbon Dioxide Information Analysis Center (CO_2 data), CDIAC (http://cdiac.esd.ornl.gov/).



http://www.wdc-mare.org/



http://cdiac.esd.ornl.gov/

Data on this CD-ROM/DVD are limited to published non-CO_2 data and reflect the status as of November 30, 2004. A data compilation on a CD-ROM represents a snapshot of the time of production only. In the meantime the number of datasets at WDC-MARE may have increased. Thus we strongly recommend that the most recent and quality-checked data set versions be retrieved.
Without exception, any original data lies within the responsibility of the *Principle Investigator* (PI). In any case, when using data, original scientific references and data origin (WDC-MARE) must be cited properly!

10. Technical Data Description

WDC-MARE makes use of the information system PANGAEA (Network for Geoscientific & Environmental Data, http://www.pangaea.de/) as its operating platform. Both operate in the sense of the *Budapest Open Access Initiative* (2002) and guarantee long-term availability of scientific primary data related to publications following the *Recommendations of the Commission on Professional Self Regulation in Science for safeguarding good scientific practice* (1998). The policy of data management and archiving follows the *Principles and Responsibilities of ICSU World Data Centers* (1987).

As stated before, we strongly recommend checking for the most recent version of ORFOIS data collections at WDC-MARE:

http://orfois.wdc-mare.org/

There are several tools to retrieve data from WDC-MARE or from the CD-ROM/DVD. The most useful one for your search query may be PANGAVISTA, a powerful, yet easy-to-use search engine (cf. chapter 12.4).
However, only the data on the CD-ROM/DVD can be accessed through your computer system locally. These datasets are archived in the folder **`\docs\datasets\`** . To browse the data inventory without the use of the search engine start **`browse.html`** from the CD-ROM/DVD.

Data sets are also given as ASCII files whose content is organized as tab-delimited text files. Each data file consists of the data description (so-called *meta-information*) and the scientific primary data itself (often referred to as *analytical value*).

(1) **Data Description** consists of:

- *Citation* … is the formal correct citation to use if you refer to a specific data set (e.g., in your manuscript) and comprises a persistent *Digital Object Identifier* (comparable to the DOI for publications in journals, as e.g., *nature*);
- *Reference(s)* … is/are the related publication(s) in which the data set is used (e.g., your publication);
- *Project(s)* … is/are the framework under which the data set has been produced or compiled;
- *Spatial Coverage* … gives the four geographic boundaries (W-E-S-N) of a rectangle around a data set; if the data are related to one point, W and E as well as N and S have similar values;
- *Event(s)* … corresponds to the label of the sample taken by a device at a certain geographical spot (sometimes also named as “site”, “hole”, etc.) Information means latitude, longitude, and elevation (below (-)/above (+) mean sea level) as well as device type, campaign label, and the name of the basis used (ship, platform, research station, etc.);
- *Parameter(s)* … shows the list of parameters with unit (modellers use the term *variable* as synonym) for which scientific data exist in the data set. Each

parameter is related to at least one column showing the short cut as used in the header of the data matrix, the principle investigator (PI), the method and optional comments;

- *Size* … displays either the number of data values or points of the data set. The size of the downloaded data set approximates a tenth of the number of data points in [kbyte].

Additional information may be given for some expressions as hot link: PIs whose names are archived in the data base together with an E-mail address/personal home page, and Internet links are marked in a different colour and will automatically connect to your preferred e-mail or browser software. A link with the Project will lead the user to the projects home page, the DOI or URL given with a reference enables the download of the publication in .pdf format or shows the related page in e.g. Science Direct. Similar may appear for optionally hyper-linked fields like Method, Parameter or Further Details.

(2) **Data** consist of a header with the data table.

- Event related data sets display in the table header:
    1. Event label which is the name of the event (only in tables with several events);
    2. One to several Geo-Codes as “Depth water [m]”, “Depth sediment [m]”, “Age [kyr BP]”, “Date/Time”, etc.;
    3. One to several parameters (or variables) with units;
- Surface or space related data sets additionally display latitude and longitude for each data point, time series may include Date/Time;
- Any line of the data table comprises at least one respective Geo-Code and one datum.

Since the term *data* comprises a vast variety of information (numeric, alpha-numeric, text, image, URLs, etc.) there exist exceptions to the general description given above. However, in number they are of minor importance.

11. CD-ROM/DVD Access

11.1 Computer system requirements

To read the ORFOIS project data CD-ROM/DVD, you need access to a computer with a CD-ROM/DVD reading device.

In order to attain full performance we recommend (in alphabetical order) employing the following software (minimum requirement):

- *Linux*: SUSE, Novel Linux, Gentoo, Debian, Redhat
- *Macintosh*: Mac OS X
- *Solaris*: Version 8
- *Windows*: Windows 2000 or XP using Java Runtime Engine (JRE 1.3 or higher)

11.2 Installation procedure (only if necessary)

Usually, there is no need at all for manual installation since the CD-ROM/DVD starts automatically.

The data collection is supplied with a simple search engine, PANGAVISTA, allowing a sophisticated access to the inventory. The search engine is running on a web server supplied with the CD-ROM/DVD. Both the web server and the database engine employed are built on Java™ Technology (http://www.java.com/).

In order to run the database properly your computer must have a Java Runtime Engine (JRE) installed. On *Linux*, *Macintosh*, and *Solaris* computers JRE is already part of the operating system.
Usually, computers using the *Windows* operating system need separate installation of JRE. The start-up routine supplied on the CD-ROM/DVD will automatically detect the respective computer system, the version of its operating system, and whether JRE is available and which version. If JRE is not yet installed or the version number is not appropriate the start-up routine will offer to install the most recent JRE version.

11.3 Getting started

The CD-ROM/DVD will start automatically once you have inserted it in your CD-ROM/DVD device.

If the CD-ROM/DVD does not start automatically, you can launch it manually.

- *Linux*, *Solaris*, *Unix*, etc.: execute **`./unixstart.sh`** from terminal and follow the instructions;
- *Macintosh*: double click the **`start`** application on the CD-ROM/DVD;
- *Windows*: double click the file **`winstart.exe`** on the CD-ROM/DVD.

If the Java™ environment is not found on your system, the starting procedure offers the option to install the latest JRE (cf. http://www.java.com/). Be aware that *JavaScript* must be enabled in your browser configuration !

If your browser does not display the homepage after having started the local web-server, you should disable *proxies* in your browser configuration. If you cannot do so due to firewall or access restrictions ask your system administrator, add **`127.0.0.1`** to the proxy exemptions, or send an e-mail to info@wdc-mare.org

11.4 Creating search queries

Assuming that the search engine PANGAVISTA properly displays the search query mask you can create search queries.

To enter a search query, just type in a few descriptive words and hit the *Enter* key or click on the *Search* button. Since the search engine only returns data sets that contain **all** the words in your query, refining or narrowing your search is as simple as adding more words to the search terms you have already entered.

A search query typically results in a list of *n* data sets that you subsequently access through striking a hot link. The outcome displays the *Data description* and the options to:

- Download data set as tab-delimited text;
- View data set as HTML.

Download and display of an immense data set takes time. Depending on the operating system used download and display can take a few minutes.

Additionally, you can download the entire result (i.e., all data sets displayed) as .zip file.

Be aware that the first search query takes more time than any subsequent query since the search index has to be cached first in the memory of your machine, which in turn depends heavily on the capacities of your computer and your JRE software.

On all platforms (except Macintosh) you can visualize the locations of the data sets with the Java map supplied with the search engine. For this purpose click the *Show map* button.

When using data that have been downloaded from WDC-MARE, please:

ALWAYS QUOTE THE ORIGINAL CITATION !

ALWAYS ACKNOWLEDGE THE RESPECTIVE PROJECT !

Citation and project are always given in the data description.

12. Software

The CD-ROM/DVD contains no software for visualisation and analysis of data. However, several software tools that assist subsequent handling of data have been created. You may find help at the Internet location http://www.pangaea.de/Software/ where the public domain software is available.

PanMap …is a Mini-GIS (Geographical Information System) to draw point and vector data in maps and to quickly generate maps. Additional map resources are available at:
http://www.pangaea.de/Software/PanMap/

PanPlot …enables the user to plot data versus time or space in multivariable graphs on uniform scales:
http://www.pangaea.de/Software/PanPlot/

ODV ODV (Schlitzer, 2001) is a software package for the interactive exploration, analysis and visualization of oceanographic and other geo-referenced profile or sequence data. ODV data and configuration files are platform-independent and can be exchanged between different systems. Software, updates, data, manual and other useful stuff are available at: http://www.awi-bremerhaven.de/GEO/ODV/

Helpful software for the handling of files on this CD-ROM/DVD might be:
Adobe® Acrobat Reader
http://www.adobe.com/products/acrobat/
TextPad®
http://www.textpad.com/
ZIP®
http://www.info-zip.org/pub/infozip/

13. Scientific Data Description

The main scientific objectives of project ORFOIS are to identify and quantify globally the mechanisms underlying the transformation of biogenic particles to dissolved substances within the ocean water column in order to correctly predict surface ocean carbon dioxide sources and sinks; to develop a refined particle flux model for operational use in ocean general circulation models which realistically describes particle dynamics in the water column, deposition of material to the sediment, and the interaction with the carbon dioxide partial pressure (pCO_2); to provide a global closed carbon and nutrient budget for modern (pre-industrial) conditions including the water column sediment interaction; and to estimate the changes in CO_2 sea surface source/sink patterns and vertical redistributions of carbon as well as nutrients for future global change, climate change as well as carbon sequestration scenarios including the associated potential economic impacts.

13.1 Multi-tracer stations/sites data sets

At the *ORFOIS Modelling Meeting* (March 21-22, 2002 in Yerseke, The Netherlands) a decision was taken concerning "What variables (and in what units) do the modellers want to be seen in the data base ?". During the *ORFOIS First annual workshop (January 20-21, 2003 in Hamburg, Germany)* this decision was specified even more so that this compilation of multi-tracer data sets for the model validation would be desirable for the following sites (in alphabetical order):

AESOPS: Antarctic Environment and Southern Ocean Process Study. For further information, please visit the AESOPS web site: http://usjgofs.whoi.edu/research/aesops.html

BATS: Bermuda Atlantic Time-series Study & Hydrostation "S" Research. For further information, please visit the BATS web site:

http://www.bbsr.edu/cintoo/bats/bats.html

BENGAL: Benthic Biology and Geochemistry of a Northeastern Atlantic Abyssal Locality. For further information, please visit the BENGAL web site at *IOC*:
http://ioc.unesco.org/oceanportal/detail.php?id=942
or the BENGAL web site at *Marine Institute*, respectively:
http://www.marine.ie/information+services/data+and+info+products/cd-roms/bengal+mariner.htm

BIGSET: *Biogeochemische Stoff- und Ener gietransporte in der Tiefsee* / Biogeochemical Transport of Matter and Energy in the Deep Sea. For further information, please visit the BIGSET web site:
http://www.geomar.de/projekte/bigset/

EqPac: Equatorial Pacific Process Study. For further information, please visit the EqPac web site:
http://www1.whoi.edu/research/eqpac.html

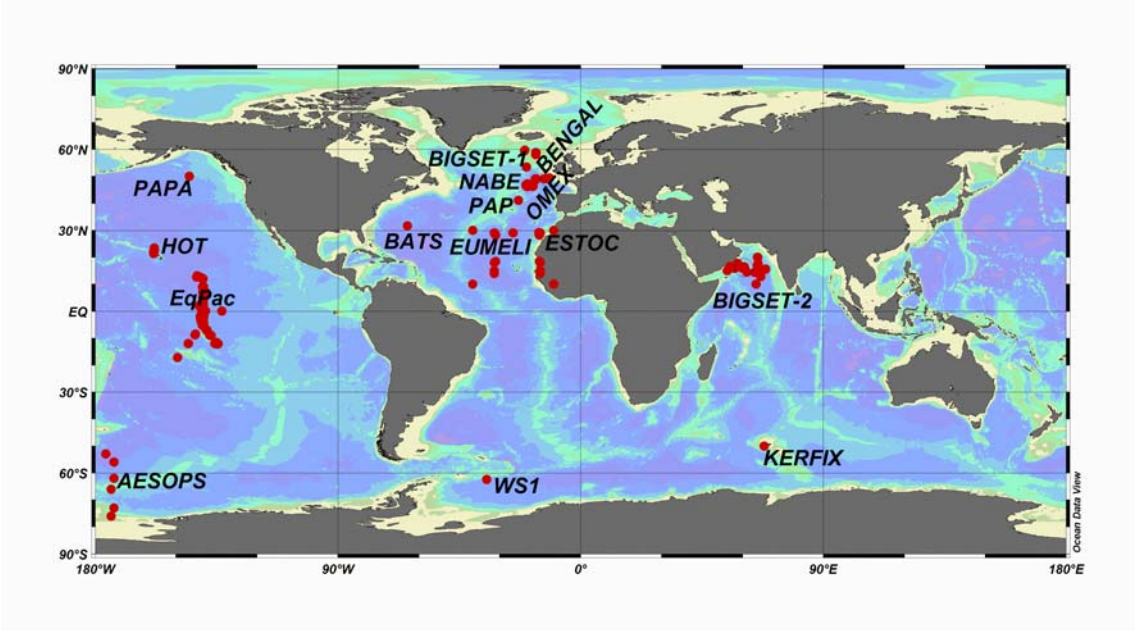


Figure 1: Global map of multi-tracer stations/sites.

ESTOC: European Station for Time-series in the Ocean, Canary Islands. For further information, please visit the ESTOC web site:
http://www.marum.de/ESTOC_European_Station_for_Time-series_in_the_Ocean_Canary_Islands.html

EUMELI: Comparaison des zones EUtrophe, MEsotrophe et oLIgotrophe pour l'étude des processus qui gouvernent la production primaire de l'océan du large. For further information, please visit the EUMELI 1-5 web sites:
http://www.ifremer.fr/sismer/program/jgofs_france/htql/index_jgofsfr_cruise.htql

HOT: Hawaii Ocean Time-Series. For further information, please visit the HOT web site:
http://hahana.soest.hawaii.edu/hot/hot.html

KERFIX (Southern Ocean, Indian sector): A fixed time-series station in the Southern Ocean near the Kerguelen Islands. For further information, please visit the KERFIX '90-'95 web sites:
http://www.ifremer.fr/sismer/program/jgofs_france/htql/prj_edmerp.htql?CPRJ=JGOF1

NABE: North Atlantic Bloom Experiment. For further information, please visit the NABE web site:
http://oceanography.tamu.edu/%7Epdgroup/SMP_prj/DataDir/HTM_Files/JGOFS_NABE.htm

OMEX: Ocean Margin EXchange project. For further information, please visit the OMEX web site:
http://www.bodc.ac.uk/projects/omex/

PAP: The Porcupine Abyssal Plain Observatory - *time series observations in the open ocean*. For further information, please visit the PAP web site:
http://www.soc.soton.ac.uk/GDD/pap/index.html

PAPA: Ocean Station PAPA ("*P*" is the North Pacific weather station). For further information, please refer to the .pdf document OSP_presentation:
http://www.uib.no/jgofs/Time-Series/OSP_presentation.pdf
or, visit the Line P Oceanographic Data web site:
http://www-sci.pac.dfo-mpo.gc.ca/osap/data/linep/linepselectdata_e.htm

SOUTHERN OCEAN: The Southern Ocean extends from the coast of Antarctica north to 60°S latitude, which coincides with the Antarctic Treaty Limit:

Atlantic sector:	070°W – 020°E	(cf. WS)
Indian sector:	020°E – 147°E	(cf. KERFIX)
Pacific sector:	147°E – 70°W	(cf. AESOPS)

WS1: The Weddell Sea time series station WS1 is related to the former Sonderforschungsbereich (Collaborative Research Centre) no. 261 at the University of Bremen, Germany. For further information, please visit the SFB261 web site:
http://www.pangaea.de/Projects/SFB261/The_South_Atlantic/Abstracts/index.html#Fischer

13.1.1 Water column concentration data

13.1.1.1 *AESOPS* transects (Southern Ocean Pacific Sector)

The U.S. JGOFS Antarctic Environment and Southern Ocean Process Study (AESOPS) began field work on August 29, 1996 and ended during April of 1998. The cruises were staged from Lyttleton, New Zealand. The Southern Ocean field program was coordinated by Antarctic Support Associates (ASA).
All ORFOIS related data with respect to AESOPS are continuously updated and available online at: http://orfois.wdc-mare.org/Results/AESOPS.html

Whenever you use data of the ORFOIS data compilation that refer to the AESOPS multi-tracer transects, please quote the citations of the following publications: http://orfois.wdc-mare.org/AESOPS_References.php

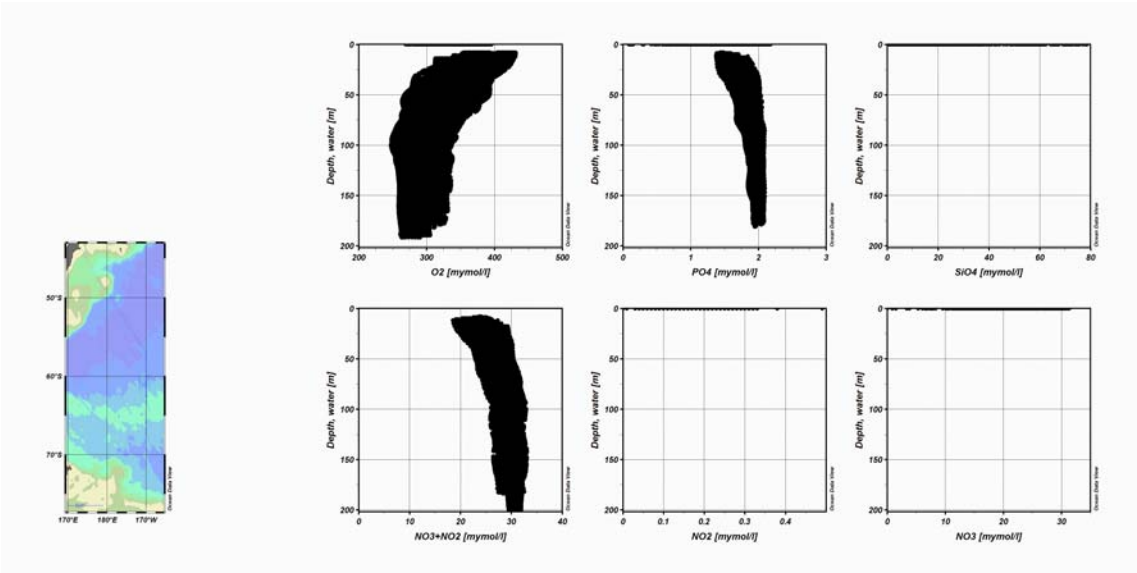


Figure 2: *AESOPS* water column concentration data.

13.1.1.2 *BATS* site

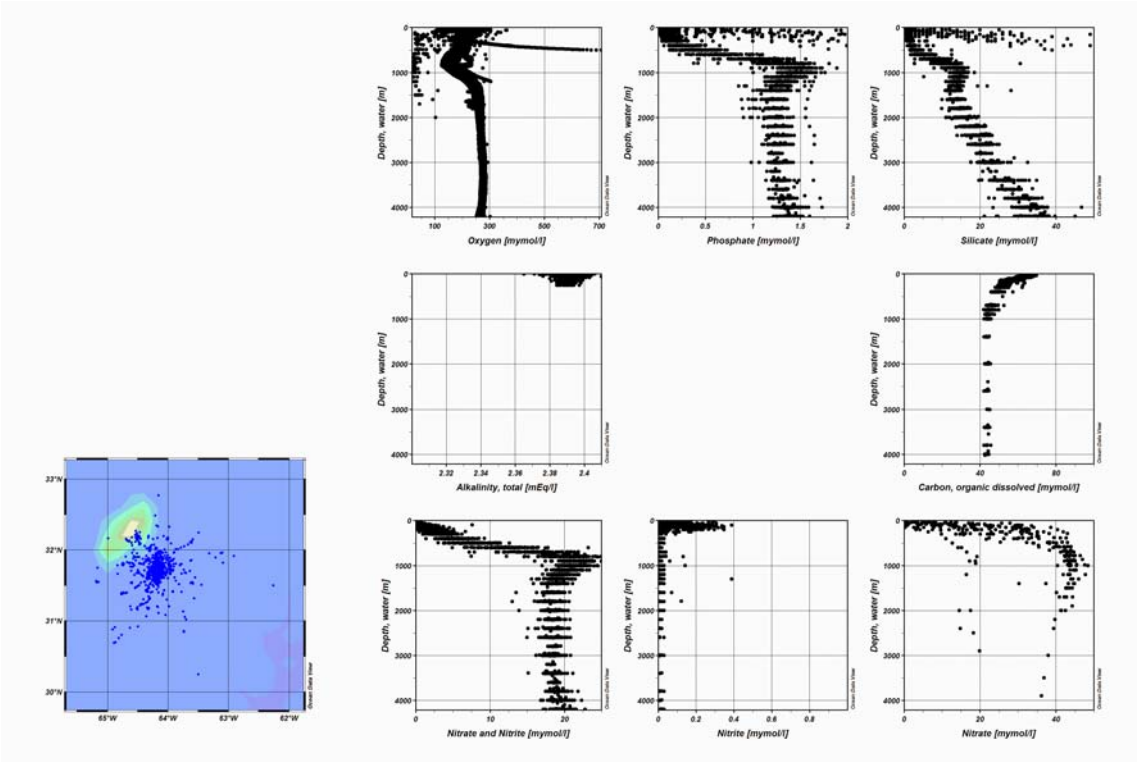


Figure 3: *BATS* water column concentration data.

The Bermuda Atlantic Time-series Study (BBSR) & Hydrostation "S" Research have a long history of oceanographic innovation. 1954 saw the implementation of the world's first significant deep-ocean time series, Hydrostation "S" Research , from which data

are still being collected. The longevity and success of the program eventually led to BBSR linking with the U.S. Joint Global Ocean Flux Study (JGOFS) program to start the Bermuda Atlantic Time-series Study (BATS), another long-term time-series study examining biogeochemical cycles in the Sargasso Sea near Bermuda.
All ORFOIS related data with respect to BATS are continuously updated and available online at: http://orfois.wdc-mare.org/Results/BATS.html
Whenever you use data of the ORFOIS data compilation that refer to the BATS multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/BATS_References.php

13.1.1.3 *BENGAL* site

Looking closer at each of the areas (BENGAL / BIGSET / NABE / OMEX / PAP) it becomes obvious that these five sites are next to each other. For this reason the data extraction from the PANGAEA information system has been done for the whole area 47°N to 52°N and -18.83°W to -11.52°W.
All ORFOIS related data with respect to BENGAL are continuously updated and available online at: http://orfois.wdc-mare.org/Results/BENGAL.html
Whenever you use data of the ORFOIS data compilation that refer to the BENGAL multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/BENGAL_References.php

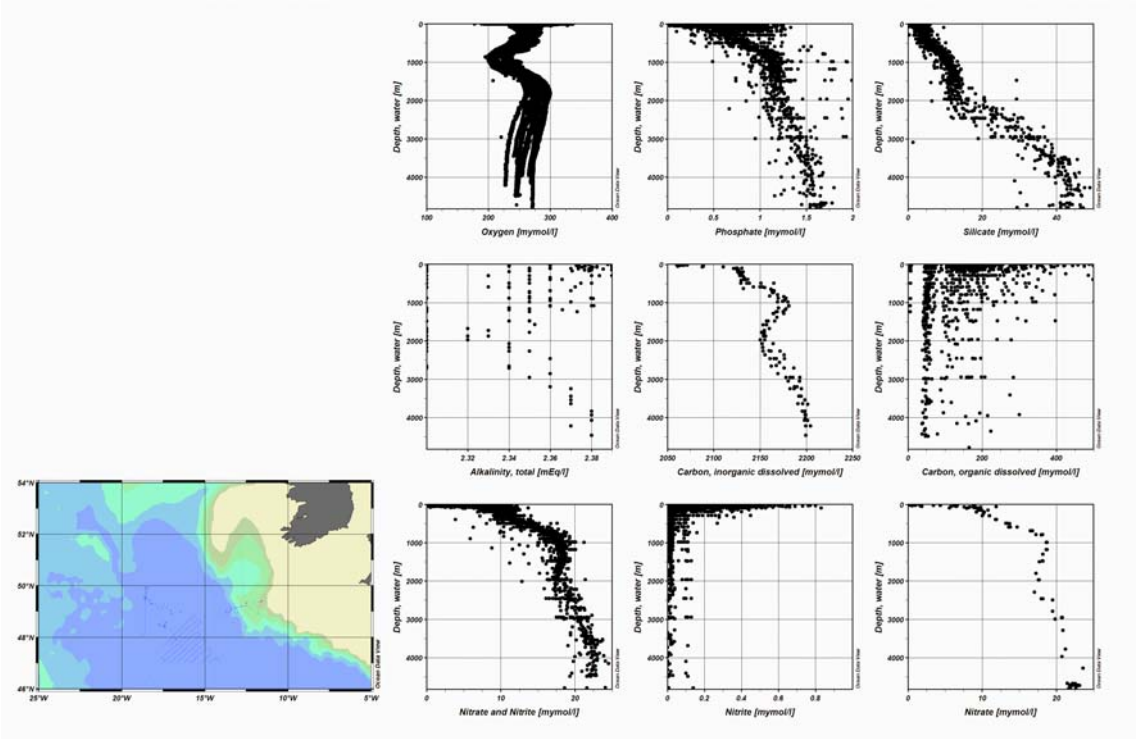


Figure 4: *BENGAL* / *BIGSET* / *NABE* / *OMEX* / *PAP* water column concentration data.

13.1.1.4.1 *BIGSET-1* site

Looking closer at each of the areas (BENGAL / BIGSET / NABE / OMEX / PAP) it becomes obvious that these five sites are next to each other. For this reason the data extraction from the PANGAEA information system has been done for the whole area 47°N to 52°N and -18.83°W to -11.52°W.
All ORFOIS related data with respect to BIGSET are continuously updated and available online at: http://orfois.wdc-mare.org/Results/BIGSET.html
Water column concentration data are displayed in chapter 13.1.1.3.
Whenever you use data of the ORFOIS data compilation that refer to the BIGSET-1 multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/BIGSET-1_References.php

13.1.1.4.2 *BIGSET-2* site

The overall objective is to identify, quantify and model the principal processes within the abyssal benthic boundary layer, which intercede between the incoming material flux and its incorporation into the permanent sedimentary record. BIGSET field studies In the Arabian Sea are characterised by strong temporal variations in export fluxes from the upper mixed layer.

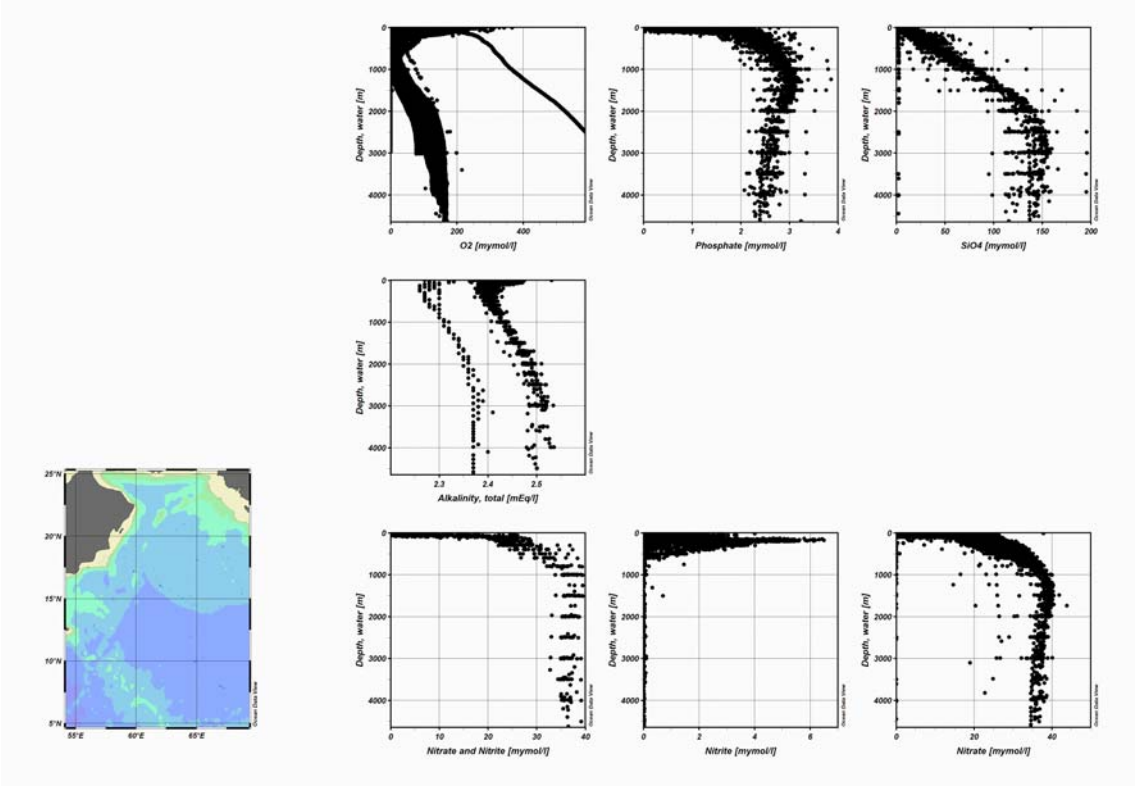


Figure 5: *BIGSET-2* water column concentration data.

All ORFOIS related data with respect to BIGSET are continuously updated and available online at: http://orfois.wdc-mare.org/Results/BIGSET.html

Whenever you use data of the ORFOIS data compilation that refer to the BIGSET-2 multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/BIGSET-2_References.php

13.1.1.5 *EqPac* transect

The EqPac process study was conducted along 140°W during the calendar year 1992. Four process cruises took place, with a fifth benthic cruise and sediment trap legs adding to the overall study. The scientific objectives of this study were to determine the fluxes of carbon and related elements, and the processes controlling these fluxes between the Equatorial Pacific euphotic zone and the atmosphere and deep ocean. The broad outlines of the project were described by Murray et al. (1992). The scientific results have been described in a series of Deep-Sea Research Special Issues.
All ORFOIS related data with respect to EqPac are continuously updated and available online at: http://orfois.wdc-mare.org/Results/EqPac.html
Whenever you use data of the ORFOIS data compilation that refer to the EqPac multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/EqPac_References.php

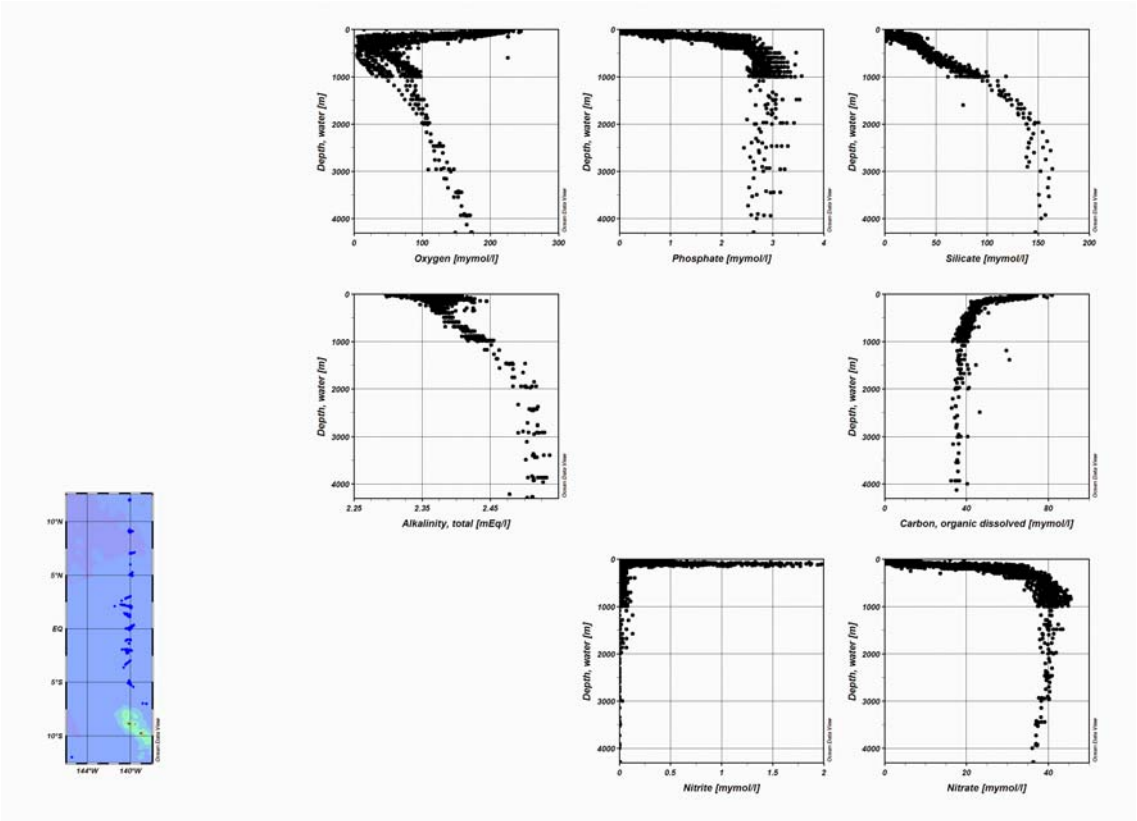


Figure 6: *EqPac* water column concentration data.

13.1.1.6 *ESTOC* site

The ‘European Station for Time-series in the Ocean, Canary Islands’ (or ‘Estación Europea de Series Temporales del Oceano, Islas Canarias’, ESTOC) is located 100 km

north (upstream) of Gran Canaria in the eastern boundary flow of the subtropical North Atlantic gyre (at 29°10'N and 15°30'W). The station is situated in the northern Canary Basin about 460 km west of the Moroccan coast and is surrounded by deep water (water depth at ESTOC is 3600 m).

All ORFOIS related data with respect to ESTOC are continuously updated and available online at: http://orfois.wdc-mare.org/Results/ESTOC.html

Whenever you use data of the ORFOIS data compilation that refer to the ESTOC multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/ESTOC_References.php

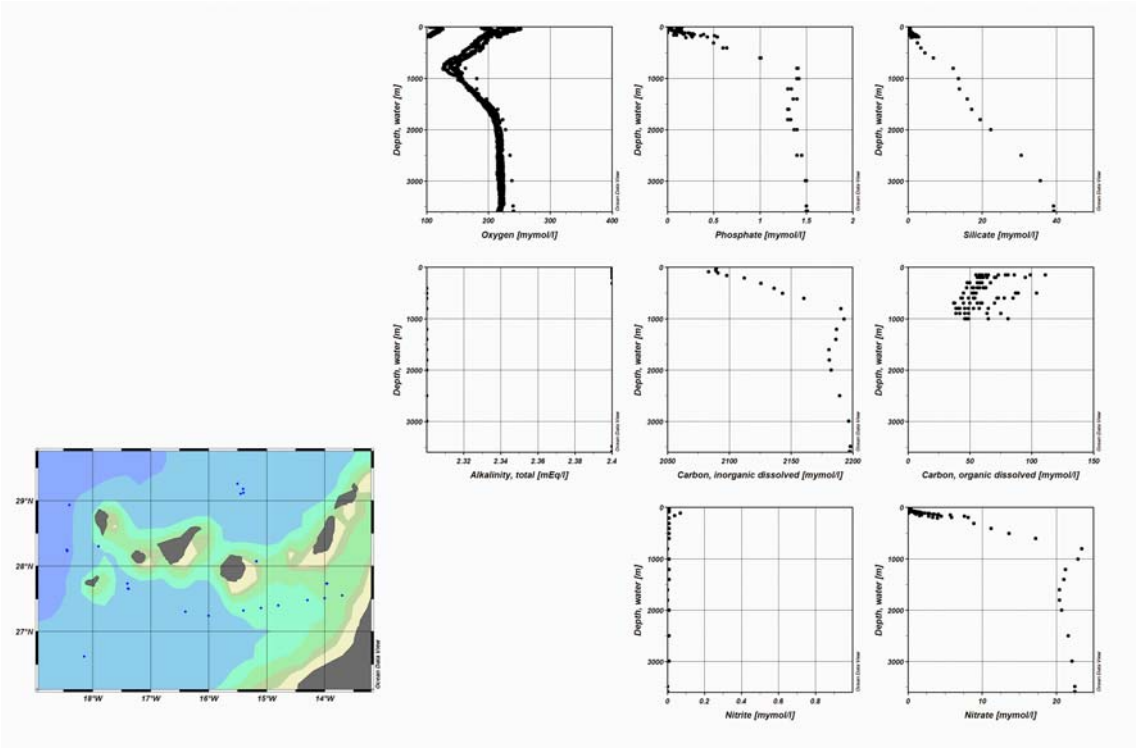


Figure 7: *ESTOC* water column concentration data.

13.1.1.7 *EUMELI* site

One of the objectives of the French program FPO (Flux Particulaires Océaniques) of INSU (National Institute of Science of the Universe) is to evaluate particle fluxes of the surface ocean to the sediments at global scale. The program EUMELI (one of the components of FPO) aims at studying three geographic zones at basin-wide scale of the tropical North-East Atlantic:

1. The high productive, *EU*trophic zone which is linked to the upwelling off Mauretania;
2. The intermediate, *ME*sotrophic zone of the Cap Verdes;
3. The oceanic, o*LI*gotrophic zone of the abyssal plain of the Cap Verdes.

All ORFOIS related data with respect to EUMELI 1-5 are continuously updated and available online at: http://orfois.wdc-mare.org/Results/EUMELI.html

Whenever you use data of the ORFOIS data compilation that refer to the EUMELI multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/EUMELI_References.php

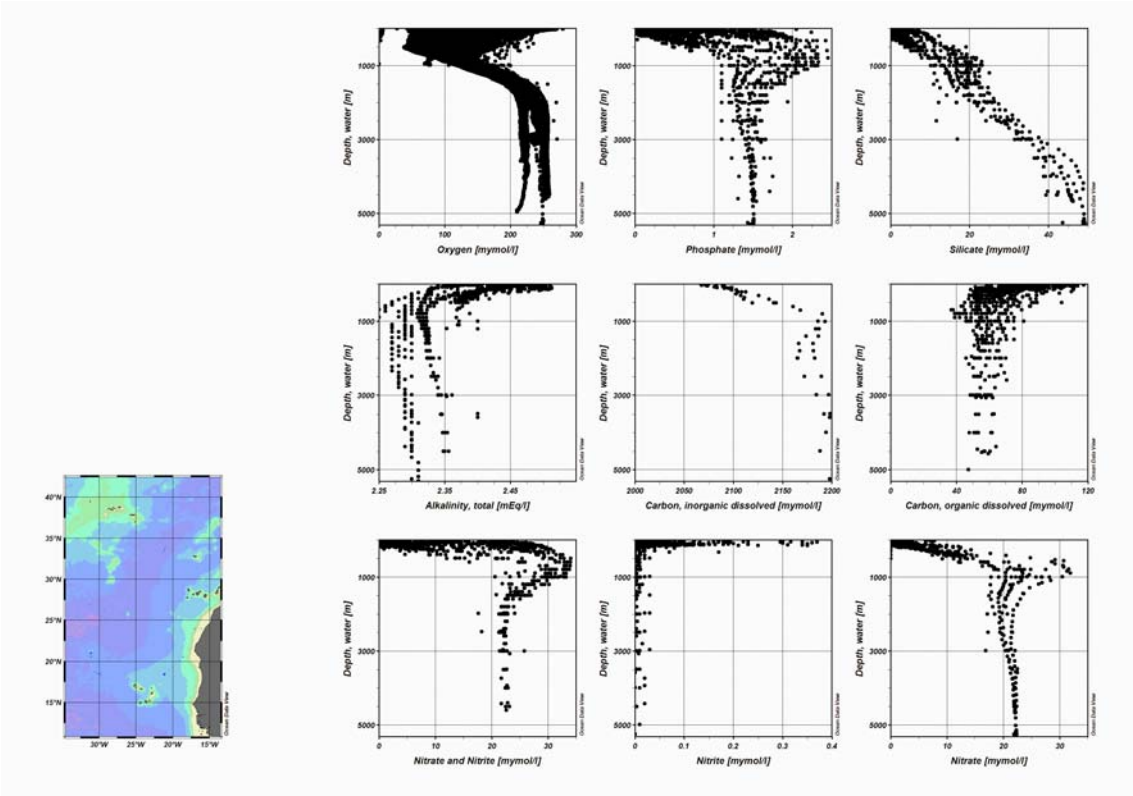


Figure 8: *EUMELI* 1-5 water column concentration data.

13.1.1.8 *HOT* site

Scientists working within the Hawaiian Ocean Time-series (HOT) project have been making repeated observations of the hydrography, chemistry and biology at a station north of Hawaii since October 1988. The objective of this research is to provide a comprehensive description of the ocean at a site representative of the central North Pacific Ocean. Cruises are made approximately once a month to Station ALOHA, the HOT deep-water station (22 45'N, 158W) located about 100 km north of Oahu, Hawaii. Measurements of the thermohaline structure, water column chemistry, currents, primary production and particle sedimentation rates are made over a 72-hour period on each cruise.

All ORFOIS related data with respect to HOT are continuously updated and available online at: http://orfois.wdc-mare.org/Results/HOT.html

Whenever you use data of the ORFOIS data compilation that refer to the HOT multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/HOT_References.php

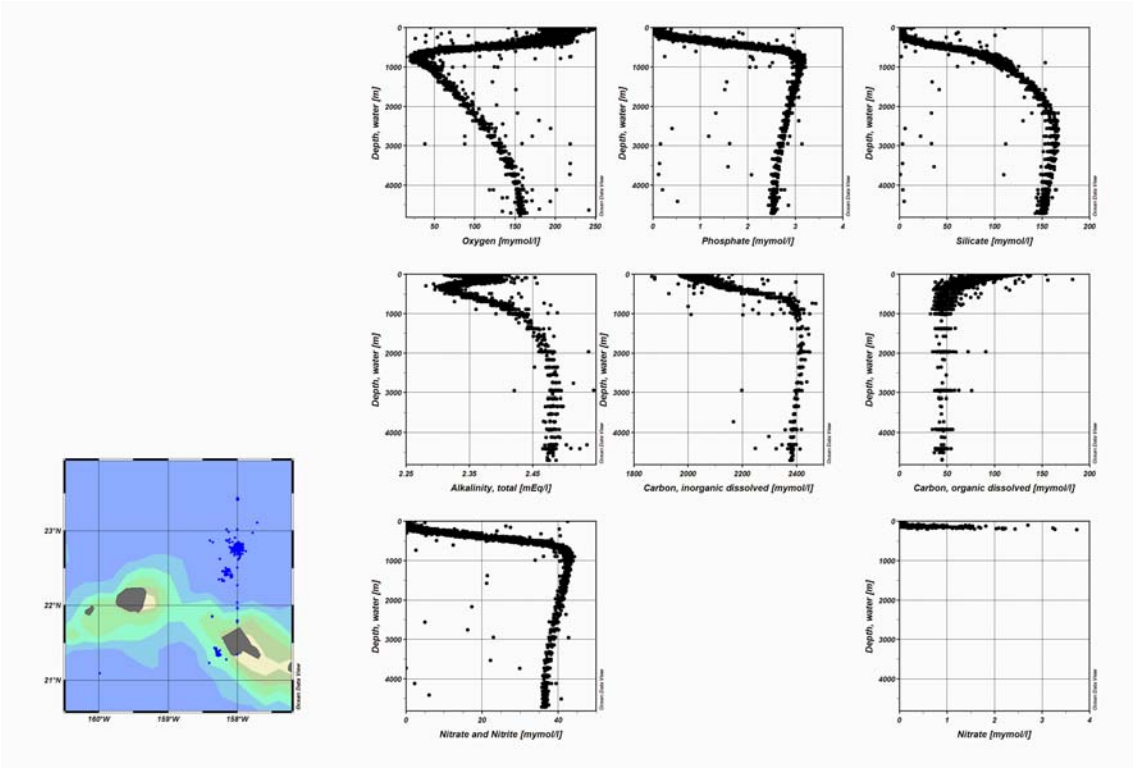


Figure 9: *HOT* water column concentration data.

13.1.1.9 *KERFIX* site (Southern Ocean Indian Sector)

Between January 1990 and March 1995 the scientific program KERFIX proposed the first continuous, multi-annual, non-coastal studies to measure parameters that are linked to the carbon cycle in the Southern Ocean at a fixed time-series station in the South-West corner off Kerguelen Island (50°40'S – 68°25'E). The objectives of the program are:

1. Understanding the processes that govern the exchange of oxygen and carbon dioxide between ocean and atmosphere;
2. Observing and interpreting seasonal and inter-annual variations of production and decay;
3. Carbon flux and associated elements at this particular site.

Additionally, micropaleontological studies yield a documentation of today's and past material flux dynamics at this site, which allows for refining our knowledge of certain oceanographic proxies.

All ORFOIS related data with respect to KERFIX are continuously updated and available online at: http://orfois.wdc-mare.org/Results/KERFIX.html

Whenever you use data of the ORFOIS data compilation that refer to the KERFIX multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/KERFIX_References.php

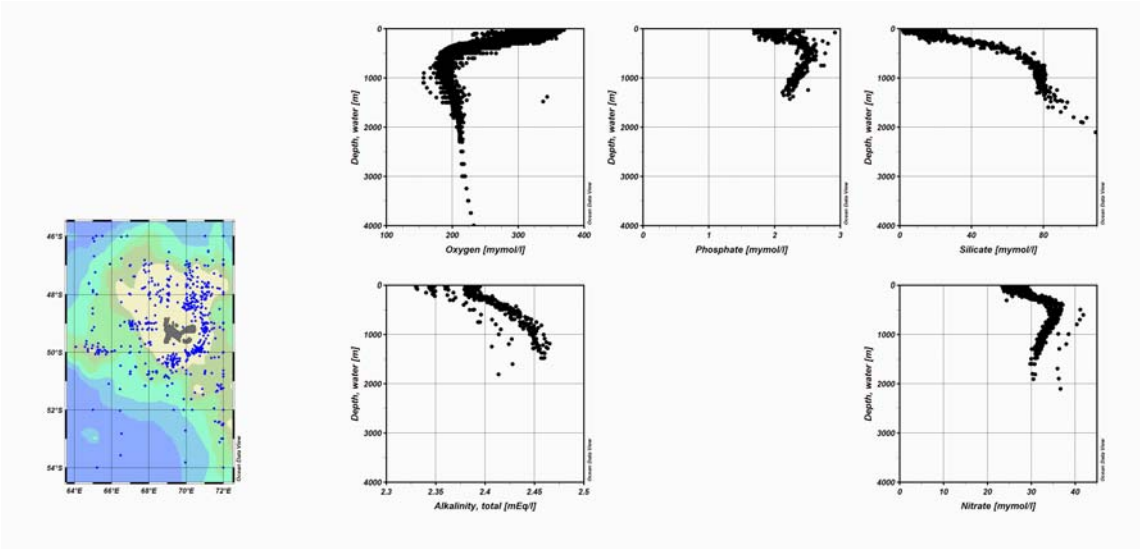


Figure 10: *KERFIX* water column concentration data.

13.1.1.10 *NABE* site

Looking closer at each of the areas (BENGAL / BIGSET / NABE / OMEX / PAP) it becomes obvious that these five sites are next to each other. For this reason the data extraction from the PANGAEA information system has been done for the whole area 47°N to 52°N and -18.83°W to -11.52°W.
All ORFOIS related data with respect to NABE are continuously updated and available online at: http://orfois.wdc-mare.org/Results/NABE.html
Water column concentration data are displayed in chapter 13.1.1.3.
Whenever you use data of the ORFOIS data compilation that refer to the NABE multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/NABE_References.php

13.1.1.11 *OMEX* site

Looking closer at each of the areas (BENGAL / BIGSET / NABE / OMEX / PAP) it becomes obvious that these five sites are next to each other. For this reason the data extraction from the PANGAEA information system has been done for the whole area 47°N to 52°N and -18.83°W to -11.52°W.
All ORFOIS related data with respect to OMEX are continuously updated and available online at: http://orfois.wdc-mare.org/Results/OMEX.html
Water column concentration data are displayed in chapter 13.1.1.3.
Whenever you use data of the ORFOIS data compilation that refer to the OMEX multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/OMEX_References.php

13.1.1.12 *PAP* site

Looking closer at each of the areas (BENGAL / BIGSET / NABE / OMEX / PAP) it becomes obvious that these five sites are next to each other. For this reason the data extraction from the PANGAEA information system has been done for the whole area 47°N to 52°N and -18.83°W to -11.52°W.
All ORFOIS related data with respect to PAP are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PAP.html
Water column concentration data are displayed in chapter 13.1.1.3.
Whenever you use data of the ORFOIS data compilation that refer to the PAP multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/PAP_References.php

13.1.1.13 *PAPA* site

Ocean Station Papa (OSP or Sta. P) is located at 50°N, 145°W, approximately 1,500 km due west from the approaches to the Juan de Fuca Strait at 125°W in 4,200 m of water, and is representative of the northeast subarctic Pacific Ocean (southern edge of the Alaska gyre). JGOFS-relevant research at OSP evolved from the co-located Canadian weathership sampling program (December 1949 - June 1981), the Subarctic Pacific Ecosystem Research (SUPER) programme (1984– 1988) and the Canadian JGOFS field programme (1992 - 1997). Since 1998, the scientists and technical staff in the Ocean Science and Productivity Division of the Department of Fisheries and Oceans, Canada (DFO) have continued to support two or three cruises to OSP per year to continue the previous decades of seasonal sampling.
All ORFOIS related data with respect to PAPA are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PAPA.html
Whenever you use data of the ORFOIS data compilation that refer to the PAPA multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/PAPA_References.php

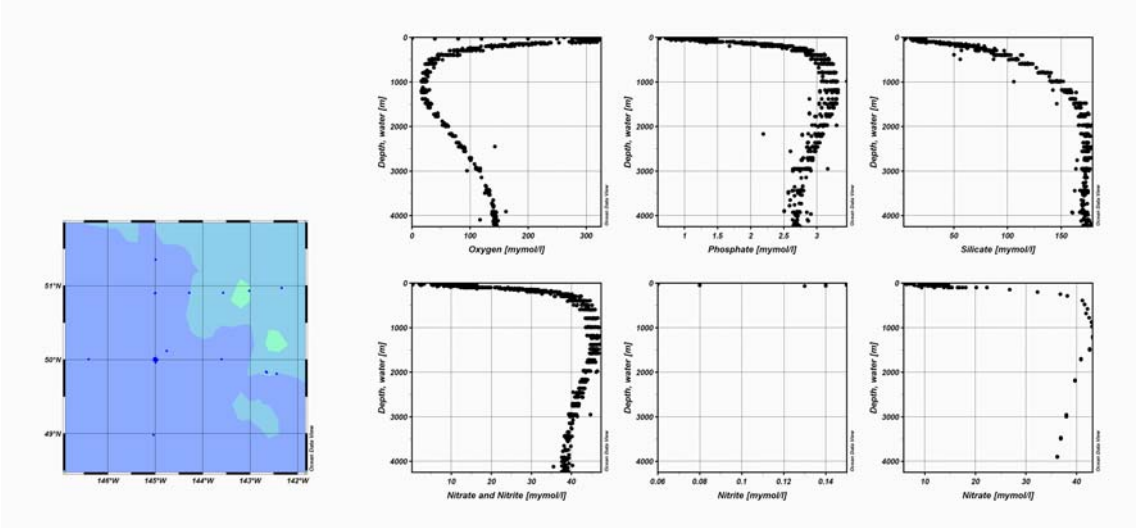


Figure 11: *PAPA* water column concentration data.

13.1.1.14 *WS 1* site (Southern Ocean Atlantic Sector)

The time-series stations Weddell Sea WS1 and WS 2 both are located South of the Polar Front in the Atlantic sector of the Southern Ocean and have been operated through 1985 and 1987 for 363 days and 304 days, respectively.
All ORFOIS related data with respect to WS1 and WS2 are continuously updated and available online at: http://orfois.wdc-mare.org/Results/WS1.html
Whenever you use data of the ORFOIS data compilation that refer to the WS1 multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/WS1_References.php

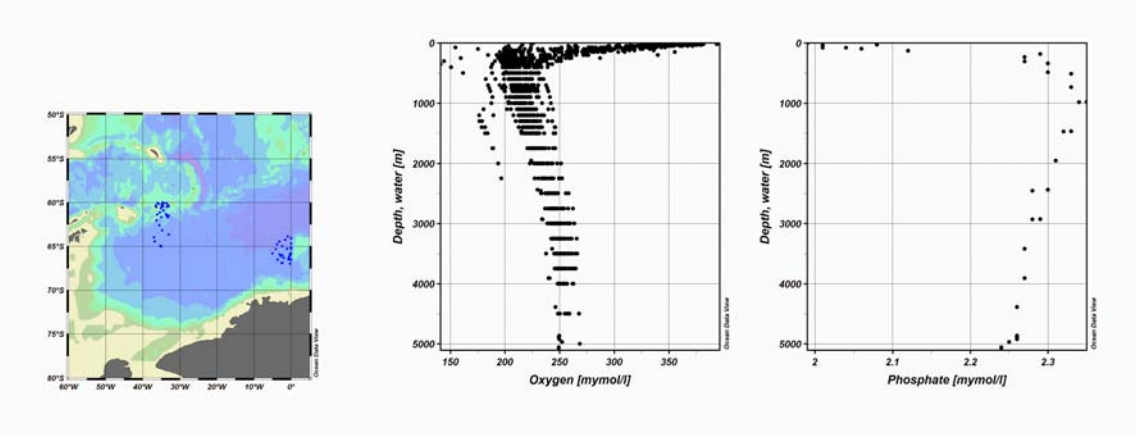


Figure 12: *WS1* and *WS2* water column concentration data.

13.1.2 Pore water concentration data

Pore water investigations usually need much more time to get in the public domain than water column investigations since there is less automated work in the respective compartment available. Number of data sets are not that extensive and the decision was made to focus on two multi-tracer stations/sites during ORFOIS, only: *PAP* and *EqPac*.

13.1.2.1 *PAP* site

All ORFOIS related data with respect to PAP are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PAP.html
Whenever you use data of the ORFOIS data compilation that refer to the PAP multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/PAP_References.php

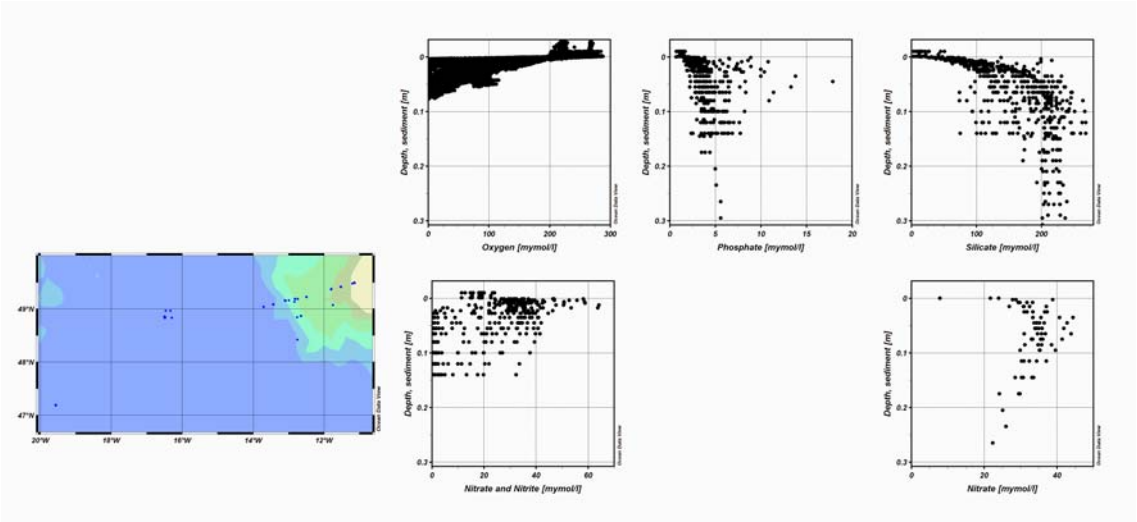


Figure 13: *PAP* pore water concentration data.

13.1.2.1 *EqPac* transect

All ORFOIS related data with respect to EqPac are continuously updated and available online at: http://orfois.wdc-mare.org/Results/EqPac.html
Whenever you use data of the ORFOIS data compilation that refer to the EqPac multi-tracer station/site, please quote the citations of the following publications: http://orfois.wdc-mare.org/EqPac_References.php

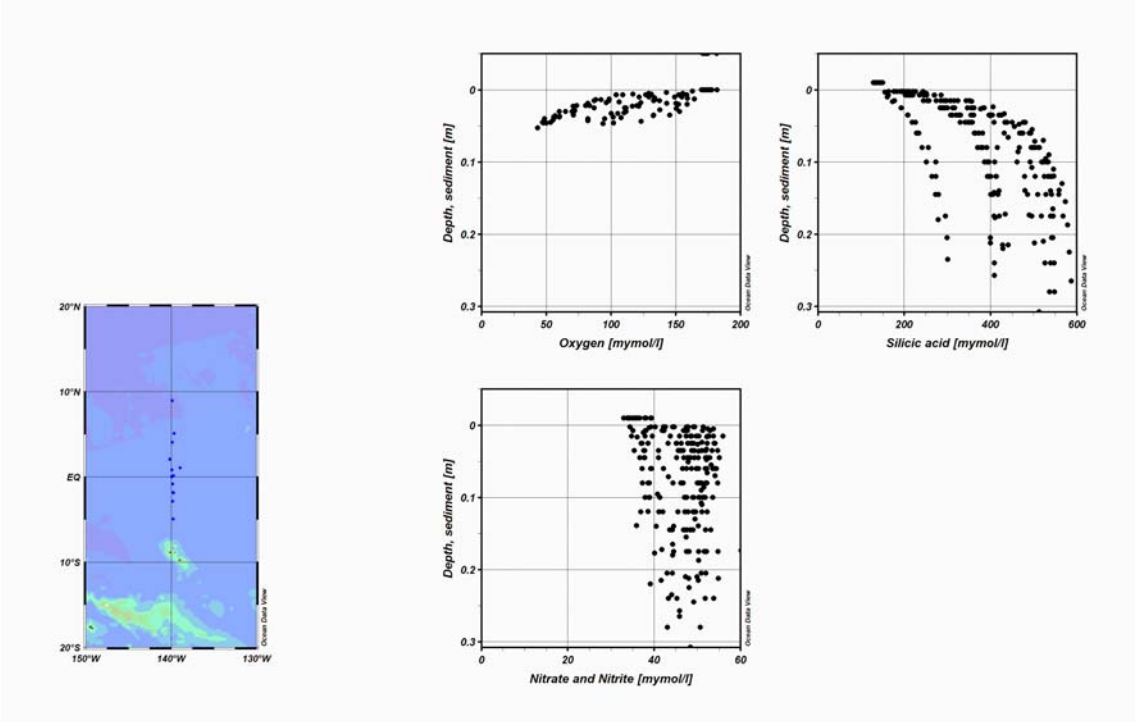


Figure 14: *EqPac* pore water concentration data.

13.2 Global data sets

In order to achieve goal 3 of the scientific/technical objectives as stated in the technical annex 1 (Description of Work) global data sets have been compiled, too. This goal is designated to "*Provide a global closed carbon and nutrient budget for modern (pre-industrial) conditions including the water column sediment interaction* ". This goal would not have been achieved without significant contributions from other sources (cf. Acknowledgments), and these data compilations are not treated as ORFOIS-only owned success.

13.2.1 Solid surface sediment concentration data

There are many thoughts what sediment depth would be the best to retrieve a maximum of valuable data. We decided to [wrongly] define the sediment surface as the depths interval between 0 cm and 35 cm sediment depth. This is scientifically not correct and corresponds to a technical working solution rather. Thus: If you refer to other sediment depths as given here in order to model the surface sediment of the global ocean, please, cut the data that you need out of the data files.

13.2.1.1 Global $BSiO_2$ [weight-%] distribution data

All ORFOIS related data with respect to global solid surface sediment biogenic silica data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/BSiO2.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment biogenic silica data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/BSiO2_References.php

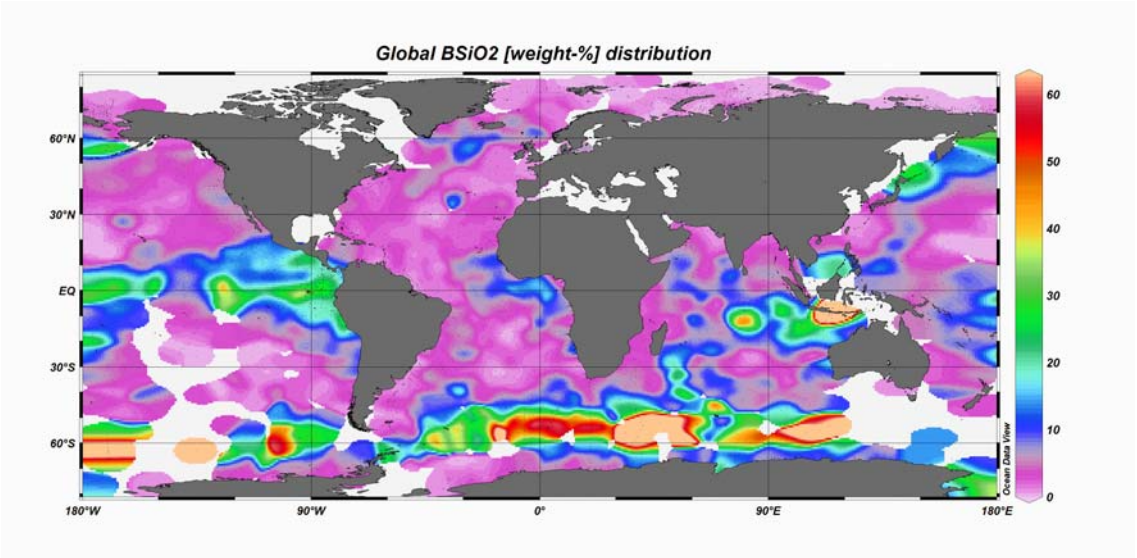


Figure 15: Global solid surface sediment Biogenic Silica ($BSiO_2$; opal) concentration data [weight-%].

13.2.1.2 Global $CaCO_3$ [weight-%] distribution data

All ORFOIS related data with respect to global solid surface sediment calcium carbonate data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/CaCO3.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment calcium carbonate data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/CaCO3_References.php

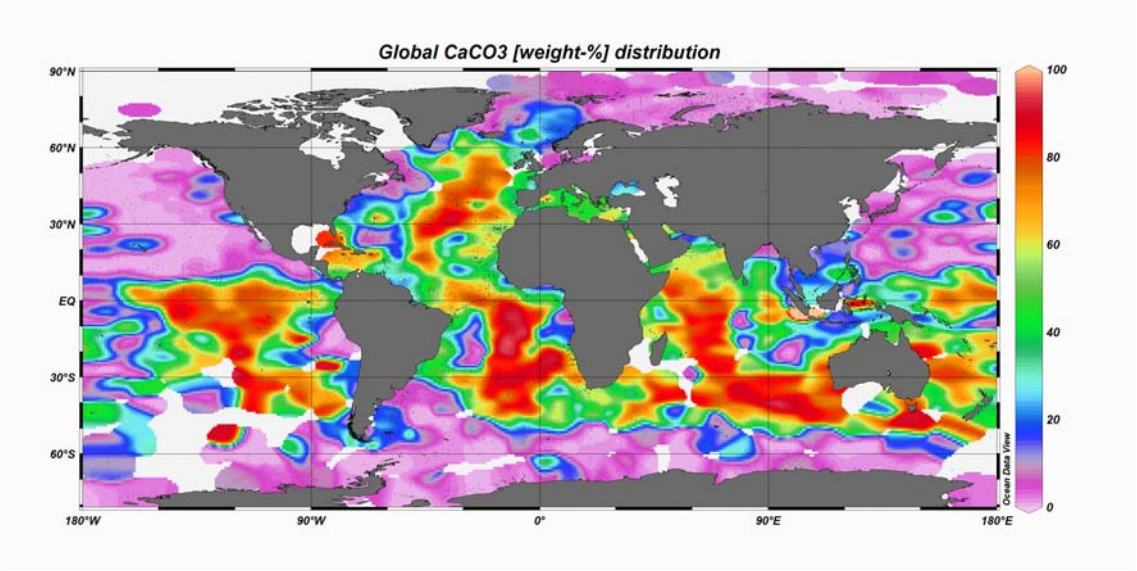


Figure 16: Global solid surface sediment Calcium Carbonate ($CaCO_3$; calcite) concentration data [weight-%].

13.2.1.3 Global TOC [weight-%] distribution data

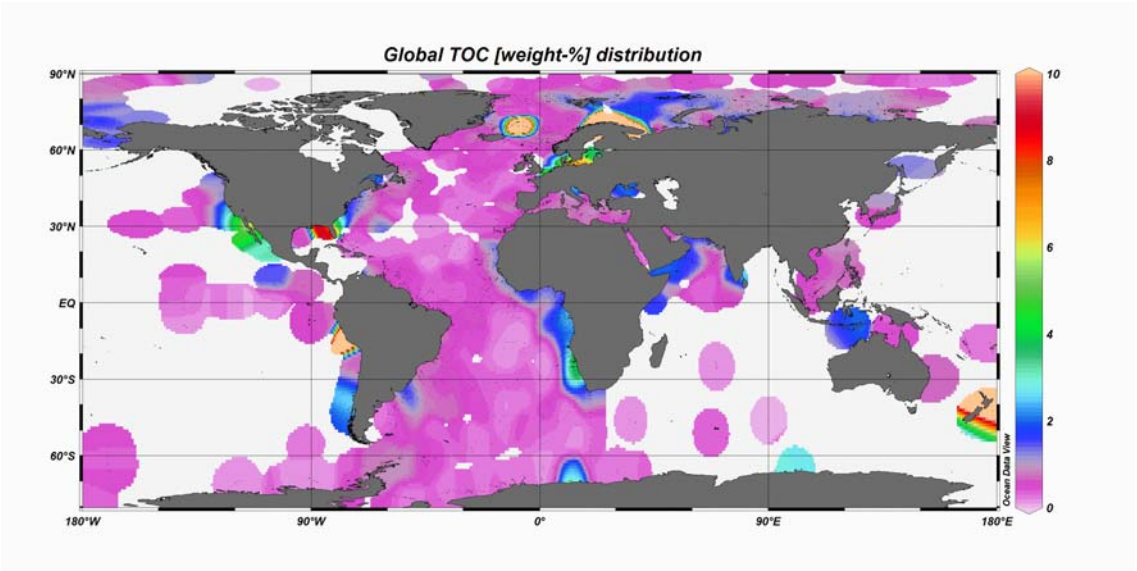


Figure 17: Global solid surface sediment Total Organic Carbon (TOC) concentration data [weight-%].

All ORFOIS related data with respect to global solid surface sediment total organic carbon data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PAP.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment total organic carbon data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/TOC_References.php

13.2.1.4 Global AR [g/cm^2/kyr] distribution data

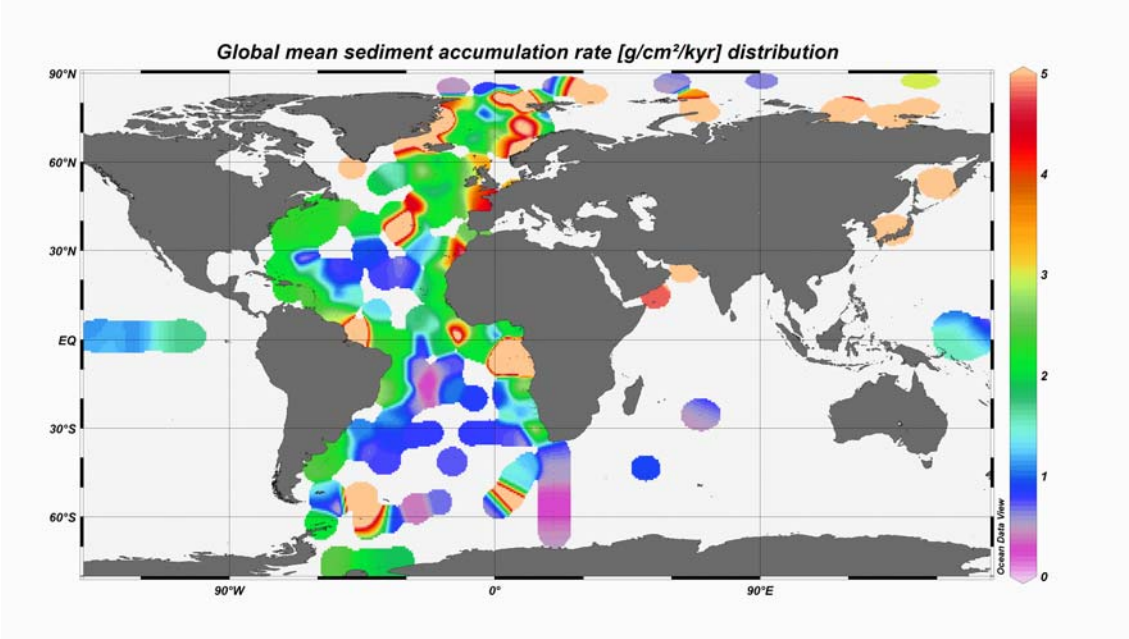


Figure 18: Global solid surface sediment mean accumulation rate (AR) data [g/cm^2/kyr].

All ORFOIS related data with respect to global solid surface sediment mean accumulation rate data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/AR.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment mean accumulation rate data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/AR_References.php

13.2.1.5 Global SR [cm/kyr] distribution data

All ORFOIS related data with respect to global solid surface sediment sedimentation rate data are continuously updated and available online at http://orfois.wdc-mare.org/Results/SR.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment sedimentation rate data collection, please quote the citations of the following publications:

http://orfois.wdc-mare.org/SR_References.php

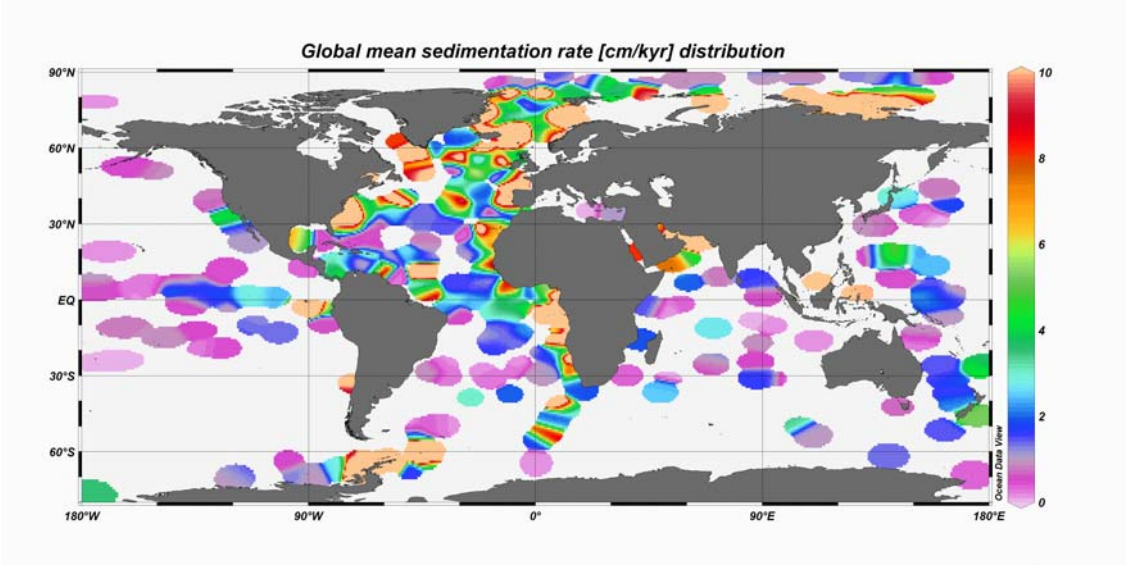


Figure 19: Global solid surface sediment mean sedimentation rate (SR) data [cm/kyr].

13.2.1.6 Global porosity [%] distribution data

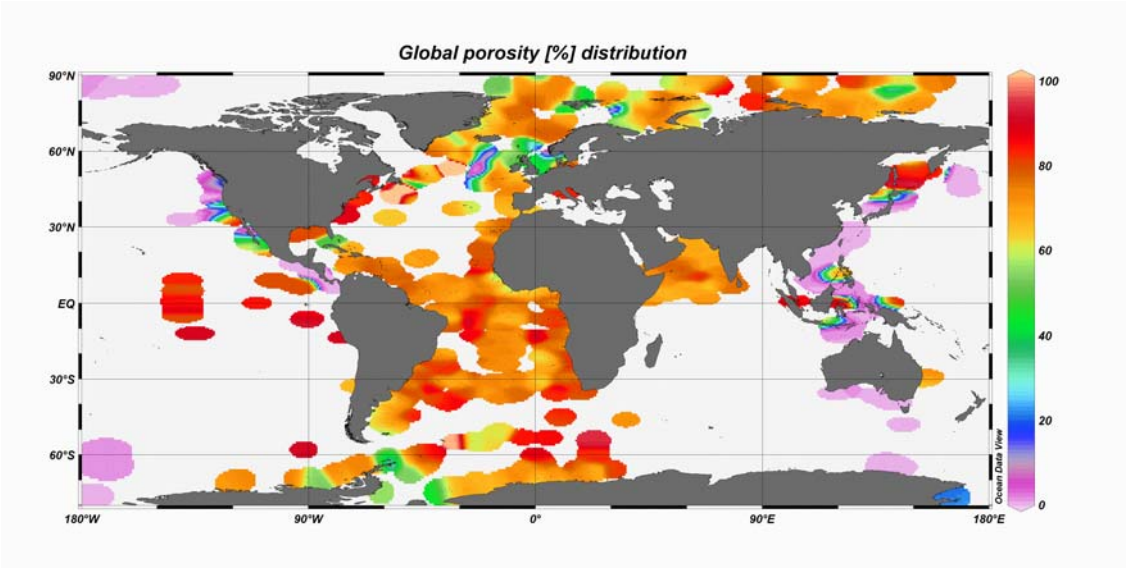


Figure 20: Global solid surface sediment porosity data [%].

All ORFOIS related data with respect to global solid surface sediment porosity data are continuously updated and available online at http://orfois.wdc-mare.org/Results/Porosity.html
Whenever you use data of the ORFOIS data compilation that refer to the global solid surface sediment porosity data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/Porosity_References.php

13.2.2 Water column concentration data

Around the globe, there are many data collections available that contain water column concentrations of Oxygen, Phosphate, Silicate, Alkalinity, Dissolved Inorganic Carbon, Dissolved Organic Carbon, and Nitrate, as it is requested by the modelling group. However, it is up to the single scientist to decide whether she/he wants to include other data than the present data compilations. WDC-MARE data collections yet explicitly exclude WOD 2001 and WOA 2001. Since we offer global data compilations as ODV collections, you may add data as necessary.
In the aftermath of ORFOIS the several MB comprising high quality data collections eWOCE *Electronic Atlas of WOCE Data* (Schlitzer, 2000) and *Hydrographic Atlas of the Arctic Ocean* (Nikiforov, 2001) will be included in the ORFOIS compilation at WDC-MARE and then multiply the actual data compilation.
Data given below have been plotted using ODV and interpolated through VG Gridding (20 X-/Y-Scale-Length [perm.]) weighted means. These data compilations are available at http://orfois.wdc-mare.org/ as ODV collections. The plots refer to the uppermost layer of the global ocean. Data, however, are available for the whole water column.

13.2.2.1 Global oxygen [µmol/l] distribution data

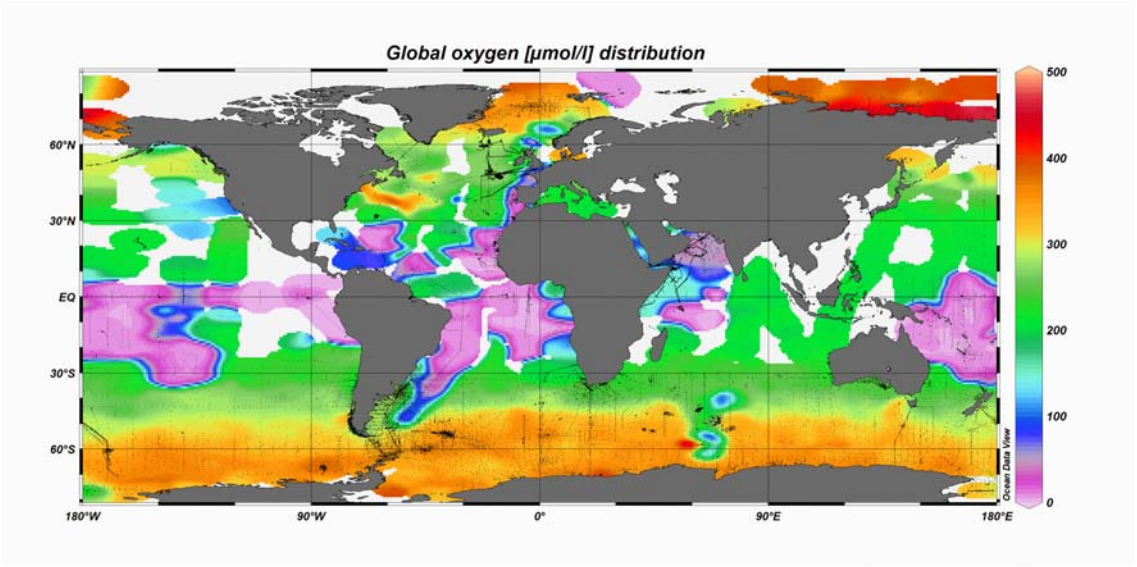


Figure 21: Global distribution of oxygen [µmol/l] data in the water column.

All ORFOIS related data with respect to global water column oxygen concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/O2.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column oxygen concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/O2_References.php

13.2.2.2 Global phosphate [µmol/l] distribution data

All ORFOIS related data with respect to global water column phosphate concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PO4.html

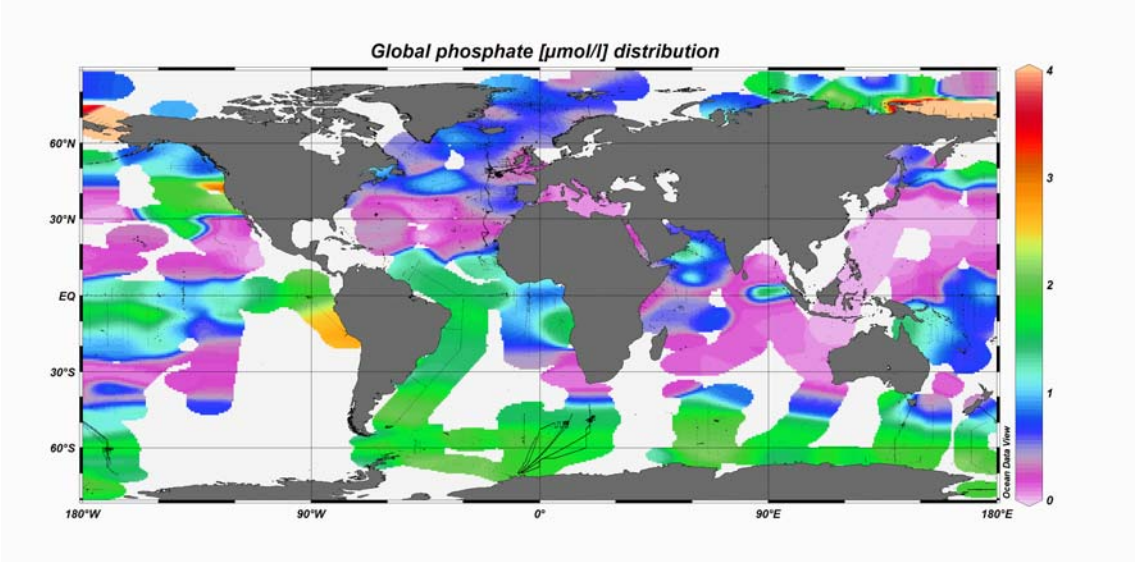


Figure 22: Global distribution of phosphate [µmol/l] data in the water column.

Whenever you use data of the ORFOIS data compilation that refer to the global water column phosphate concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/PO4_References.php

13.2.2.3 Global silicate [µmol/l] distribution data

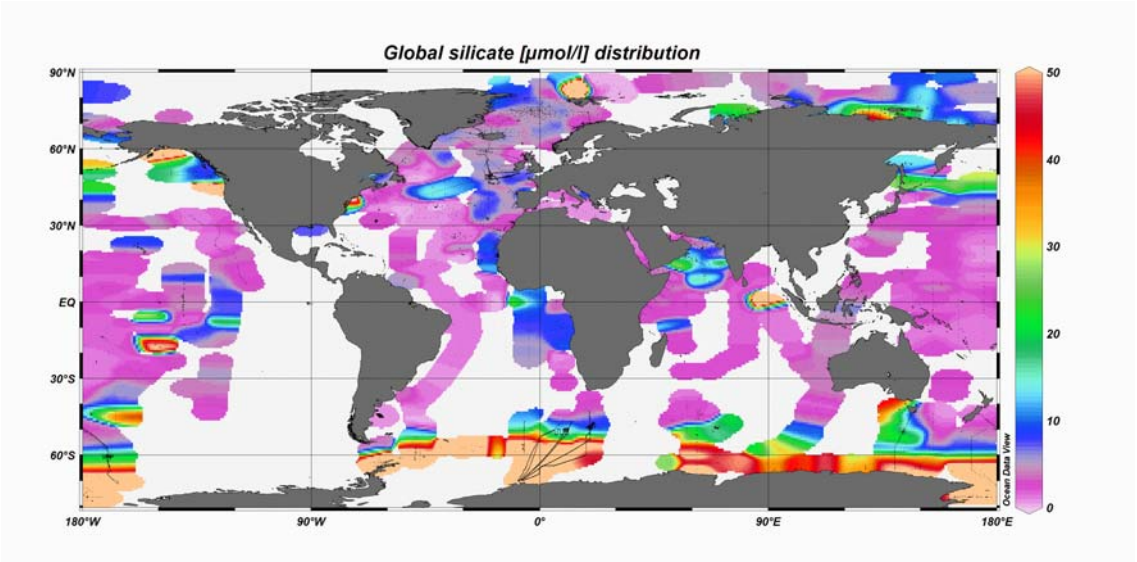


Figure 23: Global distribution of silicate [µmol/l] data in the water column.

All ORFOIS related data with respect to global water column silicate concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/H4SiO4.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column silicate concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/H4SiO4_References.php

13.2.2.4 Global alkalinity [µEq/l] distribution data

All ORFOIS related data with respect to global water column alkalinity concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/ALK.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column alkalinity concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/ALK_References.php

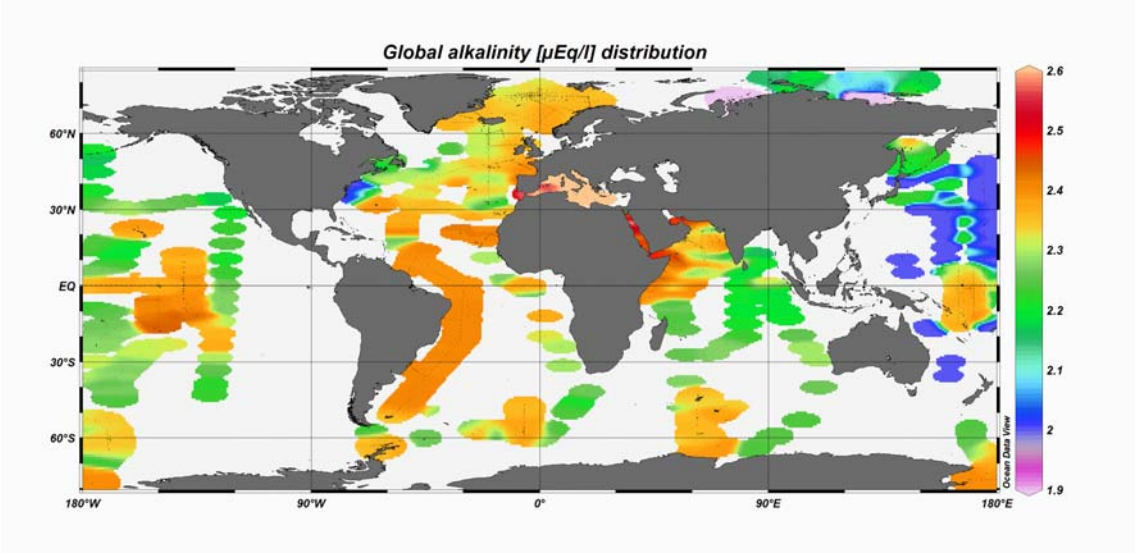


Figure 24: Global distribution of alkalinity [µEq/l] data in the water column.

13.2.2.5 Global dissolved inorganic carbon [µmol/l] distribution data

All ORFOIS related data with respect to global water column dissolved inorganic carbon concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/DIC.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column dissolved inorganic carbon concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/DIC_References.php

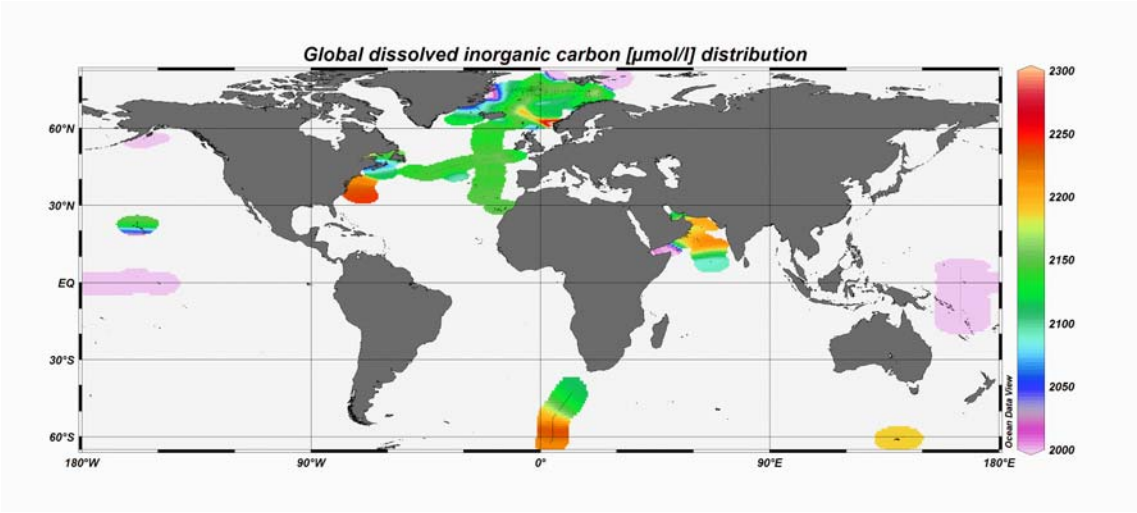


Figure 25: Global distribution of dissolved inorganic carbon [µmol/l] data in the water column.

13.2.2.6 Global dissolved organic carbon [µmol/l] distribution data

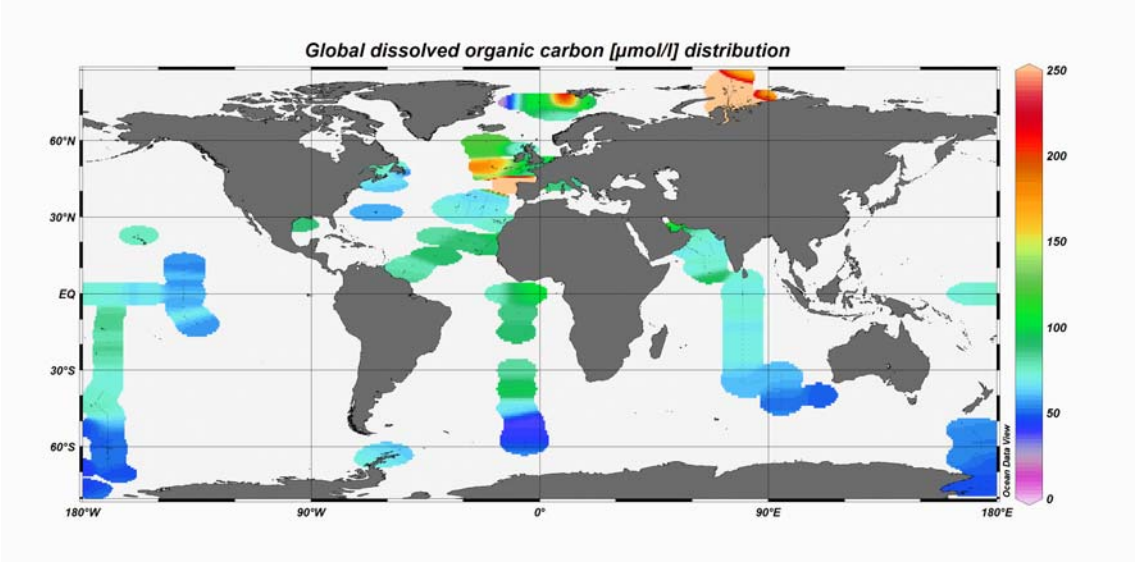


Figure 26: Global distribution of dissolved organic carbon [µmol/l] data in the water column.

All ORFOIS related data with respect to global water column dissolved organic carbon concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/DOC.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column dissolved organic carbon concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/DOC_References.php

13.2.2.7 Global nitrate [µmol/l] distribution data

All ORFOIS related data with respect to global water column nitrate concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/NO3.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column nitrate concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/NO3_References.php

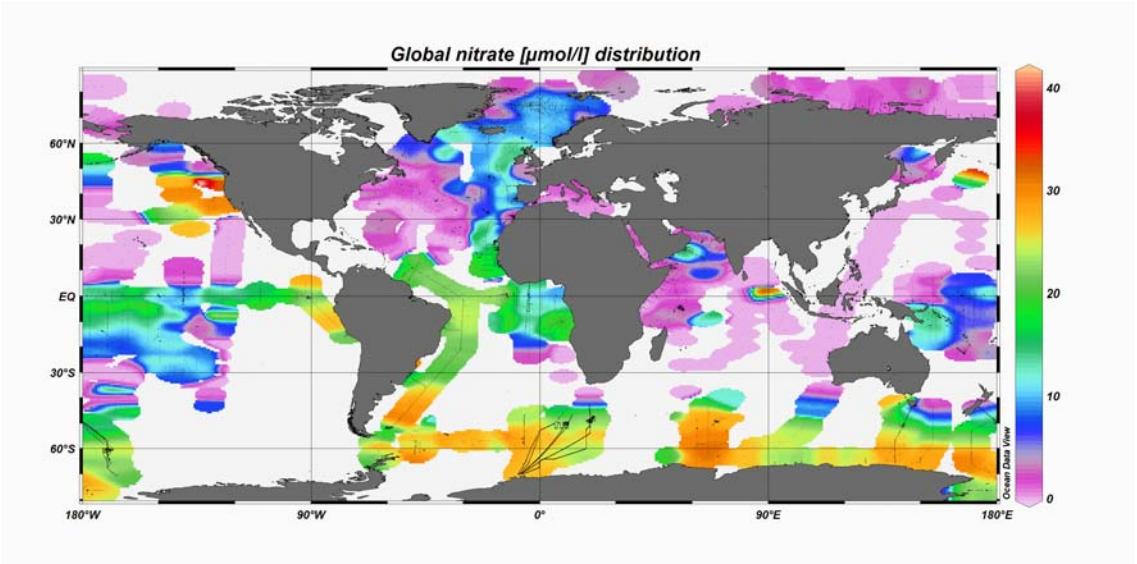


Figure 27: Global distribution of nitrate [µmol/l] data in the water column.

13.2.2.8 Global chlorophyll-a [µg/l] distribution data

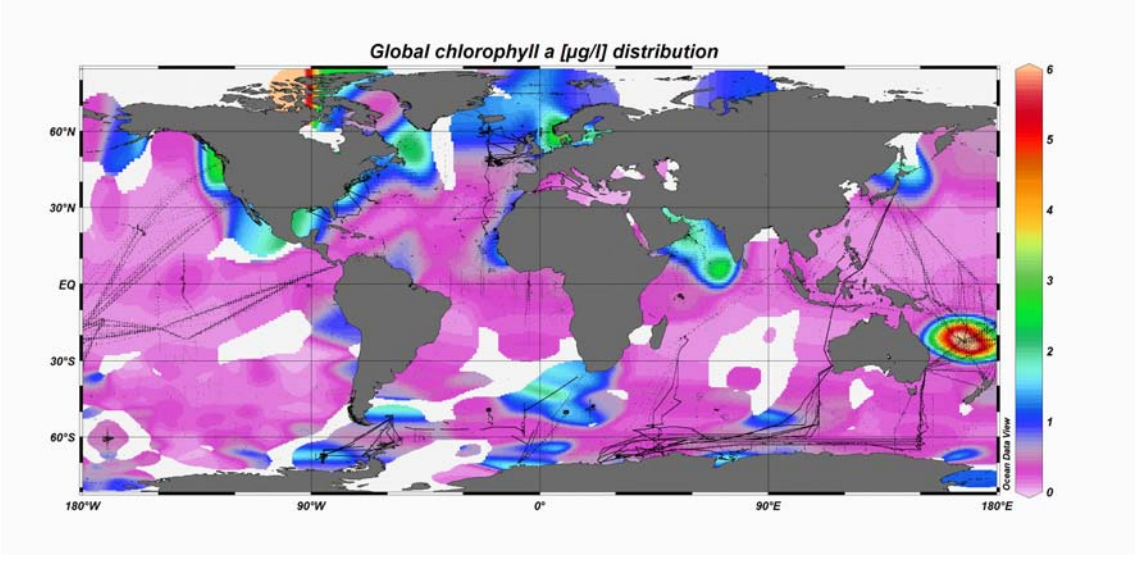


Figure 28: Global distribution of chlorophyll a [µg/l] data in the water column.

All ORFOIS related data with respect to global water column chlorophyll-a concentration data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/Chl-a.html

Whenever you use data of the ORFOIS data compilation that refer to the global water column chlorophyll a concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/Chl-a_References.php

13.2.2.9 Global primary production distribution data

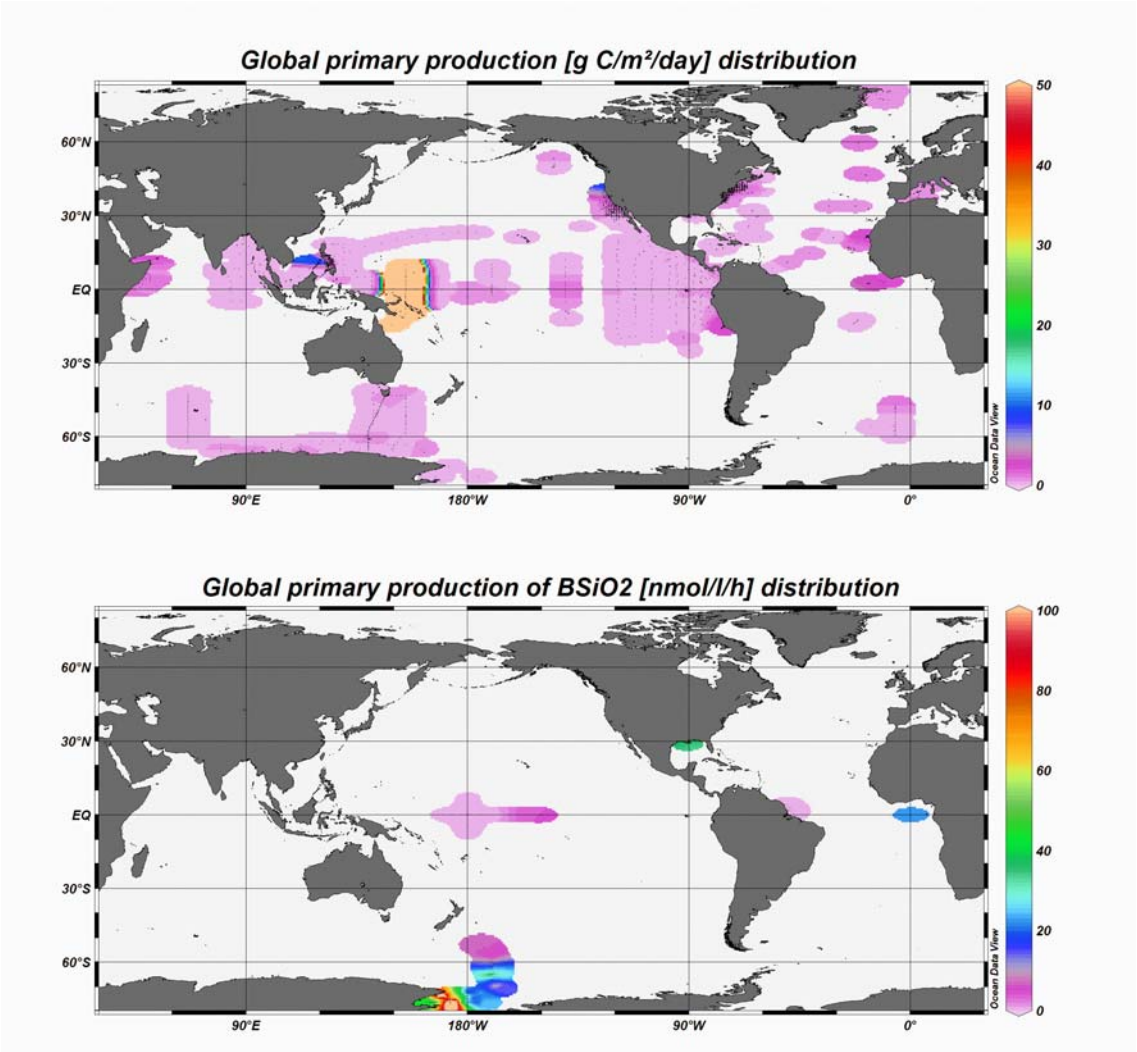


Figure 29: Global distribution of carbon and biogenic silica primary production data in the water column.

All ORFOIS related data with respect to global water column primary production data are continuously updated and available online at: http://orfois.wdc-mare.org/Results/PP.html
Whenever you use data of the ORFOIS data compilation that refer to the global water column primary production concentration data collection, please quote the citations of the following publications:
http://orfois.wdc-mare.org/PP_References.php

14. References

Additionally to the references listed below, all references that are related to scientific data as compiled through ORFOIS sum up to more than 140 printed pages. For this reason the willing reader is kindly invited to plough through this list at the ORFOIS web page at http://orfois.wdc-mare.org/References.php

Archer, D., H. Kheshgi, and E. Maier-Reimer, 1997, Multiple timescales for the neutralization of fossil fuel CO_2, *Geophysical Research Letters*, 24 (4), 405-408.

Archer, D., and E. Maier-Reimer, 1994, Effect of deep-sea sedimentary calcite preservation on atmospheric CO_2 concentration, *Nature*, 367, 260-263.

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