Development of global plankton database and model system for eco-climate early warning

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Final Report Summary - GREENSEAS (Development of global plankton data base and model system for eco-climate early warning)

Executive Summary:
The goal of the 3.5 years long project GreenSeas - involving nine partners from six nations circumscribing the Atlantic Ocean - was to advance the quantitative knowledge of how planktonic marine ecosystems, including phytoplankton, bacterioplankton and zooplankton, will respond to environmental and climate change. Towards its fulfillment, the following has been achieved –

- collating and analysing plankton data: ~70,000 records of harmonized plankton and environmental data of the Arctic, Nordic, Atlantic and Southern Ocean from early 20th century till present; available on the portal http://greenport/web/guest/database,
- identification of regular planktonic patterns – biomes – through statistical analysis,
- obtaining new ecosystem data: establishment of the mixotrophic basis of the oligotrophic Atlantic, questioning the boundary between photo- and heterotrophic bacterioplankton and eukaryotes, also utilizing first measurements of group-specific primary production
- demonstration of the taxonomic-based experimental approach to understand ecosystem functioning in the photic layer of the oligotrophic ocean,
- confirming markedly larger than Redfield (C:N) element ratios of Net Community Production in the N. Atlantic/Arctic seas, questioning the N-based method for NCP,
- first winter biooptical characterization ever in the Southern Ocean, identifying climate sensitive primary productivity in the Subantarctic Zone resulting from fluctuations of the mixed layer, allows rapid growth in this light light environment,
- demonstration of unprecedented high resolution phytoplankton biomass estimates from gliders throughout the season water column, enhancing our understanding production and export processes at submeso-space and sub-seasonal time scales. Mesoscale variability in the central South Atlantic Subtropical Gyre was associated with the presence of westward propagating isolated vortices,
- nitrification rates are demonstrated to represent an important proportion of nitrate uptake rates just after an upwelling event or at the end of a bloom,
- developing a delivery system: serving users such as ecosystem modellers with web based viewing, down-loading and analysing capacity of in situ, EO data and model derived data,
- projecting ecosystem states: model performance improves with higher spatial resolution, while a more high-frequency forcing does not necessarily improve predictability of a bloom.
o biomass loss and acclimation are identified as major sources of uncertainty, only partly alleviated by data assimilation.

o identification of the need for more efficient ways to combine advanced parameterizations of plankton dynamics and high-resolution models,
• developing ecosystem indicators: changes in climate patterns can cause shifts in plankton species, like opening the way for diatoms in windier and more turbulent environments,
 o detection of up to two annual chlorophyll-a peaks in the N. Atlantic by development of new phytoplankton phenology algorithm, also applied to the past satellite record (1978-1986) with a confidence level of 30% or better in approximately 20% of the global oceans,
 o identification of oceanic regions where remote sensing based indicators can be reliably extended three decades back (to 1978) and thus assess long-term ecosystem state trends,
 o discrepancies in the estimates of phytoplankton biomass, size fractions and phenology between modes and observations facilitates our understanding of the degree of complexity that is needed in biogeochemical models to describe phytoplankton phenology and population structure, and contributing to a roadmap for future development of models.

Project Context and Objectives:

Context

Climate change is arguably the greatest challenge facing mankind in the twenty-first century (IPCC, 2013). Resulting from natural variability and anthropogenically induced changes, climate change can only be understood through improved knowledge of the coupling and feedback mechanisms between dynamic processes in the Earth system as well as the interaction with the anthroposphere. These processes, feedback mechanisms and interactions, in turn, can have unprecedented and dramatic impacts on marine ecology. Phytoplankton is a key component of the marine ecosystem, fixing atmospheric carbon and providing the primary food source for the zooplankton, and together they form the base of the oceanic food chain. Larger invertebrates, fish, and mammals depend on plankton for their survival.

The last two decades have witnessed huge shifts in our understanding of how ocean biology functions (Hansen et al, 1999). One of these shifts has been the emergence of microbial populations as dominant drivers of upper ocean biogeochemistry. Even in the Southern Ocean the classical ecosystem paradigm of large diatoms fuelling competing krill and copepods (Atkinson et al, 2012) that feed warm-blooded predators is also changing. For example, small phytoplankton proliferate (Edwards et al, 1998), the major predators can often be protists (Burkill et al, 1995) and >50% of the primary production carbon may cycle through bacterioplankton (Ducklow, 1995). Microbial populations play an important role in the recycling and remineralisation of materials and energy within the food chain. These processes regulate the elemental cycles of elements such as C, N, P, Si, Fe in the ocean, the biogeochemical feedback processes between the land, ocean and atmosphere and their implications for climate.

The timing and production of plankton are in turn directly dependent on light, water temperature and nutrient availability (which is indirectly controlled by basin scale and mesoscale circulation patterns as well as spreading of continental fresh water runoff). Changes in climate can affect the timing of the seasonal plankton blooms, with effects that pass up the food chain. Strong relationships between larval fish survival and the timing and production of their food have been demonstrated (e.g. Koeller et al. 2009). Longer term changes in climate are changing the plankton species composition, changing the feeding environment of the larval fish. In addition, planktonic ecosystems are highly susceptible to ocean acidification (e.g. Raven
overfishing (e.g. Petrie et al 2009) and anthropogenic nutrient pollution potentially leading to Harmful Algal Bloom (HAB) events (e.g. Glibert and Burkholder 2006). One of the great challenges we are facing is the need to understand and predict the consequences of changes in climate, biogeochemical cycles, human resource use, among other things, and mitigate the impacts.

To cope with the above challenges the Group on Earth Observations (GEO) is leading the process towards a Global Earth Observation System of Systems, or GEOSS. GEOSS will also yield a broad range of societal benefits, such as understanding, assessing, predicting, mitigating, and adapting to climate variability and change, improving the management and protection of terrestrial, coastal and marine ecosystems and understanding, monitoring and conserving biodiversity. Furthermore, the Global Climate Observing System (GCOS) has established a list of Essential Climate Variables (ECV), Essential Biodiversity Variables (EBV) and Essential Ocean Variables (EOV), whose purpose is to improve and harmonize existing monitoring schemes and guide the implementation of new ones, especially where information on change is still very sparse. EBVs are crucial for obtaining the 2020 targets of the Convention on Biological Diversity. Such variables should be able to be measured or modelled globally, by combining satellite remote sensing observations with in-situ observations.

The ambition of GreenSeas was to make a significant contribution to the monitoring of EBVs on species populations and traits, community composition, ecosystem structure and function. Essential Ocean Variables (EOV) are currently in the process of being defined. Working groups have been set up for the following topics: 1) trophic; primary producers; 2) trophic; zooplankton, 3) trophic; large marine vertebrates, 4) habitats, 5) human impacts and 6) water quality. GreenSeas contributes to working groups 1, 2 and 4.

Objectives

In accordance with the GEOSS and GCOS goals and faced with the challenges of changes in climate and the biogeochemical cycles, the GreenSeas consortium defined a 3 and a half year project with the primary goal to:

Advance the quantitative knowledge of how planktonic marine ecosystems, including phytoplankton, bacterioplankton and zooplankton, will respond to environmental and climate change.

To reach this goal, GreenSeas targeted the following EU FP7 research priorities:

I. improved data access and delivery of in-situ, earth-observation and modelled plankton data and stimulation of plankton monitoring and research into new marine areas;

II. development of innovative indicators to monitor the structure and functioning of marine ecosystems and their effects on global biogeochemical cycling and fisheries;

III. integration of coupled physical and biogeochemical models which target marine planktonic ecosystems with suitable observations;

IV. innovative methods for efficient integrated management and use of resources.

To address these priorities GreenSeas identified the following key scientific, technological and communication objectives, defined for the duration of the project:

• To assess the current state of the marine planktonic ecosystem by providing benchmarks of its present state for the future assessment of climate change.

• To improve the knowledge base and understanding of the impacts of climatic and anthropogenic change on planktonic ecosystem structure and function.

• To improve the ability to model and project future marine ecosystem states.

• To apply the ecosystem approach to GreenSeas data to derive a suite of indicators of which describe
changes in ecosystem function.

• To improve the technology for accessing historical plankton and associated environmental data sets, along with earth observation data and simulation outputs.
• To enhance international cooperative links with other plankton monitoring and analysis surveys around the globe.
• To transfer knowledge to society

The work was organized within seven workpackages (WPs) comprising the essence of the GreenSeas concept, i.e. to set up a core service following the open and free data access policy implemented in the Copernicus (former Global Monitoring for Environment and Security - GMES) programme (Figure 1). The core service delivers both new and historical plankton data and information products along with numerical simulations to a range of users using state of the art web based delivery systems. It builds on historical data-sets, existing data delivery systems and ongoing multidisciplinary ocean planktonic ecosystem monitoring programs in the Atlantic, Arctic and Southern Oceans. Plankton data collection is enhanced where possible with an emphasis on the Southern Ocean. The planktonic ecosystem may be classified into provinces i.e. regions of coherent physical forcing and biological conditions, which are eventually representative of macro-scale ocean ecosystems (Longhurst 1995). The focus has been on capturing the latitudinal gradients, biogeographical distributions and provinces in the planktonic ecosystem from the Arctic, through the Atlantic and into the Southern Ocean, as proof of concept.

Project Results:
This report, including summary, objectives and illustrations is also found as GreenSeas report D1.6 and will be published on the web-page greenseas.eu

Tools for plankton data delivery and analysis

In-situ plankton data are required for a variety of purposes. GreenSeas data has been accessed from various sources and combined into an analytical database. Such a database allows data from different sources to be combined and analyzed as though they were from a single source. The successfullness of this approach relied to a large extent on the development of the database structure with great emphasis on data inter-comparability, metadata, quality assurance and taxonomy. After populating the database statistical analytical methods have been used to examine spatio-temporal variation on a range of scales. To create interoperability across in situ plankton data, model output and indicators the GreenSeas Analysis Framework (GSAF) is established as a protocol to ensure a responsible data sharing policy that further ensures scientific robustness of the resulting joint analyses.

In parallel, a data delivery system based on standard open source web-GIS protocols has been developed. The partners and other sources have provided historical and new plankton data, as well as simulation output and indicators in predefined formats, also providing metadata, some making their databases available through OGC compliant servers. The system is designed to comprise a set of distributed data nodes offering the various products. Users access the system through a common web browser, where they can search for plankton data from all providers and display the retrieved datasets on the same map. Selected datasets can also be downloaded for processing in the user’s own information systems.

Analytical database
Developing the combined analytical database for plankton data has involved integrated work on historical and new plankton data, environmental indicators and ecosystem modelling. A data protocol and collection template was collectively designed, also with input from BODC (British Oceanographic Data Center). The joint approach and harmonizing of data from all the data supplying partners allowed the building of a comprehensive capture of data from the Arctic (MMBI), Atlantic (PML, NERC) and Southern Ocean (UCT, CSIR, FURG, Uni-Research). This analytical database contains 70,000+ in-situ based sampling records, covering a latitudinal gradient ranging from the Arctic (13,000+ records), Nordic seas (13,000+) through the Atlantic (19,000+) and to the Southern Ocean (20,000+), with a wide combination of physical, planktonic based, environmental and chemically based information.

The definition of the data protocol also implies that the required plankton taxonomy has been agreed; the key variables needed to address the project science themes have been defined and collecte, and the outputs of the merged and analyzable data are provided in a common format. For instance, statistical analysis of long term time series signals has been carried out with integrated data from the numerical models, earth observation and the in-situ data in the analytical database, providing consistent plankton datasets by which analyses from various angles (process studies, modelling etc) can provide an updated cross-disciplinary and integrated understanding of the state and function of the Atlantic sector plankton ecosystem in the light of future climate change. The analyses may be extended to global, as the data base is augmented in the future.

Data delivery system

In order to advance our understanding and predictive capacities of how marine ecosystems will respond to global change, GreenSeas has employed a combination of observation data, numerical simulations and a cross-disciplinary synthesis to develop a high quality, harmonized and standardized plankton and plankton ecology long time-series, data inventory and information service. In so doing GreenSeas will contribute to monitoring and assessment of environmental pressures and risks, including tensions and conflicts related to the depletion of natural resources and environmental services (Worm et al 2006) which may arise due to rapid environmental changes and/or natural and man-made hazards.

The essence of the GreenSeas concept is the establishment of a ‘core’ service following the open and free data access policy implemented in the Copernicus programme. A specific task has been to define an architecture of the data delivery system based on a distributed client-server model, where a set of data nodes will offer plankton data and/or derived products from a WMS, WFS of WCS compliant data server. The development builds on previous achievements (e.g. DISMAR, InterRisk, NETMAR, MyOcean, ICEDS and ESA-SSE), using established standards for web-GIS and web services, including standardization of data and metadata. Within the present achievements the capabilities of web-GIS with support for handling of global plankton data have been extended.

The GreenSeas consortium defined the following generic features and requirements of the data delivery system: Ease of access; Clear inventory; Visualization – web map; Gridding / Binning; Model- data matchup; Statistics; Taylor diagram

Main users: Modelers, Earth Observation community, Plankton Biologists; Oceanographers; Policy makers. For the present implementation modelers have been the main target. The main features include ingestion, processing, data base and viewing.
System architecture.

The GreenSeas DDS is a distributed system where multiple data providers can be connected to the web GIS portal and client through standard protocols. The analytical database of in situ data is connected to the portal through OGC WMS and WFS by means of GeoServer. The database of EO and model data is connected through WMS and OPeNDAP, another community standard allowing data streaming, i.e. the client can download selected parts rather than entire files. Adherence to standards for data exchange makes it easy to connect to other external data sources. The DDS will not see any difference between local or external data servers.

The web GIS client offers query, metadata and data download, presentation and export, as well as simple statistics and different forms of in situ-EO/model intercomparison tools, using open source tools and libraries. The main components include Liferay as a web platform on which the client is created, OpenLayers is used for map display including management and colouring of layers, jQuery is used for menus, input fields and the “parameter tree” used to select parameters to include in a search, and Highcharts is used for plotting.

In situ data

The data collection template used to create the GreenSeas analytical database defined the metadata to be collected for each measurement, including:

- Location: latitude, longitude, depth (of sample and sea), date and time
- Ownership: 1: PI/ Originator, 2: Institute, 3: Research group, 4: Data collection details

For each parameter the following was specified:

- Data title and up to 3 subtitles
- Units used and BODC data quality flag
- Field description

During the compilation, fields for GreenSeas originator (including contact information) and cruise/station (fixed) ID were added. The template was used to collect:

- Physical variables, such as temperature, salinity, optical depth, mixed layer depth, and dissolved Oxygen
- Plankton data, such as diatoms and flagellates (full list in Somerfield et al., 2011)
- Nutrients, such as N, P, Nitrification N2, NO3, NO2, NH4, Urea, Si, Calcite

EO data and model output

EO data prepared by PML generated five ocean colour based , whereas currently model fields from the NORWECOM (Sakov et al., 2012; Skogen and Soiland, 1998) and PELAGOS (Vichi and Masina (2009)) ecosystem models are supported.

Search by area

Bounding box

The user types in min/max latitude/longitude manually or directly on the map. Then

- Longhurst provinces or biomes - a set of predefined areas explained previously can be selected.
- Search by time – date or month range – user selects a date range (and optionally a time-of-day interval) and/or a month range.
- Search by depth - The user can specify a depth range to search by.
- Search by cruise or fixed station - The cruises and fixed stations is presented to the user as a dropdown menu from which he/she can select a specific cruise or fixed station to search by.
- Select metadata - By default, all metadata will be output by a query. There are 15 metadata variables, of which all may not needed by the user.
• Filter for specific parameters
From a tree structure the desired pre-categorized and grouped parameters can be selected from a list of currently 240. At the highest level, there are 6 nodes or categories: Chemistry, Light/Chlorophyll, Plankton, Rate measurements, Salinity and Temperature. To further enhance the selection of parameters, there are four functions:
• Search for any text string in the tree. The results will be highlighted in red and appropriate nodes opened to display all the matches.
• Toggle between sorting the tree by plankton type and plankton size.
• Download information. (Short name, long name, unit, description).
• Display number of occurrences of each parameter in the search result.

Statistics, Plotting and intercomparison features
• Statistics - can optionally be calculated for each parameter in the search: number of samples, min, max, average, median, lower quartile, upper quartile, sample standard deviation, variance.
• Time series - A time series graph of a selection of parameters can be generated. The user can zoom on the graph to take a closer look at a specific time period. Information on each point is displayed when hovering over it with the mouse. The graphic can be exported (png, jpeg, pdf or svg format).
• Property-property plot - allows plotting of any two parameters from the search against each other, matched on station and depth. Optionally, one can bin depth in case of multiple hits.
• Match-ups - Optionall the average value (over depth) can be used in stead of all data points.
• The user has the option to match on month and/or year, and the option to choose exact match, or nearest match.
• Scatter plot - User selects a pair of parameters from any source to create a scatter plot as an easy way of comparing the data.
  a data source and a variable, a form for choosing time and elevation interpolation is displayed. The time resolution of the model and EO data in the database is monthly or yearly, so an interpolation is sensible in order to match the data. By hovering over the map with the mouse, more information on nearest point is displayed: time, latitude, longitude, depth and value from both sources, and ID (for in situ data).
The depth resolution varies, but it is never high enough to be able to match the data at exact depths. The user could either pick a specific depth in the raster and match all in situ points to that depth or choose to compare each point to the closest level.

New plankton data and processes understanding

Arctic Sea – extensive historical plankton data sets

A special feature of the GreenSeas database is the inclusion of plankton data from the Arctic. MMBI delivered Arctic phytoplankton digitized data from two sources: Biological Atlas of the Arctic Seas 2000: Plankton of the Barents and Kara Seas (Matishov et al 2000) and recent MMBI cruises conducted in 1999-2011. It contains 4276 Arctic phytoplankton samples from 1539 stations conducted in 1921-1999, in addition to 385 stations with chlorophyll data. During 1999-2011 MMBI sampled and analyzed 1439 phytoplankton samples from 46 expeditions conducted in the Greenland, Barents, White and Kara Seas, digitized from protocols prepared by MMBI planktonologists. Arctic zooplankton were digitized data from three sources: Biological Atlas of the Arctic Seas 2000: Plankton of the Barents and Kara Seas and recent
Nordic Seas – revising our view on carbon uptake by plankton

Improving our knowledge on the relationships between biogeochemical elements – the stoichiometry - in the ocean during biological processes is a key to understand how the different elemental cycles are related, and thereby understand their sensitivity to climatic changes. The generally accepted view dates back to Redfield and co-workers (1963), who found an average carbon-to-nitrogen-to-phosphate (C:N:P) ratio of 106:16:1 in marine phytoplankton. This ratio has been adopted as the standard procedure to convert changes in N and P into carbon. However, deviations from the so-called Redfield ratio are numerous (e.g. Sambrotto et al., 1993; Takahashi et al., 1993; Daly et al., 1999; Körtzinger et al., 2001; Koeve, 2006; Frigstad et al., 2013; Tamelander et al., 2013; Frigstad et al., 2014), both for regional, as well as seasonal, comparisons. In addition the C:N ratio presence in the oceans depend on the type of plankton, and particles, observed (see, e.g. Daly et al., 1999). This challenges the use of a fixed ratio between the major nutrients and carbon, but also calls for seasonal varying stoichiometry, when possible. Another key question is if and how the stoichiometry will change in the future, due to the on-going anthropogenic perturbations. Hence there are many uncertainties related to the elemental stoichiometry in biological processes, and this could have a large impact on our understanding of the marine systems, but also on projections from biogeochemical models.

Uni-Research has carried out several studies in the northern high latitudes, evaluating the net stoichiometry of net community production (NCP). The studies cover different approaches, where three analyse observational data from time-series stations in the North Atlantic (the PAP site) and the Nordic Seas (the Iceland Sea time-series station, and the Station M in the Norwegian Sea), one analyse data of particulate organic matter in the Arctic Ocean, and one model study project future changes in the Arctic Ocean connected to increased atmospheric CO2. The observational studies illustrate clear regional and seasonal differences in the stoichiometry, often with higher carbon-to-nitrogen (C:N) ratio than the traditional Redfield, challenging the use of fixed stoichiometry. Thus the conversion of nitrate-based production into carbon seems to significantly underestimate the actual NCP, and corresponding export production. The regional differences seem to be largely connected to the hydrographical setting, where different water masses carry different compositions of carbon, nutrients, and particulate matter. Taken these together there is obvious that model-based work using constant stoichiometry may significantly underestimate the actual primary production and related export production, and thereby the oceans’ ability to take up and sequester atmospheric CO2. This could have a large impact on future climate projections.

Atlantic – revising our view on planktonic ecosystems and taxonomy

The Atlantic Meridional Transect (AMT) is a multidisciplinary programme which undertakes biological, chemical and physical oceanographic research during an annual voyage between the UK and destinations in the South Atlantic. The programme was established in 1995 and since then has included 23 research cruises involving 223 scientists from 18 countries. NOC (NERC) used the AMT as the main platform for experimental investigations with the overarching aim to advance mechanistic understanding of functioning of the microbial communities dominating the photic layer of the central subtropical gyres and adjacent regions of the Atlantic Ocean.
Oligotrophic – nutrient poor - ecosystems of subtropical oceanic gyres are the most extensive ecosystems on Earth, covering ~40% of the planet’s surface, with their area currently expanding. Current knowledge about the functioning of these systems is relatively limited, owing to the difficulty of studying microbes in a photic layer typified by nanomolar concentrations of inorganic macronutrients. The roles of different microbial populations are thought to be tightly defined (conventional view), i.e. phytoplankton such as Prochlorococcus, Synechococcus cyanobacteria and pigmented eukaryotes use light to fix CO2, and take up inorganic nutrients. These primary producers of organic matter fuel the entire system, allowing heterotrophic bacterioplankton of Bacteria & Archaea to thrive. Populations of both cyanobacteria and heterotrophic bacterioplankton are controlled by viruses and unpigmented protist predators. Organic matter and inorganic nutrients, released by these control processes, in addition to cell death and bacterioplankton remineralisation of dissolved organic matter, sustain both heterotrophic bacterioplankton and phytoplankton.

It is generally accepted that prokaryotes are more efficient than protists in acquiring nutrients at low concentration because of their higher cell surface-to-volume ratio. Indeed, in the North Atlantic subtropical gyre, bacterioplankton dominate phosphate uptake and outcompete protists for this nutrient. However, despite their low phosphate uptake, pigmented eukaryotes are major contributors to CO2 fixation. The C:P ratio, calculated using CO2 and phosphate uptake rates by pigmented eukaryotes, is unrealistically high, suggesting that osmotrophic uptake of phosphate cannot satisfy protist requirements for growth. Therefore, to sustain themselves in oligotrophic ecosystems, pigmented eukaryotes must somehow be able to compensate for a lack of inorganic nutrients.

Hence our research efforts were concentrated on explaining sustainable co-existence of dominant groups of both prokaryotes and smallest eukaryotes focusing on four main research lines: 1). The growth rates of main prokaryotic and eukaryotic CO2 fixers were directly compared and the efficient use of light by Prochlorococcus was revealed; 2). Photoheterotrophy, i.e. the use of sunlight for direct uptake of organic molecules making bacteria even more efficient in nutrient acquisition, of the two dominant bacterial groups was compared; 3). The major role of phototrophic eukaryotic in consumption of bacterioplankton – mixotrophy was shown at the ocean basin scale; 4). The efficient assimilation (with minimal respiration) of organic molecules by bacterioplankton was unambiguously shown.

In the oligotrophic open ocean, the majority of the cells of Prochlorococcus cyanobacteria in the top half of the photic layer have levels of photosynthetic pigmentation barely detectable by flow cytometry, suggesting low efficiency of CO2 fixation compared with other phytoplankton living in the same waters. To test the latter assumption, CO2 fixation rates of flow cytometrically sorted 14C-labelled phytoplankton cells were directly compared in surface waters of the open Atlantic Ocean (30oS to 30oN). In fact CO2 fixation rates of Prochlorococcus are at least 1.5–2.0 times higher than CO2 fixation rates of the smallest pigmented eukaryotes and Synechococcus cyanobacteria when normalised to photosynthetic pigmentation assessed using cellular red autofluorescence. Therefore, our data indicate that in oligotrophic oceanic surface waters, pigment minimisation allows Prochlorococcus cells to transfer plentiful sunlight energy more effectively than other phytoplankton cells can do.

Among other things, using a combination of flow cytometric cell sorting and dual tyramide signal amplification fluorescence in situ hybridization we collected direct visual evidence from the surface mixed layer of the Atlantic Ocean, that bacterioplankton are internalised by pigmented eukaryotes. Pigmented Prymnesiophyceae and Chrysophyceae cells were found to contain Prochlorococcus and, to a lesser extent, SAR11 cells. This demonstrates the commonness and likely selectivity of bacterivory by pigmented eukaryotes in the surface mixed layer of both the North and South Atlantic subtropical gyres and adjacent
equatorial region, broadening our views on the ecological role of the smallest oceanic pigmented eukaryotes.

The experimental evidence taken together advance our understanding of how the microbially-driven ecosystems of oligotrophic ocean are functioning (recent advances). In brief, photoheterotrophy of SAR11 alphaproteobacteria broaden photosynthesis beyond conventional light-dependent CO2 fixation, the boundary between photrophic and heterotrophic bacterioplankton is ‘eroded’ because both SAR11 and Prochlorococcus appear to be photoheterotrophs; the other boundary between phototrophic and heterotrophic eukaryotes becomes far less clear because apparently mixotrophic pigmented eukaryotes consume more bacteria than their unpigmented counterparts. Consequently, the microbial communities cannot be any more shoehorned into the conventional view. Thus, the research presented above shows fruitfulness of the taxonomic-based experimental approach to advance mechanistic understanding of ecosystem functioning in the photic layer of the oligotrophic ocean.

Publications relevant to this research include Hartmann et al. (2012, 2013, 2014), Gomez-Pereira et al. (2013), Hill et al. (2013) and Zubkov (2014).

Southern Ocean – unique high-resolution biophysical data in a shifting environment

Despite its importance, little is known about the sensitivity of the Southern Ocean carbon pump to climate change driven adjustments and the scales at which these mechanisms interact. There is increasing evidence in the Southern Ocean that seasonal scales, meso- and submesoscales play an important role in the coupling of ocean carbon cycling and climate. In the Southern Ocean, the seasonal cycle is known as one of the strongest modes of variability and the mode that couples the physical mechanisms of climate forcing to ecosystem response in production, diversity and carbon export (Rogers et al., 2012).

TA/PRO-OASIS

FURG has provided and analysed datasets derived from the surveys TA (Brazil-Africa TransAtlantic) and PRO-OASIS (Processes of nutrient enrichment in the Austral Ocean and its influence on the marine ecosystem). During TA it was found that the ocean is a CO2 sink in the spanned area and that mesoscale spatial variability in the phytoplankton biomass (chlorophyll-a concentration) in the centre of the South Atlantic Subtropical Gyre was associated with the presence of features caused by isolated vortices that propagate mainly westward.

The PRO-OASIS cruises were conducted on February 2013 and 2014 around the Antarctic Peninsula. Experiments on iron limitation on the physiological Antarctic diatom-dominated phytoplankton assemblages in both cruises show that differences on assemblage succession between treatments were the main response of our results, reflecting on abundance of shorter diatoms specially Pseudonitzschia spp. that have better adapted to such conditions of iron limitation on +DFA treatment.

SANAE/SOCCO/SOSCEx

To improve predictions of marine ecosystem responses to environmental and climate change, plankton physiologists and ecologists need to determine how to quantify and parameterize the key physiological responses of plankton that will in turn affect marine food webs and the carbon-climate system. In order to achieve this, one needs to assess not only variability in primary productivity, but also to routinely provide information on phytoplankton functional types and physiology, as these will dramatically affect carbon exported to depth.

CSIR has completed a number of surveys between Cape Town, Marion Island, Gough Island, South
Georgia and the SANAE base in Antarctica. A key feature is the Southern Ocean Seasonal Cycle Experiment (SOSCEx), a new type of large-scale experiment that reflects a shift from the historical focus on ship-based descriptive Southern Ocean oceanography and living resource conservation, to a system-scale dynamics study spanning much greater time and space scales (Thomalla et al., 2011). It took place around six research voyages spread over four seasons using two ships and five gliders providing a new and unprecedented opportunity to gain a better understanding of the links between climate drivers and ecosystem productivity and climate feedbacks in the Southern Ocean. CSIR and UCT’s contributions include: new high resolution plankton data sets with physical and biogeochemical setting delivered to the analytical database (cf. Section 3.1); collation of high resolution underway data of surface fluorescence, temperature, salinity and dissolved oxygen from pCO2 system.

One of the highlights include investigating the spring bloom initiation in the Subantarctic Southern Ocean using high-resolution glider data. The novelty of this study is that gliders provide an unprecedented high-resolution dataset to assess the seasonal cycle of phytoplankton biomass, thus enhancing our understanding of net community production and export processes in submeso-space and at sub-seasonal time scales. Initiation date is an important parameter for marine ecosystems and fisheries. Five different methods were applied to ~6 months of in-situ high-resolution glider data to investigate the spring bloom initiation in the SAZ. The bloom initiation dates were analyzed in terms of net community production from both Sverdrup’s Critical Depth (Sverdrup, 1953) and Behrenfeld’s Disturbance Recovery (Behrenfeld, 2010) models. Two more methods developed during GreenSeas (Thomalla and Racault, this project), were found to be less sensitive to subjective thresholds, methods which may potentially have large impact in the phenology community. The bloom initiation dates combined with in situ glider data of chlorophyll, light, and mixed layer depth allow us to determine the seasonal evolution of net community production and respiration rates and the potential for carbon export.

Analysis: Biomes – regular planktonic patterns useful for model validation

Plankton is crucial in verifying and parameterising unresolved processes in models. Observations may also be used to formulate functions or function-related parameters that can be used to test or improve the similar functional representations in models. More specifically, to validate models we require information on the larger scale emergent patterns (time, space, and emergent ecosystem properties such as biogeography, size spectra, trophic levels, connectivity, diversity, and also key functions such as primary and secondary production, respiration and stability measures).

PML has performed a detailed statistical analysis of data from the GreenSeas database focusing on identification of regular repeating planktonic patterns, and distinguishing these from longer-term underlying trends. Advanced Time Series Analysis (TSA) also incorporating a wealth of statistical methods was applied to time-series examples derived from ESA CCI ocean colour satellite data. The methods are then applied in detail to a complex 22-year time-series of microbial in-situ data from a temperate location (L4, in the English Channel). The analysis is then extended to the global scale, being applied to 15 years of satellite-derived chlorophyll. For each 3° square TSA is applied to characterise the annual plankton bloom dynamic (climatology) at that location. These climatologies are then spatially clustered using a semi-structured approach with self-organising maps (SOMs). This produced 9 ‘Biomes’ within which the temporal patterns in chlorophyll is consistent. The Biome typology is an objective framework for aggregating and extrapolating observational data for the development, validation and testing of models. It is based on the observation that large ocean regions are characterised by coherent physical forcing and
biological conditions, (Longhurst, 1995, 2007; Hardman-Mountford et al., 2008). There have been several attempts at providing a conceptual classification of the pelagic marine environment, based mainly on either the biogeography of distinct taxonomic groups (e.g. copepods) or the spatial variability of physical properties, such as temperature, salinity, mixing state and empirically-derived chlorophyll and primary production estimates (Longhurst, 1995; Longhurst et al., 2007; Sathyendranath et al., 1995). Longhurst’s (2007) partitioning of the oceans into four major biomes (polar, westerlies, trade winds, tropical), realised as ~50 ocean provinces (regional expressions of the different biomes), remains the most comprehensive and widely accepted biogeographic classification. Vichi et al., 2011 demonstrated that the concept of biogeochemical provinces can be used as a diagnostic tool for the analysis and validation of global marine biogeochemistry models. They showed that it provides a method of overcoming the limitations to model verification imposed by data scarcity and the general under-sampling of relevant ocean biogeochemical properties.

Mapping features derived from the analysis also provides a novel view of global change as well as providing an objective assessment of longer-term trends in the global plankton ecosystem based on data, and also provides a wealth of additional detail such as the shape and magnitude of seasonal patterns with which to develop, test and compare models.

Understanding the relationships between model outputs and observations is a crucial step in the development, parameterisation and validation of numerical models of plankton. Recognising that in-situ measurements don’t map directly onto model state variables very often we have also considered the challenge of mapping existing data (e.g. abundance) to the necessary formats (biomasses, carbon and process rates) required for modelling, and provided information on plankton abundance and biomass along with a revised empirical relationship to convert cell biovolume to carbon biomass.

The concept of biogeochemical provinces can be used as a diagnostic framework for the simplification of the analysis and validation of global marine biogeochemistry models. The GreenSeas typology of biomes has been defined based on harmonic analysis of the satellite ocean colour record and applied to the GreenSeas analytical database to derive plankton and environmental properties for each region. We have provided tabular summaries of the environmental and plankton properties for each biome, allowing both the data and the underlying statistical relationships to be used by modellers for data assimilation and model skill assessment.

Testing biogeochemical models utilizing the GreenSeas data base

The GreenSeas Database mostly consists of data from the AMT cruises, and therefore the spatial and temporal coverage is limited. The province-based approach is one possible way to compare with model output although the problem of timing match-ups still remains. To overcome this issue, it has been proposed to assess the quality of model by analysing property-property plots obtained from the chosen biogeochemical provinces or stations.

The assessment of the model quality was done for both the NORWECOM model and for the global ocean PELAGOS. The latter exercise was done using the two model versions developed during the project, both a coupling between the BFM and NEMO models. PELAGOS2 (LO-res) is the 2 degrees version of the model that was used for the climate scenario projections; PELAGOS025 is the version at ¼ of degree (HI-res) was run to assess the role of resolved physics in the simulation of plankton dynamics.

The NORWECOM model was assessed against data from the database from two different stations in the North Atlantic where time-series data were available, the Iceland Sea (12.7°W, 68°N) and Station M in
the Norwegian Sea (24°E, 66°N). To visually evaluate the model-data correspondence property-property plots as temperature against different nutrients were used. In addition different statistical metrics were computed. Two model runs were assessed; one where ocean colour has been assimilated and one free-run version of the same model.

Province-based assessment and projection of plankton indicators

CMCC performed quality assessment of two simulations with PELAGOS model at high and low resolution, comparing them against satellite data provided by PML and data from the Greenseas Database. In addition time series of relevant environmental and biogeochemical variables over the Longhurst provinces for 6 Earth System Models (ESMs) were computed. They were taken from CMIP5 (the Climate Model Intercomparison Project that led to IPCC AR5), including the coarse resolution biogeochemical model PELAGOS used by CMCC. When the projected change in Plankton Functional Type abundance is plotted against the change in total chlorophyll concentration, it is revealed that some regions are likely to experience a change in magnitude and abundance, a change in magnitude or no change at all. There is a large dispersion among the 6 CMIP5 ESMs; this may be attributed to differences in the parameterization of plankton dynamics as e.g. two ESMs using the same biogeochemical model but different physics of climate show a very similar response.

4 models out of 6 indicate a significant reduction of phytoplankton biomass in the NA subtropical region (NASE), while the South Atlantic gyre and the sub-Antarctic region are projected to be less affected. This may be attributed to a lack of process resolution by current plankton models. The reduction of diatoms and increase of nanoflagellates is a widespread response of all models. This was initially speculated on the basis of generic considerations on phytoplankton behaviour and numerical models now confirm it.

Future development of ecosystem models

The traditional approach to modelling marine plankton has generally been to build modelling frameworks by coupling bulk biomass plankton functional type (PFT) models to 1D and 3D hydrodynamic models. The resulting model ecosystems are commonly used to quantify the interactions between climate and ocean biogeochemical cycles (e.g. Moore et al., 2004; Bopp et al., 2005; Le Quéré et al., 2005), to assess ecosystem response to anthropogenic change (e.g. Schrum et al., 2006; Holt et al., 2009) and to drive models for fisheries (e.g. Werner et al., 2007). Many existing models have some ability to produce plausible patterns and organisation of ecosystem community structure and biogeochemical function (e.g. Moore et al., 2004; Blackford et al., 2004; Follows et al., 2007; Sinha et al., 2010; Vichi et al., 2011). These patterns are strongly influenced by the external forcing and while the responses are non linear, in many cases mechanisms can be inferred or postulated. The high order patterns reorganise in response to changes in external forcing which then drive feedbacks through nutrient recycling, self shading and grazing. Some existing models also demonstrate capacity to produce weak emergence in terms of an unexpected response, for example the relationship between ecosystem variables and climate indicators (Taylor et al., 2002) and the regime shift in the North Sea (Allen et al., 2006).

However, while these properties are useful and give insight into ecosystem processes, the models do not evolve to new states which could not be envisaged from their formulations and this make them unsuitable to properly predict ecosystem changes under changing environmental forcing.
The work undertaken in GreenSeas has indicated the benefit of the application of new knowledge to the development and evaluation of models. We have identified a number of key biogeochemical processes that modellers should take into account in the future, including mixtrophy, explicit descriptions of prokaryote cyanobacteria and improved description of plankton stoichiometry. In addition we have shown the importance of resolving physical processes and appropriate scales, model skill assessment and the value of data assimilation. Finally when considering the use of large data sets with models we make the following recommendations:

• Use the huge spread in data for stochastic understanding of the model
• Deconstruction of data, finding structure in the "data cloud"
• Use expert witnesses to help look through data, understand experiment/measurement and reject them if necessary
• Get people to share data (they don’t know it might be worth something to us)
• Worth of a data in case of designed experiment (pinpoint specific rate in specific conditions)
• Question of the model properly uses available data: i.e. respecting known limits while pushing the limits.
• Collaborate with experts to get a better sense of the data and the metadata
• Tighter collaboration with those who generate data to get extra information or new experiments done.
• Encourage the sharing of data (Greenport, http://greenport.nersc.no/web/guest/database )

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Further reading


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Potential Impact:

Introduction

One of the most pressing and challenging issues is to understand how global change, the result of natural and anthropogenically induced climate change, will impact upon the structure and function of the planktonic marine ecosystem. To do this, it is essential to investigate and understand the processes that regulate plankton communities as they drive the response of the ocean carbon cycle to environmental change, impacting on the global earth system, environmental status and fisheries. The evolution of plankton communities under changing environmental forcing is a complex phenomenon generated from non-linear interactions between abiotic (temperature, pH, light environment, nutrients supply, contaminant exposure, currents etc.) and biotic (physiological responses, predator prey interactions) components. Planktonic ecosystems provide essential goods and services to man. These include ecosystem services (e.g. production, biodiversity), intermediate supporting services (e.g. nutrient cycling, oxygen), intermediate regulating services (e.g. carbon sequestration) and final services (e.g. fisheries, climate regulation, cultural).

Policies related to marine resources and environments today require the development of management strategies that are robust to changes in the drivers affecting ecosystem productivity, such as climate change. The successful implementation of an ecosystem based approach to management requires evaluation of management strategies which take into account biological processes such as species interactions and their variability over space and time. It is important that the marine environment is observed and monitored to provide high quality environmental information / data, understand its role in our Earth system, track changes and predict the potential response of the ocean to stressors. The GreenSeas project was designed to advance the quantitative knowledge of how planktonic marine ecosystems, including phytoplankton, bacterioplankton and zooplankton, will respond to environmental and climate change. The target audience for GreenSeas research is primarily the wider marine science research community involved with development of ocean plankton model and monitoring, stakeholders, decision makers in both the policy and management arenas but also includes SMEs interested in the application of knowledge, and the interested public.

A tailored data delivery system
Following the open and free data access policy implemented in the European Programme for the establishment of a European capacity for Earth Observation – Copernicus, the GreenSeas plankton delivery service is a prototype demonstration of how new and historical plankton data, information products (e.g. biome analysis) along with error-quantified numerical simulations to a range of users via a state of the art web based delivery systems. It utilizes historical data-sets and ongoing multidisciplinary ocean planktonic ecosystem monitoring programs in the Atlantic, Arctic and Southern Oceans, together with satellite based information. The web address of the portal is (http://greenport.nersc.no/web/guest/database).

The basic purpose of the system is to make all the diverse data types interoperable for the user community - which includes environmental managers and scientists of various disciplines. Data are either stored locally or accessed through standard interfaces, using the Open Geospatial Consortium (OGC) Web Map Service (WMS) and Web Feature Service (WFS), and OPeNDAP protocols (Open-source Project for a Network Data Access Protocol), respectively.

To access and easily display data, a web based Geographical Information System (webGIS) has been implemented. The user first specifies a bounding box to define a geographical area and a depth range, time limits or month. To navigate the huge number of plankton parameters, plankton and related quantities are grouped according to category, enabling the user to quickly get an overview of available data and choose a suitable level of detail. Once a selection is made, the system will retrieve the corresponding available data. The user can also visualise and compare data products, shown as plots (e.g. scatter plots), through simple statistical measures and data may be exported for further analysis.

A special feature is that a user can select from a list of Earth Observation products or output from simulation models on which the in situ information can be readily overlain for comparison. This first generation data delivery system demonstrates that a customized tool for searching, presenting and exporting ocean data from multiple platforms (in situ, satellite, model), makes it easy to compare various sets of independent observation and model simulations. This method will be further developed in future research, to benefit the wider community of ocean scientists, stakeholders and managers. One example is the European Marine Observation and Data Network (EMODnet). It is a consortium of organisations within Europe that assembles marine data aiming to unlock fragmented and hidden marine data resources and to make these open and freely available. The GreenSeas data portal and delivery system is a tool to support this endeavour. Looking to the future the challenge is how to encourage the wider community to use and further develop the data and tools without access to significant resources. The GreenSeas portal is open source GIS and members will be free to take the portal and develop their own bespoke applications, but will be encouraged free sharing of such developments. We will form a follow on GreenSeas user consortium (see GreenSeas report D7.5) based around a light touch consortium agreement with an open source ethos.

GreenSeas and GEO
The Group on Earth Observations (GEO) is coordinating efforts to build a Global Earth Observation System of Systems, or GEOSS. GEOSS will yield a broad range of societal benefits, those most pertinent to the marine environment being: understanding, assessing, predicting, mitigating, and adapting to climate variability and change, improving the management and protection of terrestrial, coastal and marine ecosystems and understanding, monitoring and conserving biodiversity. Moreover the data and methods developed through GreenSeas make a direct contribution to the Global Climate Observing System.
GCOS has established a list of Essential Climate Variables (ECV), Essential Biodiversity variables (EBV) and Essential Ocean Variable (EOV). The purpose of these essential variables is both to improve monitoring and facilitate the harmonization of existing monitoring schemes and guide the implementation of new monitoring schemes, especially in gap areas where information on change is still very sparse.

Essential Biodiversity Variables (EBVs) are measurements required for study, reporting, and management of biodiversity change. EBVs are crucial for robust estimation of the indicators to assess progress towards the 2020 targets of the Convention on Biological Diversity. The candidate EVB’s cover a range of indicators for genetic diversity, species populations and traits, community composition, ecosystem structure and function. Such variables should be able to be measured or modelled globally, by combining satellite remote sensing observations with in-situ observations. GreenSeas makes a significant contribution to the monitoring of EBV’s on species populations and traits, community composition, ecosystem structure and function.

GreenSeas delivers information on the following ECV’s; temperature, salinity, ocean colour (for biological activity), carbon dioxide partial pressure, nutrients, carbon, and phytoplankton. Essential Ocean Variables (EOV) are currently in the process of being defined. An initial list of 49 EOVs for GOOS Biology, grouped into several ‘themes’ have been identified. Working groups have been set up for the following topics: 1) trophic; primary producers; 2) trophic; zooplankton, 3) trophic; large marine vertebrates, 4) habitats, 5) human impacts and 6) water quality. GreenSeas contributes to working groups 1, 2 and 4.

Indicators for Marine Ecosystem Management

The Integrated European Maritime Policy (IEMP), is the EC’s move towards an integrated vision for the future management of its oceans and seas. Based on multidisciplinary scientific knowledge it seeks to maximise knowledge of the oceans and seas through scientific research and modern technology. The IEMP aims to provide answers as to how decision making and the conciliation of competing interests in marine and coastal areas can contribute to reverse environmental degradation, sustainable ecosystems and at the same time to investment and development of economic activities. The use of ecological indicators in policy processes and their importance in political context is now well-established. The need to develop a holistic strategy for natural resource management has emerged from marine statutory policies formulated in Europe (Water Framework Directive, 2000 and Marine Strategy Framework Directive, 2008), in South Africa (National Water Act, 1998), in Canada, USA, and Australia (Oceans Act, 1996, 2000, and 2006 respectively). Specifically, policy action and implementation plans endorse an ecosystem-based management (EBM) approach involving integrated management of ocean biotic and abiotic aspects, and humans as components of a larger ecosystem. The EBM approach provides support to national task forces and monitoring strategies aiming at maintaining a good status for marine waters, habitats and resources. The directives generally establish the description of ‘good status’ (e.g. MSFD, 2008/56/EC), however its assessment relies on a comprehensive selection and comparable implementation of indicators.

One of the GreenSeas project’s key challenges was to define a set of indicators which can be used to describe changes in the state of the marine ecosystem. Indicators are a measure of relevant phenomena that help characterise the impact of various forces on the system e.g. human activities such as pollution and global ocean warming. Indicators have been widely developed as instruments to provide specific information about the state of a system. Assessment of the system can be discipline-specific with
economical, societal, and environmental indicators, or linking two disciplines with socio-economic indicators, or taking a holistic approach with sustainability indicators. The term indicator then is used collectively by scientists, policymakers, and the general public. However, understanding and applications of indicators by the different groups are widespread. For instance, indicators can be used to judge the effectiveness of policies on nature, objectify the quality of nature and monetise the functions of nature. In ecology, indicators are used essentially as highlights of the condition of the environment, as early-warning signals and as barometers of long-term trends.

GreenSeas has developed innovative methods for data interpretation which overcome discrepancies in measurements and sampling from the ocean observing systems to allow large datasets to be compared. These novel methods have improved our ability to measure properties of marine ecosystems and to provide ecosystem indicators. Analysis of ecosystem indicators has helped GreenSeas scientists to describe the state of marine ecosystems and in turn assess the potential impact of climate and environmental changes. Remote sensing observations have provided long-term, synoptic-scale, time-series of Essential Climate Variables (ECVs), which have been shown to be particularly relevant to monitor and assess the influence of climate on the oceans. In fact, part of the evidence used in the Assessment Report #5 of the IPCC (Hoegh-Guldberg et al., 2014, Working Group 2, Chapter 30 – The Ocean; cf. reference ‘IPCC’) comes from analysis of phytoplankton phenology using ocean-colour data (GreenSeas contribution, Racault et al., Integration of ecological indicators with the global network of ocean observations, paper presented at 2nd Climate Change International Symposium Effects of Climate Change on the World’s Oceans, Yeosu, Korea, 2012).

We adopted the Driving forces-Pressure- State-Impact-Responses (DPSIR) framework used by the European Environmental Agency (EEA). The DPSIR represents a systems analysis view:- social and economic developments exert pressure on the environment and, as a consequence, the state of the environment changes. This leads to impacts on e.g. human health, ecosystems and materials that may elicit a societal response that feeds back on the driving forces, on the pressures or on the state or impacts directly, through adaptation or curative action. It is therefore highly valuable to show how indicators derived from ocean observations can be incorporated into the management of environmental issues. Ocean observations play a pivotal role in connecting pressures and societal drivers with environmental impact assessments and policy responses. Interpretation and analysis of ocean observations and indicators of marine ecosystem changes carried out in the GreenSeas project are essential to underpin strategic and long-term stewardship of the oceans. GreenSeas has provided information and analysis on the following indicators of plankton: species diversity, phytoplankton biomass and community structure, primary production, timing of particular events in the growing cycle of phytoplankton (so-called phenology of phytoplankton). Thus GreenSeas can help monitor the state of the environment using ocean observing systems, which in turn allows for the assessment of the impacts (i.e. broader effects) of society on the environment.

Case study: Decadal variability in phytoplankton phenology (life cycle events)
A comparison of the phytoplankton biomass time-series measured by the two independent and different observing systems was made by analysing the timings of particular events in the annual cycle of phytoplankton biomass. These timings of events correspond to the phenology of phytoplankton. Phenology relates to the study of timing of periodic biological events as influenced by the environment. Estimates phenological indices such as duration (in weeks) of the annual phytoplankton growth period, measured from the two types of observations (i.e. in-situ and remote-sensing), agreed closely at lower latitudes (Area


2) but showed larger offsets at higher latitudes (Area 1). Analysis of the different data sets revealed an apparent large variation in phytoplankton phenology in the N. Atlantic over five decades 1960-2010. Such variations can have a profound impact altering: (1) the efficiency of the biological pump, with knock on effects to the global carbon cycle; and (2) the interactions across different trophic levels, which can impact commercially important fish and seafood. These findings are relevant to the food web, fisheries and carbon cycle aspects of marine policymaking. This shows how once plankton indicators have been identified, (in this case: biomass, size structure and life cycle events), and analysed using a combination of observing systems, their true function and cycles can be better understood. This allows us improved knowledge of what is happening within a phytoplankton community, revealing hidden changes and providing planners and decision makers with a more accurate picture of the state of the marine ecosystem.

Enhancing model simulations of the marine environment

Ocean models provide information on the distribution of ocean state variables in space and time. These variables can include; temperature, currents, nutrients, and living organisms like phytoplankton and zooplankton.

Ocean models range in scale from those representing the global ocean to those representing a single bay, but all are built on the same principles, respecting the laws of physics and the ecological interactions between the components of the marine ecosystem. Ocean models can be used to compute valuable information such as the global carbon export to the deep sea, eutrophication in coastal areas, or to explore ‘what if’ scenarios for example investigating the effect of climate change on ocean productivity. The GreenSeas project has collated observations and satellite data to inform and test and improve existing ocean models in two key operational areas, notably the earth system modelling for the IPCC and operational oceanography for the Copernicus marine core service.

Models are useful because they provide regular information in the area they cover, without the gaps that frequently occur in observation data. However, models are not reality, so in order for the model to provide useful information we must also know how accurately the model reflects reality. This can be evaluated by comparing the model results to observations while keeping in mind that observations as well as models contain errors and uncertainties. The GreenSeas analysis framework provides an integrated analysis protocol to share and analyse in-situ, earth observation and numerical modelling information in an integrated manner to assess model skill and inform the future development of models.

The GreenSeas project has contributed to the analysis of IPCC class ocean biogeochemical models, providing valuable information to inform the future development of Earth System Models. The PELAGOS model is the ocean biogeochemistry component of the Italian Earth System Model (ESM) and was used to make climate projects for the IPCC CMIP5 experiments. A biome based assessment of a number of IPCC models from CMIP5 (including PELAGOS) indicated that primary production is well captured by global biogeochemical models and that they all show a decline in primary production at the end of the century, This allows an estimation of the range of uncertainty to be used for the future projection of primary production. GreenSeas has examined the impact of resolving mesoscale processes on global biogeochemistry by performing simulations at 2° (LO-res) and 1/4° degree resolution (HI-res) using the PELAGOS model. While the global large-scale oceanographic features (fronts, gyres, etc) are captured in both simulations, differences in the mesoscale structures, and in particular the resolved vertical physics in the HI-res simulation generate very different behaviour in the biogeochemical system. Significantly a spun-up LO-res system is driven into a new regime in the HI-res simulation, with significant reduction of typical
biases. These experiments provide highly important information to inform the development of the next generation of Earth System model systems. For instance the GreenSeas data, EO derived plankton indicators and model skill assessment procedures where used by PML to inform the selection of the ocean biogeochemical component of the next UK ESM.

To ensure the legacy of the GreenSeas project recommendations for the future development of plankton models have been made. Based on the process studies (bacterioplankton and perturbation experiments) data will be synthesised with a view to parameterising models. Emphasis is placed on the representation of plankton functional types and improving ways to scale processes from physiology to functional types. Data assimilation is the process of merging models with observations to improve the quality of a simulation. It is used both to improve historical simulations (reanalyses) and to provide the best available initial conditions for operational forecast. GreenSeas has shown that the use of data assimilation is capable of reducing the bias with respect to the observations, but unfortunately it cannot be used to constrain future projections. The GreenSeas database and analytical framework, along with the associated methodologies for data assimilation and simulation skill assessment will be exploited both in new national and European research programs and through the development of Operational Ecology within the Copernicus Marine service. Operational Ecology refers to the provision of operational services for biogeochemical and ecological parameters through a forecast system to project the future state of marine ecosystems by delivering a suite of error quantified indicators which describe changes in ecosystem function. Such systems should include observational network along with models of the hydrodynamics, lower and higher trophic levels (plankton to fish) and biological data assimilation. Such systems are also clearly required to help assess and manage the risks posed by human activities on the marine environment as targeted in the DPSIR framework concept.

Training the next generation of scientists
To ensure its legacy and contribute to the training of the next generation of plankton scientists, the GreenSeas project organised an interdisciplinary summer school on global plankton data with focus on ecosystems, monitoring and modelling in an era of global warming in Jan-Feb 2013, host by UCT, Cape Town, SA. 20 students participated from both EC member states and international cooperation countries. Students learnt how to employ a combination of observation data, environmental indicators and numerical simulations to obtain an integrated, cross-disciplinary, global-in-scope understanding of global planktonic ecosystems. This was placed in the context of a global information service, for assessment of environmental pressures and risks, including tensions and conflicts related to the depletion of natural resources. The Summer School consisted of a mixture of lectures and practical sessions and was designed to promote and encourage lecture/student interactions. Following the summer school the website was further developed to provide a source of information and communication tool for the students.

Participation of International Cooperation Partner Countries
GreenSeas was a genuinely international project. It brought together expertise and intellectual resources from across Europe and combined it with that of ICPC partner institutions from Russia (MMBI), South-Africa (UCT, CSIR) and Brazil (FURG). Examples of the exchange of expertise and historical plankton data from the Nordic, Barents and Kara seas, held at MMBI is now available to the wider community thanks to the GreenSeas project. Researchers at UCT have been trained to use state of the art measurements of nitrogen uptake by plankton by PML; scientist from PML and CSIR have synthesised in-situ and EO measurements to gain a better understanding of physical controls on plankton blooms. The
progress made by the GreenSeas project advancing the quantitative knowledge of how planktonic marine ecosystems, respond to environmental and climate change and developing data bases and modelling tools was only possible through this successful international interdisciplinary cooperation.

Reference list is provided at the end of the S&T results part.
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Documents connexes

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