Project information

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Summary of Results

Introduction

Activities planned for 2015 are:

(i) Collection of available data for model parameterization, calibration and validation;

(ii) Implementation of biogeochemical subroutines with EcoDynamo, for ice algae and ice biogeochemistry and zooplankton physiology with the Dynamic Energy Budget (DEB) approach;

(iii) Integration of the CICE model or, alternatively, the ice sub-model of the Regional Ocean Modeling System (ROMS) in the SYMBIOSES platform;

(iv) Coupling of EcoDynamo – an object oriented ecosystem modeling software - and other biogeochemical sub-models with ROMS;

(v) Start of model testing and calibration.

During the first seven months of the current year we worked mostly on activities i) and iv). Regarding the former, we took advantage of the N-ICE2015 cruise, during which a significant amount of data was collected in the Arctic Ocean regarding physical, chemical and biological variables and processes in the sea water and in the sea ice. Amongst this data, it is important to emphasize that obtained from experimental work with phytoplankton and ice algae, to measure photosynthetic rates as a function of light intensity and under different nutrient concentrations, and with zooplankton, to measure respiration and excretion rates of main Arctic meso-zooplankters. These experiments allowed to obtain an important number of physiological parameters that will be incorporated in the ecosystem model under development in the current project.

In what concerns (iv), we managed to couple the Regional Ocean Modeling System (ROMS) (https://www.myroms.org/) with EcoDynamo (Pereira et al., 2006). This was one of the most challenging and important goals of the project. After gaining some experience with the biogeochemical models available in ROMS, such as the Powell and the BESTNPZ, we found out some serious limitations such as: (i) **representation of some biogeochemical processes based on outdated paradigms**; (ii) **lack of modularity to combine or to add to one of the available models the most adequate simulation algorithms from different models described in the literature**.

ROMS biogeochemical models are implemented as long subroutines that resolve sequentially the marine food web and some biogeochemical processes. Therefore, replacement of a calculation method by another one implies changing the subroutine. The methodology we followed here is to call EcoDynamo object subroutines from a ROMS biogeochemical model to resolve specific processes. This approach has several advantages such as: (i) **EcoDynamo includes a large number of biogeochemical processes and alternative ways to calculate them**; (ii) **The inheritance and polymorphic properties of objects allows reusing the same object with different parameters and with a minimum programming overhead**. For example, let's suppose that it is necessary to include more than one phytoplankton species group in the ROMS version of the Powell model. This implies changing the corresponding subroutine, adding the code for the new phytoplankton group or, as a minimum, introduce some code changes to rerun the phytoplankton part of the code as many times as phytoplankton groups are defined, even if the simulated processes for each group are exactly the same. In the case of EcoDynamo, it is necessary to "construct" and initialize a pointer to the same object as many times as different phytoplankton groups are to be simulated and each time a different set of parameters is associated with each instance of the object. Unlike subroutines, that reinitialize their parameters every time they are called, objects "memorize" their properties. Knowing the memory addresses of each pointer, object properties, parameters and variables may be accessed at any time during a simulation. Therefore, each time the object functions are called there is no need to send arguments with the values of object "local" parameters but only the memory address of the object being used and the variables that are relevant for object calculations and that are changed elsewhere in the code. So, if, at some point, it is decided to change the algorithm used for some process, another object may be called from ROMS and this implies only changes in compiling directories and, at most, one line of code creating a pointer to a different object. This easiness of incorporating new object functions and changing available ones adds to the modularity of these mixed code subroutines and to their flexibility for usage in different simulations.

EcoDynamo was originally developed to be used as a standalone modeling software, coupling physical and biogeochemical processes and running in Windows, with a user friendly interface. It was implemented using C++ and an object oriented methodology. Different functional groups or important processes are represented by different objects. Thermodynamic objects calculate energy exchanges between the water and the atmosphere. Hydrodynamic processes are simulated by objects that encapsulate equations and variables to solve the primitive and the continuity equations. Biogeochemical cycles are simulated by objects that include mineralization, nitrification, denitrification and other relevant processes. Phytoplankton objects simulate physiologic and population level processes explaining growth and biomass decay. The same applies to many other functional groups such as ice algae, zooplankton, macroalgae, shellfish, finfish, etc. Objects also encapsulate interactions with other objects to account for trophic relationships and feedbacks with the biogeochemical cycles. Furthermore, properties that are dissolved or suspended in the water are transported by physical processes, simulated by the hydrodynamic objects. Each object is represented by a number of variables, parameters and methods that define and control their behavior. During a model run, these methods are called sequentially and calculated by independent subroutines or functions. EcoDynamo was used to implement fully coupled physical-biogeochemical models for several coastal ecosystems such as Ria Formosa coastal lagoon (Duarte et al., 2007; 2008), the Douro estuary (both in Portugal) (Azevedo et al., 2010; 2014) and Ria de Ares-Betanzos in Galicia (Spain) (Duarte et al., 2014) and aquaculture systems (Serpa et al., 2012; 2013a). It was also used to implement models for several species or groups of species allowing their possible later inclusion in ecosystem models, such as mussels (Duarte et al., 2010; 2012), finfish (Serpa et al., 2013b) and ice algae (Duarte et al., 2015a).

Since the beginning of EcoDynamo implementation, one of the goals was to make it possible to link its objects with other modeling environments. Therefore, a methodology was developed and tested (Pereira et al., 2006) whereby EcoDynamo objects were coupled with COHERENS (Luyten et al., 1999) – a 3D marine coastal model implemented in Fortran. This served to show that coupling could be achieved and helped defining some "general rules" to mix Fortran code based on structured programming with C++ code based on object oriented programming.

Considering the overall goal of the present project –implement a fully coupled physical-biogeochemical model to simulate the Arctic Ocean – the magnitude of the spatial domain and the time resolution requirements demand the usage of super computer facilities. Therefore, one of the first tasks was to have a Linux version of the EcoDynamo software that could run in the supercomputers available through Notur - The Norwegian metacenter for computational science (https://www.notur.no/about). This was accomplished in a previous Fram Centre project - **Coupling different modeling platforms: an activity across Fram Centre Flagships** – that took place in 2013-2014, during which EcoDynamo was coupled with SINMOD using SYMBIOSES as the model coupler. The results achieved then and the availability of a three dimensional circulation and sea-ice model for the Arctic Ocean, implemented with ROMS in another Fram Centre project (**Mesoscale modeling of ice, ocean and ecology of the Arctic Ocean**), stimulated the elaboration of the present project. One of the challenges was to couple EcoDynamo with ROMS, as a way to deal with some of the limitations found in available biogeochemical code for ROMS (see above). Therefore, two coupling options were considered: (i) ROMS provide the velocity field used by other models that receive the corresponding data through the SYMBIOSES platform and perform the relevant transport calculations in their own spatial grids; (ii) ROMS "transport" all "pelagic" variables using its transport equation by receiving data from the other models. The experience gained during the first year of the present project lead to the conclusion that option (i) is not efficient for variables that are calculated all over the model grid, such as those related with the biogeochemical cycles and lower trophic levels, and that are computationally very demanding, using the same spatial and temporal resolution of the circulation processes. However, it may be a good option to handle higher trophic levels that, most likely, will require different spatial and temporal resolutions due to the spatial and time scales associated with their life cycles. Thus, option (ii) seems to be more adequate to couple biogeochemical cycles and lower trophic levels with circulation processes. In fact, this is the type of approach followed in ROMS.

Technical description of performed activities

Coupling EcoDynamo with ROMS required a number of different procedures and tests and it was based on two of the available ROMS routines: ana_srflux and the Powell model (Powell et al., 2006). The former is responsible for calculating light intensity values at sea level to force thermodynamic and biogeochemical processes. The latter is a biogeochemical model based on the Nitrogen-Phytoplankton-Zooplankton-Detritus paradigm. Using these sub-routines made it easier to perform the coupling, by keeping their cycle structure and, in the case of the Powell model, the backward implicit scheme that is common among all ROMS biogeochemical sub-models. This scheme is an iterative procedure with a sequence of fractional time steps performed in a chained mode in sequence of the main food chain, whereby the concentration of the component being consumed is treated in a fully implicit manner to avoid negative values, independently of the concentration of the active consuming component. When an explicit scheme is used, negative values may arise when consumption over a model time step exceeds the availability of the consumed component. The first task was to use the EcoDynamo "equivalent" of the ana_srflux sub-routine (a "light" object) in order to calculate light intensity with a slightly different algorithm than the one used in ROMS. The second task was to replace some of the calculations performed by the Powell model by methods available in an EcoDynamo phytoplankton object. These two tasks served as a test of concepts and will be followed by the inclusion of more EcoDynamo objects in the upcoming months to simulate biogeochemical processes in the water and in the sea ice.

Both of the tasks mentioned above required some changes in EcoDynamo and in ROMS code. The former were mainly related with compiling options and object construction routines, to make sure that when EcoDynamo objects are compiled for mixed usage with Fortran, appropriate methods and variables are selected. For example, when EcoDynamo is used in standalone mode, the construction of the different objects includes data input from several files. However, when objects are used with ROMS, their construction is based on arguments passed by ROMS. Therefore, different constructors are used in these two scenarios. Furthermore, some methods and libraries that are specific for graphic user interface must be ignored under mixed usage of C++ with Fortran in a Linux or Unix environment.

ROMS follows the Earth System Modeling Framework (ESMF) conventions for model coupling: initialize, run and finalize. EcoDynamo object construction takes place during the initialize phase. A call must be made with the necessary arguments to construct each object and initialize corresponding parameters and variables. A series of files were created for this mixed application following the general ROMS "rules" and added to the directory containing other biogeochemical models: ecodynamo_def.h , ecodynamo_wrt.h , ecodynamo_var.h, ecodynamo.in, ecodynamo_mod.h, ecodynamo_inp.h and ecodynamo.h. The first two files define model input parameters that are to be read and output from/to netcdf files, the third file assigns metadata indices to the model variables that are used in input/output netcdf files, the fourth file contains model parameters and respective values, the fifth file defines parameters and allocates memory to corresponding arrays, the sixth file is responsible for reading parameter values from the input file (*.in) and the last one contains the mixed biogeochemical code. This was constructed from the Powell model to ease the process of replacing Fortran code with calls to EcoDynamo functions still maintaining the general structure of ROMS biogeochemical sub-routines. The first six files are used during the initialization phase and calls were added to ecodynamo_inp.h to construct EcoDynamo objects. ROMS launches threads for different tiles in which the model grid is divided for parallel processing. Therefore, the constructors are invoked for each tile and, each time this happens, a different memory address is associated to a new instance of the object being constructed. This memory address is created in EcoDynamo and returned to ROMS. Thereafter, it is used to identify each "tile" pointer to each object. The following are the two calls to the EcoDynamo light and phytoplankton object constructors.

```
CALL LIGHT_NEW_(LIGHTOBJ)

CALL PHYTOPLANKTON_NEW_ (PHYOBJ1,Pmax,Iopt,ImaxE,PhyIS,       &
      &                   AEiler,BEiler,                        &
      &                   CEiler,MaintResp,RespCoeff,           &
      &                   DocStressLoss,PhyMRD,RedfieldC,       &
      &                   RedfieldN,RedfieldP,                  &
      &                   TemperatureAugmentationRate,          &
      &                   RatioLightDarkRespiration,            &
      &                   minNPRatio, maxNPRatio, PMaxUptake,   &
      &                   NMaxUptake,KP, K_NO3, KNH4,           &
      &                   MinPCellQuota,MaxPCellQuota,          &
      &                   MinNCellQuota, MaxNCellQuota,         &
      &                   KPInternal, KNInternal, wPhy,         &
      &                   CarbonToOxygenProd,                   &
      &                   CarbonToOxygenResp, TminRespiration,  &
      &                   TminPhotosynthesis,                   &
      &                   NitrogenLimitation,                   &
      &                   PhosphorusLimitation)
```

The former requires only one argument of type integer (LIGHTOBJ) where the memory address of the pointer to the object created in EcoDynamo is stored. The latter requires a similar argument (PHYOBJ1) and others related with the calculations performed – most of these are physiological parameters and some were already defined in ROMS. LIGHT_NEW_ and PHYTOPLANKTON_NEW_ are the names of two EcoDynamo routines belonging to two objects. Pereira et al. (2006) described the necessary naming conventions for mixed code. More calls may be added to ecodynamo_inp.h as more EcoDynamo objects are plugged into ROMS.

During the run phase, the routine ana_srflx is called and, according to different options, calculates sea surface light intensity using different algorithms. A new option and a new call were added to compute light intensity using EcoDynamo light object:

```
# ifdef ECODYNAMO
   DO j=JstrR,JendR
     DO i=IstrR,IendR
       CALL LIGHT_NEW_GO_(LIGHTOBJ,hour,yday,latr(i,j),cloud(i,j),cawdir(i,j),srflx(i,j))
!Scalling of surface radiation from W/m2 to degC m/s
       srflx(i,j)=srflx(i,j)/(rho0*cp)
     END DO
   END DO
# else
…
```

The nested cycles run for all columns and layers of each tile. The arguments to the EcoDynamo routine LIGHT_NEW_GO_ include LIGHTOBJ, which indicates the memory address of the different pointers to the light object created for the different tiles, current hour (hour), day of the year (yday), cloud cover (cloud), sea albedo (cawdir) and a variable to receive the value of surface radiation (srflx). All these arguments are passed by reference but only the last one is changed upon "return" to ROMS.

The Powell model considers only one inorganic nutrient (nitrate) and represents phytoplankton, zooplankton and detritus in nitrogen units. Other models include several nutrients, such as phosphates and silicates and represent biological entities by carbon, nitrogen, phosphorus and other pools. Furthermore, in the Powell model photosynthesis and nutrient uptake are directly coupled. The importance of considering more nutrients, dynamic stoichiometry and decoupling photosynthesis from nutrient uptake has been discussed by several authors (e.g. Baretta-Becker et al., 1997; Jørgensen and Bendoricchio, 2001; Vichi et al, 2007). Accordingly, changes were implemented in ecodynamo.h regarding some of the calculations related with phytoplankton photosynthesis, nutrient uptake, respiration and exudation. Furthermore, new variables were added to make it possible to use multiple currencies for phytoplankton, zooplankton and detritus and to include other nutrients than nitrate, such as ammonia and phosphate. The inclusion of new variables implies changes in several ROMS files such as varinfo.dat and the header files (*.h) mentioned above. In the ecodynamo.h file, changes were introduced by adding an option that implies the usage of EcoDynamo functions instead of the Powell model algorithms in some cases. There is a first call that informs EcoDynamo phytoplankton object about the current values of some important model parameters and biogeochemical tracers:

```
CALL PHYTOPLANKTON_GO_( PHYOBJ1,                &
      &                   Hz(i,j,k),            &
      &                   dt(ng))
```

As stated above, PHYOBJ1 contains the address of the EoDynamo object pointer associated with a specific tile, Hz stands for layer thickness and dt the model time step in seconds. The following call to EcoDynamo calculates gross primary production from light, temperature and nutrient limited photosynthesis:

```
CALL PHYTOPLANKTON_PRODUCTION_(PHYOBJ1,          &
```

```
    &                          TopLight(i,k),           &
    &                          BottomLight(i,k),        &
    &                          KValue(i,k),             &
    &                          t(i,j,k,nstp,itemp),       &
    &                          1, yday,GrossProduction,  &
    &                          Bio(i,k,iPhyN),            &
    &                          Bio(i,k,iPhyP),            &
    &                          Bio(i,k,iPhyt) )
```

The arguments include light intensity at the top and at the bottom of each model vertical layer (TopLight and BottomLight), the light extinction coefficient (KValue), water temperature (t), an option indicating that nutrient limitation should be considered (1) or neglected (0), the day of the year (yday) and the argument that is changed during the call to EcoDynamo – GrossProduction. Bio is used for biogeochemical tracers and iPhyN, iPhyP and iPhyt represent phytoplankton concentration in nitrogen, phosphorus and carbon units. Unlike in the Powell model, where nutrient limitation is calculated based on nitrate concentration in the water, in EcoDynamo, it is calculated based on phytoplankton cell quotas as suggested by other authors (e.g. Jørgensen and Bendoricchio, 2001). Gross production is used to update phytoplankton carbon. Then, there are calls to routines that calculate nitrogen and phosphorus uptake, respiration and exudation.

```
CALL PHYTOPLANKTON_NITROGEN_UPTAKE_(PHYOBJ1,          &
    &                          Bio(i,k,iNH4_),             &
    &                          Bio(i,k,iNO3_), 0,          &
    &                          cff,cff1,
    &                   Bio(i,k,iPhyN),      &
    &                   Bio(i,k,iPhyt))

CALL PHYTOPLANKTON_PHOSPHORUS_UPTAKE_(PHYOBJ1,          &
    &                          Bio(i,k,iPO4_),cff,          &
    &                          Bio(i,k,iPhyN),             &
    &                          Bio(i,k,iPhyt))


CALL PHYTOPLANKTON_RESPIRATION_(PHYOBJ1,                &
&                          t(i,j,k,nstp,itemp),          &
&                          cffCResp,GrossProduction, &
&                          Bio(i,k,iPhyt))

CALL PHYTOPLANKTON_EXUDATION_(PHYOBJ1, cffCExud,          &
&                          GrossProduction,               &
&                          Bio(i,k,iPhyt))
```

Between these calls, the values of implied variables are updated according to the backward implicit scheme mentioned above. Several processes are still calculated as in the Powell model, such as zooplankton grazing of phytoplankton, phyto- and zooplankton mortality and detritus processes (with the exceptions that detritus mineralization leads to ammonia instead of nitrate production and all plankton mortality contributes to the detritus pool only). Therefore, this is an example of usage of mixed code, in trying to get the best out of different algorithms.

After the code was changed in EcoDynamo and in ROMS, following the guidelines described above, it was necessary to compile EcoDynamo objects for mixed code usage, compile ROMS and link ROMS and EcoDynamo object files. Therefore, it was necessary to write make files for each EcoDynamo object. Once ROMS and EcoDynamo were compiled and linked, several test simulations were run with the Fram Centre three dimensional circulation and sea-ice model for the Arctic Ocean mentioned above. It will be relatively straightforward to extend this work to more EcoDynamo objects towards the implementation of a state of the art ecosystem model for the Arctic Ocean.

Project activities until the end of the year

Until the end of the year we plan to add EcoDynamo objects to simulate the biogeochemical cycles of nitrogen, phosphorus, oxygen and carbon and an ice algal object. We also plan to add another phytoplankton object to make it possible to simulate simultaneously the two main phytoplankton groups present in the Arctic Ocean: diatoms and dinoflagellates. Each new addition requires some code writing in Fortran and in C, compilation and linking procedures and test runs to check for possible errors. A "hands on modeling" meeting is scheduled with other project partners for the end of October to conclude the inclusion of some of the biogeochemical components mentioned above, with emphasis on the carbon cycle.

There are also plans to develop the remaining activities with emphasis on establishing synergies with the Los Alamos National Laboratory in the USA towards a future usage of their sea ice model (CICE) to replace the ROMS sea ice model. One of the colleagues from that laboratory (Nicole Jeffery) should visit the Norwegian Polar Institute in November to start a formal collaboration. It is also planned to continue working with SYMBIOSES and to have it coupled with ROMS.

Another important aspect is to start defining boundary and initial conditions for the ecosystem model of the Arctic Ocean, regarding the newly included chemical and biological variables, to allow for realistic simulations and model tests. This is dependent on gathering information from several databases and scientific publications and it is also an ongoing task. All this preparatory work should be as completed as possible until December for we plan to carry on model calibration and validation during 2016, according to the project proposal.

Finally, the "mixed" modelling approach, using ROMS and EcoDynamo will be evaluated in terms of the time overhead associated with the usage of different EcoDynamo objects. This may be easily done by switching on/off the calls to EcoDynamo routines in different simulations and measuring the CPU time required to perform simulations with the same temporal domain.

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For the Management

Synthesis

The following table was taken from the project proposal and it summarizes the workpackages (WPs) planned for 2015 and 2016. WP1 and 2 are completed. In fact, a paper was published at the beginning of this year (Duarte et al. 2015a), describing an ice algal model implemented with EcoDynamo. Activity 4 shall be completed until the end of the year, following the work described in detail above. Activity 3 depends mostly on the UiT partner. Recently, there was a change of staff at the UiT that may lead to some delay of this activity. Activity 5 is a sort of ongoing one as more processes and variables are integrated in the model. We plan to start working with model calibration and validation in 2016.

We plan to submit a paper to a scientific journal until the end of the year describing and discussing the "mixed" model methodology described above. Also, posters and oral communications are planned to the Forum for Arctic Model and Observational Synthesis (FAMOS) Workshop, 4 – 5th November, and to the FRAM Science Days, 10-11th November.

A paper was published in the 2015 Fram Forum describing most of the modeling work developed in this project (Duarte et al., 2015b).

WPs	Task and partners involved	2015				2016			
1	Collection of available data for model parameterization, calibration and validation (NPI)	X	X	X	X				
2	Implementation of biogeochemical subroutines with EcoDynamo, for ice algae and ice biogeochemistry and zooplankton physiology with the DEB	X							

#	Task								
	approach (NPI)								
3	Integration of the CICE model or, alternatively, the ice sub-model of ROMS in the SYMBIOSES platform (UiT)	X	X						
4	Coupling of EcoDynamo and other biogeochemical submodels with ROMS (AKV, NPI and NIVA)	X	X	X					
5	Full model testing and calibration (NPI, AKV, UiT and NIVA)			X	X	X			
6	Model validation (NPI and AKV)						X	X	
7	Model usage for hypothesis testing (NPI and AKV)								X
8	Reporting (NPI, AKV, UiT and NIVA)				X				X
9	Outreach (NPI)				X				X

Published Results/Planned Publications

Published

Duarte, P., Assmy, P., Hop, H., Spreen, G., Gerland, S., Hudson, S.R., 2015a. The importance of vertical resolution in sea ice algae production models. J Marine Syst 145: 69-90. http://dx.doi.org/10.1016/j.jmarsys.2014.12.004.

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Planned until the end of 2015

Duarte et al. A methodology for merging structured and object oriented modeling platforms.

Communicated Results

Results were not communicated this year yet but, as explained above posters and oral communications are planned to the Forum for Arctic Model and Observational Synthesis (FAMOS) Workshop, 4 – 5th November, and to the FRAM Science Days, 10-11th November.

Interdisciplinary Cooperation

This project benefits from inter-disciplinary cooperation. In fact, the modeling work done so far includes ice physicists and marine biologists. Therefore, the main disciplines involved in the project were Ice Physics and Marine Biology and Ecology. Furthermore, contacts were established with colleagues at the University of

Alaska Fairbanks regarding biogeochemical modeling that, hopefully, may boost some important collaboration in the near future. Also, contacts were established with the CICE modeling team at the Los Alamos National Laboratory (USA) and the Finnish Environmental Institute.

Budget in accordance to results

Funding from the Fram Centre is fundamental to pay for the project expenses, with emphasis on labor and technical assistance. The project was not completed yet. Fram Centre funding for 2016 and 2017 is a necessary condition for completing the project. The Norwegian Polar Institute and its Centre for Ice Climate and Ecosystem have substantially contributed with in-house funding for this project. Following recommendations from the Fram Centre flagship financing this project, other sources of financing were and will be attempted.

Could results from the project be subject for any commercial utilization
   No
Conclusions

The work developed so far suggests that the coupling methodology described in this report is a good solution to combine the community model ROMS with EcoDynamo, facilitating to a great extent the implementation of relatively complex ecosystem models. Also, the project work has been according to what was planned and proposed to the Fram Centre, except in what concerns the hiring of a post-doc. This was attempted last year and again this year but without success, due to the absence of qualified candidates. Therefore, we anticipate that, in case the project will be approved for following-up next year, efforts should be made to hire a technician as was done last year and also this year. This will boost our capacity to speed-up the immense technical tasks associated with the implementation of the ecosystem model.