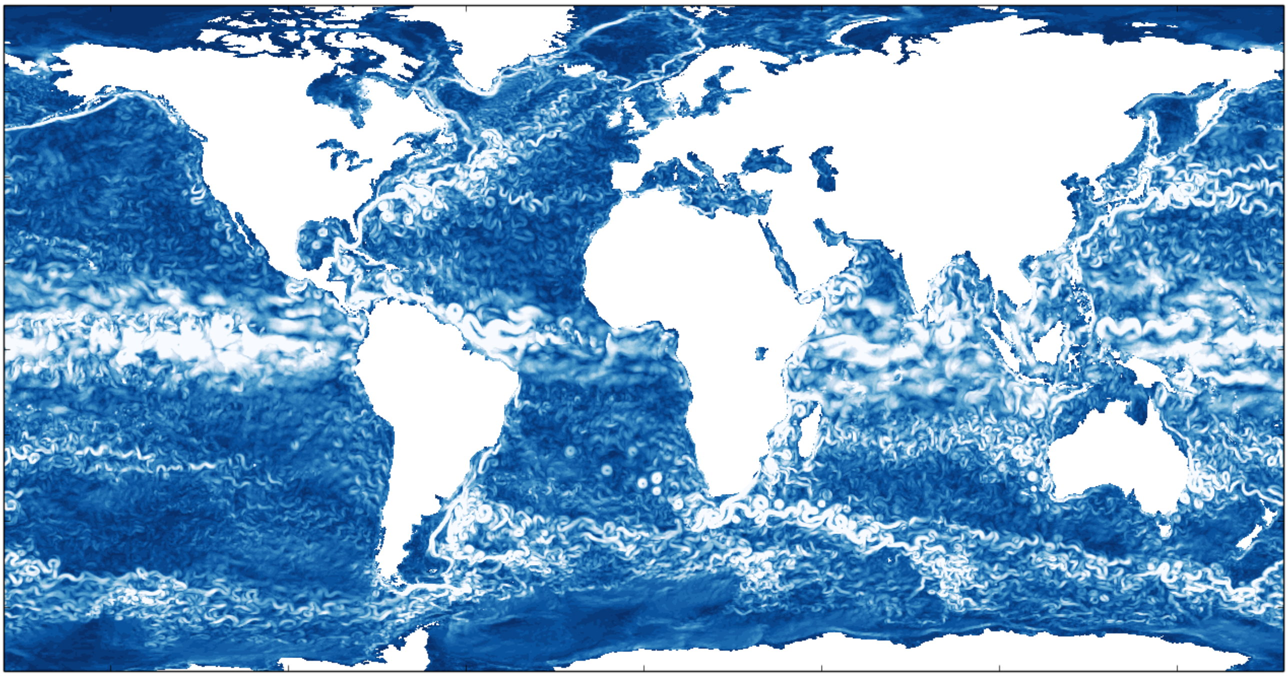
NEMO development strategy
Version 2: 2018-2022



NEMO Consortium

Legend of picture:
Daily mean surface currents from a global configuration at 1/12° resolution based on NEMO.
Courtesy from Tim Graham - Met-Office

Authors

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Preamble

History

NEMO (Nucleus for European Modelling of the Ocean) was born in 2008 with the signature of its Consortium Agreement between CNRS, Mercator, Met-Office and NERC. The Consortium widened in 2011 when CMCC and INGV joined it.

The Consortium Agreement specifies the Consortium organisation, NEMO's components, reference configurations, tools and reference versions, so as the definition of the NEMO System Team as a joint effort of experts in charge of the sustainable development of the platform. The new NEMO web site http://www.nemo-ocean.eu is set up to ensure distribution of NEMO, its documentation, history and visibility of expertise.

NEMO is the result of more than 20 years of research and operational work on numerical modelling of the ocean.

The signature of the Consortium in 2008 was the outcome of several years of intense discussions until the common mid-term goals were known and became reality during the next years. Four years later, it became desirable to update and define the new challenges for NEMO in order to identify the main development streams for the future. It has been the main motivation for the version 1 of this document, written in 2013 and published as NEMO Consortium internal document. Four years later, the NEMO Consortium decided to build a complete update of the document for the 2018-2022 period.

Why and how was this document written?

The first version of this document has been published in 2014. In 2017, the NEMO Steering Committee initiated the work towards an update on long-term perspective (5 to 10 years). Expected content was, for each institution, to summarize its main objectives, needs, motivations, questions of interest, expertise and themes in which it is willing to invest in the next 5 to 10 years, or general directions of travel or evolution which it thinks are required for NEMO and which should be taken forward together with the other partners (in case that particular partner does not have the capacity to undertake the proposed task itself).

To get into more details, the open questions cover both scientific and engineering (High Performance Computing) aspects. Expected inputs are :

- What are expected target application(s) and associated configuration(s)?
- What are the main streams for NEMO development in order to meet scientific/operational objectives?
- For each of those, what are the needs in terms of physics, numerics, efficiency, etc.?

A meeting of the Enlarged Developer's Committee meeting took place at BSC in Barcelona in April 2017. This document, the "NEMO Development Strategy" is the result of the prospective work.

The Writing Group came out of the Enlarged Developer's Committee meeting The document has been reviewed by the Developer's Committee in June 2017, and finalised by Steering Committee in December 2017.

How will it be used and updated?

This NEMO Development Strategy document will be used as guidance for the mid-term objectives (over more than one year) future yearly work plans (2018 and beyond), and possible answers to calls. It will be publicly available after endorsement by NEMO Steering Committee.

The Developer's Committee, as NEMO Scientific Advisory Board, will review the document each year to check if the document is up-to-date with NEMO and ocean modeling State of the Art. This process will allow updates if relevant. This update will be, for each chapter, under the responsibility of its author(s).

Chapter 1 - Elements of long-term strategy

This document is intended to be a practical tool for planning evolutions of NEMO beyond the next code release and for **guiding future choices** of NEMO consortium by 2025.

It outlines the **science** foundations to further develop NEMO in order to better solve fundamental processes of ocean dynamics, sea-ice and biogeochemistry, so as ocean-atmosphere interactions.

Advances in **technology** will be continuously integrated within the modelling framework, with a sustained HPC effort to ensure code portability across different computing platform and improve the execution performances of all model components. A key step will be the improvement of the existing modular structure of NEMO through the development and challenging of new computational strategies. To this regard, a significant impulse will arrive from the development of AGRIF to efficiently tackle the possibility to consistently use the model meshes with increasing high resolution.

Each chapter of this document contains its detailed conclusive remarks on the consensus and open question for the time being.

The following goals can be listed as an overall summary:

- Develop a new, efficient and scalable NEMO reference code with improved performances adapted to exploit future HPC technologies;
- Develop NEMO capabilities for describing accurately the steering of oceanic flows from global to kilometric scale through the interaction with coastlines, shelves and bathymetry;
- Prepare NEMO for the challenges of solving ocean dynamics at kilometric scale through the development of accurate numerical schemes and the explicit representation of key physical processes at kilometric scales;
- Develop a flexible, generic interface between NEMO and detailed, downstream coastal modelling systems;
- Prepare the exploitation of the next generation of high resolution observing networks.

The NEMO Consortium finds consensus on the understanding of “global kilometric scale”: NEMO development should aim primarily at improving NEMO in the prospect of a global system that would combine (i) a global configuration with a typical grid resolution of 1/36° to 1/48° and (ii) a series of interconnected higher resolution nests a 1/100° resolution covering shelf seas and key regions.

Chapter 2 - Target applications for NEMO

2.1 Scope

This chapter concerns the applications of the NEMO ocean model with the aim of identifying the configurations and systems that should be driving the future evolution of NEMO. The synthesis presented in this chapter has been established following a consultation of NEMO consortium institutions, and further discussion in Barcelona in April 2017. This chapter first reviews the range of scientific and operational applications of NEMO. We then identify the systems and configurations that are considered as drivers for the evolution of NEMO. Finally, we provide a list of key model features and areas of improvements of NEMO required for these target applications. Unless otherwise stated, this chapter reflects the consensus among NEMO consortium institutions.

2.2 The range of uses and applications of NEMO

Plans in each NEMO consortium institution involve two or more of the following uses and applications of NEMO modeling system:

- *Regional ocean process studies*: forced or coupled, eddying simulations for studying ocean circulation at regional scale with specific scientific objectives or for studying the observability of regional ocean processes;
- *Hindcasts of the global ocean circulation*: forced, global eddying simulations, in particular used (i) for studying mechanisms involved in seasonal to decadal oceanic variability and (ii) for preparing operational systems;
- *Short-range ocean forecasts*: forced, regional or global eddying configurations used in an operational system with the aim of predicting ocean circulation and properties over timescales of days to month;
- *Seasonal to decadal forecasts*: coupled, global configurations used in operational system with the aim of predicting atmosphere-ocean states over timescales of several weeks to a decade;
- *Ocean reanalyses*: forced (and eventually coupled), global or regional configurations used in conjunction with historical observations for estimating the evolution of oceanic variables over the recent decades;
- *Climate modelling*: global configurations used as components of ESMs for performing climate simulations over past century with the aim of studying the mechanisms involved in climate variability and for performing climate projections, for instance within the frame of CMIP exercices.

NEMO will also keep being used in certain NEMO consortium institutions for other applications, including in particular:

- *Paleoclimate modelling*: (coarse resolution) global configurations used as component of (simplified) ESMs in coupled simulation aiming at developing a quantitative understanding of the climate of the past;

- *Idealized ocean process studies*: forced or coupled simulations in idealized geometry and forcing for studying specific oceanic physical processes and their representation in NEMO.
- *Parameter estimation/sensitivity analyses*: model configurations used in combination with a DA scheme for solving inverse problems aiming at estimating model parameters, model sensitivity to parameters or the use of NEMO-TAM to construct optimal perturbations.

For all the above uses and applications, planned NEMO simulations will consist in single member runs or ensemble runs using one or several NEMO code components. It is also worth noting that NEMO will be used in studies aiming at designing model configurations and systems needed for all the above uses and applications.

2.3 The target configurations and applications for NEMO

Discussions have identified that three types of model configurations, corresponding to specific ranges of grid resolutions, were particularly critical for NEMO consortium institutions and should be driving the development of NEMO in the future. This includes :

- *Global mesoscale permitting configurations* (eORCA12, grid resolution ~10km) for ocean reanalyses, for seasonal to decadal forecasts and for climate modelling; this target application requires a good representation of climate relevant processes;
- *Global mesoscale eddy rich configurations* (with typical grid resolution ~3km or 1/36°) for short range ocean forecasts and for hindcasts of the global ocean circulation; this target application requires a focus on the accuracy of resolved currents and flow statistics at mesoscales and on the representation of tidal motions;
- *Regional to basin scale configurations with kilometric effective resolution* (grid resolution down to a few hundred meters, with more than 100 vertical levels) for regional process studies and for short range ocean forecasts; this target application require a focus on the representation of high frequency motions, submesoscale flows and shelves processes.

2.4 Key model features for NEMO target configurations and applications

2.4.1 Overall area of consensus

A consensus has been established on the importance of several code features where the capability of NEMO should be further consolidated in the future. These areas are in line with the above target applications and overall correspond to aspects where NEMO already shows a good potential. These areas of consensus are the following:

- Importance of ocean physical *processes affecting ocean variability at seasonal to decadal timescales*; this includes the representation of mixing processes, mesoscale processes and flow topography interactions;
- Importance of *high latitudes oceanic and cryospheric processes* affecting climate; this includes the representation of sea ice, of flows in ice-shelves cavities and the coupling with ice-sheets

models;

- Importance of *ocean physical processes affecting ocean biogeochemistry*; this includes the representation of lateral and vertical transport and OSBL processes and the coupling with BGC models;
- Importance of model features affecting the *realism of simulated flows at kilometric scale* both in open ocean and in shelf seas; this has implication for the numerical kernel, sub grid closures, and the representation of atmospheric feedbacks at fine scales;
- Importance of the *NEMO interface with observations and the representation of model uncertainty*, in particular in the context of DA.

2.4.2 Consensus on practical implications for NEMO Development Strategy

Practical implications for the NEMO Development Strategy have been identified. The consensus on these implications is the following:

- A need for *a fully functional ALE algorithm in NEMO*, with the aim of improving the representation of interior energy pathways (with reduced spurious energy dissipation) and the representation of interior mixing (with reduced spurious mixing);
- A need for *improved closures for the impact of balance turbulence*, with the aim of improving the representation of mesoscale and submesoscale eddy parameterization and the associated energy pathways; this includes in particular scale aware closures and the representation of energy back-scatter;
- A need for *improving the representation of OSBL processes*, with the aim of improving simulated upper ocean stratification; the importance of this item has motivated its treatment in a dedicated chapter;
- A need for *improving the representation of BBL processes* with the aims of improving simulated dense water masses properties; this covers the representation of overflows and processes in topographic sills;
- A need for a fully c*onsolidated representation of evolving coastlines* (wetting and drying), with the aim of improving the representation of high frequency flows in shelf seas;
- A need for *consolidating AGRIF integration within NEMO*, with the aim of unlocking the potential of AGRIF for scientific and operational uses on shelves seas and for climate relevant processes;
- Evolutions of NEMO numerical kernel should aim in priority at improving the *representation of kilometric scales and the consistency of resolved energy pathways*;

2.4.2 Points that require further investigations and decisions.

Discussions have also identified several questions and proposition that have raised an interest but for which consensus has not been reached yet. For the following questions, further description of the requirement and more demonstration of the potential for NEMO is required :

- The integration of a simplified ABL model in NEMO with the aim of improving simulated upper ocean currents by accounting for atmosphere-ocean feedbacks at fine scale has been discussed; this perspective is considered very promising and innovative but it is unclear whether this idea is mature enough for integration in NEMO;
- The need for defining an interface with coastal/estuarine models has been discussed; the potential of such development has been discussed; a precise definition of the scope of this interface should be established before a consensus can be reached;
- The potential of AGRIF for improving the representation of key ocean processes for climate in particular hotspots (eg. for dense overflows) has been discussed; whether this aspect should be a driver for improving the integration of AGRIF in NEMO is not clear yet.

List of acronyms

ABL : Atmospheric Boundary Layer
ALE : Arbitrary Lagrangian Eulerian
BBL : Bottom Boundary Layer
BGC : biogeochemistry
CMIP : Coupled Model Intercomparison Project
DA : Data Assimilation
ESM : Earth System Model
OSBL : Ocean Surface Boundary Layer

Chapter 3 – High Performance computing

3.1 Scope

In order for NEMO to remain a world leading ocean model it is essential that it is able to run efficiently on future high performance computing (HPC) architectures with a diverse range of processors such as GPUs, Knights Landing or ARM processors. These architectures can be exploited to improve the model time-to-solution only if they are efficiently used.

NEMO consortium members provided the following requirements in terms of target performance of global NEMO configurations.

Configuration	Current number of cores	Approx. number of cores to be used	Required speed
1/36° - 1/48°	unknown	20000+	1 SYPD

1/36° global or 1/12° ensemble	unknown	10000-20000 (2019-20) 50000-200000 (2021-2022) 80000 (operational; 2023) 200000 (reanalysis; 2023)	15-30 simulated days/day 0.5-1 SYPD 10 day forecast in 2 hours 2 years reanalysis per week
1/16°	~8000	>16000	2 SYPD
1/12°	~9000	~10000 (2018) 10000+ (~2020)	>2 SYPD 5 SYPD
1/12° (with tides+biology) coupled to UM atmos	-	20000+	1 SYPD
1/12° coupled to UM atmos	-	20000+	2-4 SYPD
¼°	512-1024	500-1000	10-20 SYPD
1°	-		100 SYPD

Speed requirements can be satisfied by working on the improvement of both the parallel and the sequential code efficiency. However, as the speed of individual CPUs will not increase we are unlikely to see significant gains in performance without an increase in the number of CPUs.

To run on efficiently on these architectures and achieve the times to solution required by members of the consortium, NEMO will need to scale to many more cores than is currently possible. For example, the ORCA12 which currently only scales to 10000 cores but will need to run on more than 100000 cores to meet the requirements of consortium members. This chapter will also focus on single core performance improving the efficiency and time to solution of NEMO without an increase in the number of cores.

The scope of this chapter includes understanding current limitations to NEMO's performance, strategies to reduce the time spent on communication (including MPI & OpenMP), single core performance and code design strategies to enable a readable and flexible code. To this aim, a benchmark suite of applications can be defined and profiling and analysis tools can be used to understand code performance.

HPC performance can also be improved via the use of more efficient kernels (for example changing time stepping scheme). This will not be discussed in this chapter as it is discussed elsewhere in this document.

3.2 The Main Issues

3.2.1 - Internode Communications

Communication between nodes will remain expensive on future architectures and effort is required to reduce the amount of communication and speed up existing communications.

3.2.2 - Shared Memory Parallelism

Making use of shared memory parallelism within nodes will be essential on future architectures (because the typical memory available per core is dropping as core counts increase). This will permit a reduction of intranode communication overhead as well as an increase of the code parallelism without an increase of the communication costs.

3.2.3 - Single core performance

Making more efficient use of individual cores will complement improvements in parallel efficiency by reducing time to solution with no increase in resources. Single core performance is limited by memory access and poor exploitation of vector processing units on modern HPCs.

3.3.4 - Designing a flexible user-friendly code structure

A significant challenge exists in designing a code structure which is flexible enough to be optimised for different architectures (for example including OpenMP and OpenACC directives). The code also needs to be as readable as possible for scientists to be able to continue to develop the code.

3.3 Plans for the main issues

3.3.1 - Internode communications

In order to reduce the amount of time spent on internode communications the following steps should be carried out. These should allow the number of halo update calls to be reduced as well as the time waiting for the communications. It is assumed here that shared memory parallelism will supercede the need for intranode communications.

- Detailed analysis of the performance to identify areas where communications act as a bottleneck to performance to allow optimisations to be applied to these areas of the code.
- Increase the size of the haloes in NEMO to allow fewer updates
- Add an option to remove haloes from diagnostic outputs.
- Overlapping communication and computation, taking into account the effect on memory locality

People involved: Oriol Tinto, Miguel Castrillo, Tim Graham, Silvia Mocavero...

3.3.2 - Shared Memory Parallelism

Effort should be invested in making use of shared memory parallelism approaches such as OpenMP and OpenACC to increase the code scalability when the MPI limit is reached. Previous work implemented loop level OpenMP directives within NEMO. This gave little performance gain except for allowing some speed up of the code beyond the scalability limit of the pure MPI version. Future work on OpenMP should look at a coarse grain approaches such as tiling within MPI domains in order to extend the OpenMP parallel region and to reduce the synchronization events. Trials of OpenMP and OpenACC should be carried out in consultation with the NEMO systems team as the coarse grain approach usually requires a code refactoring to be fully exploited.

People involved: Silvia Mocavero, Francesca Mele, Maff Glover

3.3.3 - Single core performance

Improvements to single core performance of NEMO will allow the model to run more efficiently on the single node of the target HPC system and complement improvements in parallel efficiency. The following tasks should be carried out to improve single core performance:

- Detailed analysis at kernel level to understand which kernels are limiting performance and what causes the poor performance of these kernels.
- Improve utilisation of memory hierarchy. Many parts of the NEMO code are limited by memory bandwidth. Work to reduce this could include introducing cache blocking or reducing the number of unnecessary arrays (e.g. masks) in NEMO. There is a large overlap between this and the tiling approach for OpenMP in 3.3.2.
- Vectorisation of loops will become more important as vector register sizes increase on future architectures. Automatic vectorisation is usually performed by the compiler but the code needs to be written in a way which helps the compiler to increase the vectorization level (e.g. solving dependency issues). Directives can also be used to help with vectorisation but care must be taken to ensure that scientific validity of the code is not compromised.

People involved: Martin Schreiber, Tim Graham, Silvia Mocavero, Andy Porter, Cyril Mazauric, ...

3.3.4 - Designing a flexible user-friendly code structure

Maintaining flexibility to optimise code for different architectures could be achieved via the “Separation of Concerns” approach. For example, using the PSyclone preprocessor as demonstrated in the GOcean project [1] or the use of macros as is being tested in the DYNAMICO model. Both of these approaches aim to separate computational science and natural science but they both require a significant change to the way NEMO is written and are therefore unpopular within much of the NEMO consortium. In light of this, work is underway to allow PSyclone to work with un-changed NEMO code – see below.

Options which should be tested:

- The ZDF module is currently being rewritten with a ZDF manager handling parallelism and calls to the scientific modules below. This structure will allow the introduction of a tiling approach suitable for coarse grained OpenMP and OpenACC. If successful this should be implemented in the rest of the code.

- The application of the PSyKAl approach to a NEMO kernel has been investigated within the IS-ENES2 project by STFC and CMCC [2]. Initial work is underway by computer scientists at STFC to develop a prototype version of the PSyclone preprocessor that can operate on the raw NEMO code (i.e. make use of the NEMO coding standards) in order to apply optimisations suitable for different HPC architectures before the code is compiled. This version of PSyclone would not deal with the MPI parallelisation (this could be added in future) but it could be used to add OpenMP and OpenACC directives and to apply cache blocking to loops. It may be possible to use this in combination with the first approach above, for example to switch between OpenMP and OpenACC directives.
- If neither of the above approaches is successful then it may be necessary to include both OpenMP and OpenACC directives in the science code.

People involved: Silvia Mocavero, Andy Porter, Gurvan Madec, Maff Glover

3.4 Additional issues

- Making more use of sea-ice in parallel
  Ocean and sea-ice components can be run concurrently coupled through OASIS. This allows an increase in the level of parallelism through the allocation of different sets of parallel processes allocated for the two components
- Biology in parallel
  Functional parallelism through OpenMP could be considered for BGC where the number of threads is very high and could increase. Separate threads which work on blocks of tracers instead of data subdomains could increase the parallelization efficiency by limiting the parallel overhead. Some key issues are: existing dependencies among tracers (if there are any), code refactoring needed to move the loop on tracers as external as possible, how the two parallel approaches (domain parallelism with MPI and functional parallelism with OpenMP) could work together.
  An alternative to OpenMP is to allow coupling of OPA and TOP via OASIS. This could be implemented using the existing OFF_SRC section of the code and modifying it to take forcing fields from OASIS instead of reading from input files.
- Mixed precision calculations
  Currently all calculations in NEMO are carried out in double precision. A consistent gain could be achieved by executing some parts of the code in single-precision. Initial tests show an improvement up to ~40% by running ocean in single-precision and sea-ice in double precision however there are significant changes to the results in these tests. Careful analysis is required to understand which parts of the code could be safely integrated in single precision without having an impact on the model solution.

References

[1] A. R. Porter and R. W. Ford and M. Ashworth and G. D. Riley and M. Modani, "Towards Compiler-Agnostic Performance in Finite-Difference Codes", in "Parallel Computing: On the Road to Exascale", editors "Gerhard R. Joubert and Hugh Leather and Mark Parsons and Frans Peters and Mark Sawyer", 27, 647-658 (2016) IOS Press, (Amsterdam, New York, Tokyo)

[2] https://portal.enes.org/ISENES2/documents/na2-working-documents/application-of-the-psykal-approach-to-the-nemo-ocean-model/view

Chapter 4 − The NEMO ocean kernel

4.1 Scope

This chapter concerns the dynamical core of the NEMO ocean model. Its scope includes : the choice of grid, the staggering of model variables and the time-stepping algorithm; the discretisation of the momentum and continuity equations; and the representation of the advection of tracers. The accuracy and efficiency of the resulting algorithms, their mimetic and conservation properties, their computational modes and their dispersive and dissipative properties are all within scope.

The efficient implementation of these algorithms on modern HPCs, which was within the scope of this chapter in the previous strategy, is now considered in its own chapter (cross-ref). The approach to regional grid refinement, which has strong links to the choice of a structured or unstructured horizontal grid, is also considered in a separate chapter (cross-ref). The choice of scale-aware parameterisation of sub-grid-scale processes, considered in the chapter on ocean dynamics (cross-ref), should take account of the choices made in the dynamical core. The dynamical core of the sea-ice model is covered in the sea-ice chapter (cross-ref).

4.2 The main issues

4.2.1 Vertical grid (ALE algorithm)

Implicit diapycnal transport associated with numerical dispersion and dissipation in the advection of tracers can result in significant, unphysical, transport of heat through the main thermocline, particularly in eddy permitting models in the Southern Ocean (Lee et al. 2002). It is judged to be strategically important for climate simulations for NEMO users to have access to algorithms similar to those used in other ocean models that could be used to improve the control of these numerical errors. NEMO has an option for an Arbitrary Lagrangian Eulerian (ALE) algorithm in which the target grid is the $\tilde{z}$ vertical coordinate. This option has not been fully explored within

NEMO and a greater choice of target grids is desirable. The vertical re-mapping step itself introduces dispersion and dissipation so needs to be implemented carefully. It is also difficult to define a target grid, which assigns desirable vertical coordinates to each region within the model. The NEMO consortium has significant expertise in these issues (e.g. Debreu, Madec, Nurser).

4.2.2 Horizontal grid (structured or unstructured)

Unlike atmospheric models, NEMO does not have a strong user requirement for its grid to be able to cover the whole sphere with uniform resolution. Also the NEMO user requirement does not include the detailed representation of estuaries. Improved grid resolution in selected areas (e.g. over important sills) is a requirement. NEMO's current strategy is to meet this requirement through a regional grid refinement approach rather than an unstructured grid approach. A second-order accurate representation of coastlines and bathymetry could be an advantage both in coarse and high resolution models but it is not clear that this is crucially important.

The NEMO consortium has limited expertise in unstructured grids and finite element methods and the implementation of such methods would be a major task that would result in a new ocean model. Whilst there is no strong evidence that unstructured grid methods are the best approach, the NEMO strategy is to keep a watching brief on their development and to focus on a regional grid refinement approach.

4.2.3 Time-stepping

Lemarié et al. (2015) show that the time-step in NEMO is usually limited by the CFL limit on explicit vertical advection in a small number of hot spots near the coast. Implicit vertical advection schemes can allow longer timesteps to be taken (Shchepetkin 2015). A compact fourth order implicit vertical advection scheme is being implemented in NEMO (Lemarié et al 2015).

A two-time-level approach to advection of tracers that is 3rd order accurate in space and time, would be preferable to the current three-time-level leapfrog approach. With this approach there is no computational mode, the calculation of flux limiters is simplified, time-step restrictions are less severe and regional grid refinement is simplified. Two-time-level approaches to the momentum equations are also available (for example a Runge-Kutta 2nd order scheme with forward / backward calculation of pressure gradients) that are as efficient as and also more accurate than the current leapfrog Brown-Campana scheme for internal gravity waves.

4.3 Plans for the main issues

4.3.1 Vertical grid (ALE algorithm)

A staged implementation seems desirable. The first stage includes:

1. Investigation of the performance of the existing $\tilde{z}$ scheme in climate model integrations
2. Design of target coordinate options and the re-zoning phase (this could include an investigation of whether the options will give sufficient flexibility to ensure that suitable coordinates are used in important regions)
3. Choice of re-mapping scheme (a vertical interpolation or a vertical advection)
4. Design of pressure forces
5. Design of (a staged) adaptation of other schemes (e.g. isopycnal diffusion)
6. Clarification of approach to vanishingly thin layers and their vertical viscosity
7. Clarification of likely costs and benefits
8. An implementation plan

The team should include: Debreu, Lemarié, Madec, Nurser, Holt, Iovino, Bell,New, Megann.

The initial planning stage should be completed by March 2018.

4.3.2 Horizontal grid (structured or unstructured)

Finite volume schemes for hexagonal and triangular grids with good mimetic properties have been investigated in detail over the last few years following the invention of the TRiSK algorithm (Thuburn et al. 2009). These grids have some inherent disadvantages. Triangular grids have an additional (spurious) branch of gravity wave solutions whilst hexagonal grids have an additional branch of Rossby wave solutions. It is also challenging to ensure the accuracy of key terms (such as the Coriolis acceleration), to avoid Hollingsworth instabilities and to represent stationary geostrophic solutions. The accuracy issues are particularly problematic on the non-orthogonal grids that would be generated if one sought to fit the boundaries of the finite volumes to bathymetric contours.

Finite element schemes are also being investigated for quads, triangles and hexagons. With carefully chosen finite element bases the hexagonal and triangular elements can have the correct number of gravity and Rossby waves (Cotter & Shipton 2012).

There is no strong evidence yet that unstructured grids are the best way ahead for ocean modelling. So at present it is proposed to continue to keep a watching brief on the above developments and focus on a regional grid refinement approach. Some members of the NEMO community (e.g. Debreu, Lemarié, Bell) have links to key members of the community developing techniques for

PDEs on the sphere. Investigations of the impact of lateral steps and shaved cells on NEMO simulations are relevant to this issue (see section 4.4.1).

4.3.3 Time-stepping

Considerable work has already been invested in simplifying the NEMO code in preparation for this change to the time-stepping algorithm. A short description of the proposed implementation would be helpful at this stage. That plan should include:

1. A proposal for the algorithm(s) to implement for tracer advection
2. Analysis of options for momentum equations (vector invariant & flux form)
3. An implementation plan

The team involved should include: Lemarié, Madec, Chanut and members of the NEMO System Team

4.4 Additional issues

There is no clear user requirement for a non-hydrostatic option to be developed within NEMO. (The French CROCO project is developing a coastal ocean with a non-hydrostatic core that is an evolution of the ROMS code. There are still links between the NEMO and CROCO teams.)

The first two issues below were mentioned as additional issues in the first version of the strategy and are still relevant.

4.4.1 Shaved cells at the lateral boundary

The een scheme and vorticity / divergence formulation of viscosity appear to allow NEMO to achieve slippery coastlines even when the coastline is stepped (Adcroft and Marshall 1998, Dupont et al. 2003). It is desirable to have a better understanding of this result and the accuracy of the coastlines.

4.4.2 Shaved cells at the lower boundary

Step-wise bathymetry probably has detrimental impacts on the flow over sills (Winton et al. 1998). It may also weaken vortex stretching by flow down bathymetry which has an important role in the bathymetric steering of the barotropic flow by (e.g. Zhang & Vallis 2006). It almost certainly generates grid-scale noise in vertical velocities. Schemes to allow smoother flow over bathymetry whilst avoiding the difficulties associated with very steeply sloping coordinates would be valuable.

4.4.3 Representation of advection of momentum

The most frequently chosen option for the horizontal momentum equations in NEMO is the vector invariant een scheme. This scheme does not attempt to dissipate enstrophy and can be prone to the Hollingsworth instability. This means it is not well suited for high resolution ocean modelling. The option(s) that should be coded for momentum advection with the new time-stepping scheme need to be clarified.

4.4.4 Wetting and drying

There is a user requirement for a wetting and drying algorithm to be available within NEMO. The approach being taken is to implement the "new" NOC scheme and a form of the ROMS scheme and to test them out in a series of idealised configurations and real world configurations, first with uniform and then with variable initial temperature and salinity fields. At present both the NOC and ROMS schemes are "working" in pure sigma-coordinates when the initial T & S fields are uniform both in idealised and small real world configurations. Testing of these schemes will continue, and we can anticipate that the wetting & drying strategy will be strongly tied to the choice of vertical coordinate. The updated version of the codes should be lodged in NEMO version 4.0.

4.4.5 Weaknesses inherent to the Lorenz grid

The Lorenz grid has some weaknesses in its representation of normal modes and baroclinic instabilities (Arakwa & Moorthi 1988). This has persuaded some atmospheric modellers to use the Charney-Phillips grid instead. Conservation of energy and potential temperature is possible but complicated on that grid (Arakawa & Konor 1996) and detrimental impacts of the Lorenz grid have not been clearly demonstrated in ocean models.

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Chapter 5 – NEMO ocean dynamics

5.1 Scope and definitions

This chapter concerns the range of oceanic (physical) processes that should be accounted for in NEMO ocean component (OPA) and which representation should be improved in the future. This chapter builds upon the priorities identified in the consultation of NEMO consortium institutions and upon the discussions held in Barcelona in April 2017.

In this chapter, the notion of *oceanic physical process* refers to a class of oceanic motions (or a series of mutually interacting classes of motion) which dynamics can be described and rationalized in an idealized setting with a limited number of dynamical ingredients. Ocean physical processes of interest for ocean modelers are often involved in exchanges of energy or information across space and time scales.

In terms of ocean modeling, oceanic physical processes can be accounted for either through the *explicit representation* of the class of motion itself (eg. mesoscale eddies in eddy rich ocean models) or through a *physical parameterization* of its bulk effect on the resolved classes of motions and scales (eg. parameterization of transport due to mesoscale eddies in non-eddying ocean models). We stress that applications (eg. forecasting ocean currents at fine scales) and processes to be represented should be clearly distinguished.

Accounting for a particular oceanic physical process in an ocean model has therefore implications as to the design of subgrid closures and as to the design of the numerical kernel. In the case of parameterized processes, the use or the design of a sub grid closure is tied to the understanding of cross scale interactions and is therefore subject to evolution depending on the status of scientific knowledge.

In this chapter, we discuss NEMO priorities and plans as to the explicit or parameterized representation of oceanic physical processes. Implications with respect to NEMO numerical kernel are flagged out. Areas where research with NEMO should be undertaken or pursued are identified. Because of their importance, priorities with respect to processes within the OSBL are discussed in a dedicated chapter.

5.2 Key oceanic physical processes for NEMO

Discussions have converged as to the importance of the representation of several key oceanic physical processes for NEMO target applications.

In terms of parameterized oceanic processes, clear needs have been identified as to

- The representation of the impact of *balanced turbulence* (mesoscale and submesoscale eddies) on larger scale/lower frequency flows; balanced turbulence affects the transport of momentum and tracers at large scales and can exchange energy with larger scale/lower frequency flows; this field of research is very active with several new approaches being discussed in the recent literature (scale aware closures, stochastic closures, energy backscatter, approaches from LES);
- The representation of *processes involved in mixing ocean properties in the BBL and the ocean interior*; several processes are actively mixing the BBL and the ocean interior therefore affecting water masses properties on seasonal and longer time scales; this includes overflows, mixing processes in sills and mixing due to internal wave breaking; NEMO should move towards a more energy constrained specification of interior buoyancy sources, which also involves reducing spurious numerical mixing.

In terms of explicitly represented oceanic processes, clear needs have been identified as to :

- The representation of processes involved in flow / topography interactions, especially in boundary currents; topography exerts a strong constraint on resolved flows through several physical processes (vortex stretching, vorticity sources/sinks in lateral boundary layers, hydraulic control, …); these processes are key for accurately modeling the evolutions of flows close to boundaries; this has implications as to the evolution of the numerical kernel, especially in terms of lateral and bottom boundary conditions;
- The representation of tidal motions, both barotropic tides and baroclinic internal tides; tidal motions are a prominent mode of variability at high frequency; baroclinic internal tides are a prominent signal at fine scale (<100km) that significantly affects ocean energy pathways; improving the ability of NEMO to simulate more accurately tidal motions is key for NEMO target applications; this has implications as to the representation of tidal forcing, choices for the numerical kernel (eg. moving coastline) and the parameterization of the dissipation of internal

waves.

More generally, there is a clear need for assessing the representation of motions at kilometric scales and high frequency (period shorter<1day) in NEMO solutions. This can be achieved through statistical comparison of NEMO solutions with observations at fine scales in hindcast simulations and through comparisons with solution from other ocean models. This assessment should provide guidance as to the evolution of the numerical kernel.

5.3 Plans for progress

Progress as to the representation of the above ocean physical processes in NEMO is critical for several target applications. But, because these areas of expertise are fast evolving, active fields of research involving few, highly specialized research groups, plans are needed for leveraging expertise within the consortium but also from outside groups on these aspects. The following section proposes practical actions to be undertaken from both from with NEMO consortium and in terms of interaction with a wider community.

5.3.1 Practical actions from NEMO consortium institutions

Several practical actions have been discussed from which the following propositions have emerged:

- Organizing targeted working groups focusing on specific physical processes with the aim of proposing improvements to NEMO reference; these working groups should be organized, for a limited lifetime, from within NEMO developers committee and should involve process oriented researchers; an example of such working group is currently focusing on balanced turbulence; a working group focusing on the assessment of resoled flows at kilometric scales could also be set-up;
- Relying more systematically on idealized demonstration case for show-casing the impact of new developments on the representation of physical processes; NEMO now comes with a practical solution for implementing idealized demonstration cases; this feature could be used systematically for any new development affecting NEMO ocean dynamic component;
- Consolidating the online diagnostics of terms affecting momentum and kinetic energy budgets; these diagnostics are currently almost available in NEMO but are not yet compatible with all code options (implicit bottom friction, time stepping); momentum and kinetic energy diagnostics (pointwise terms and integrated budgets) are key tools towards more physically consistent closures in NEMO; these tools should be consolidated and adapted to any new code feature affecting the resolved equations for momentum.

5.3.2 Interaction with NEMO users community

Discussions have converged on the idea that there is an interest for NEMO consortium to foster innovations as to the representation of ocean physical processes in NEMO coming from a wider community, in addition to the above actions involving NEMO developers committee and NEMO system team. Because of the nature of the developments impacting the representation of ocean physical processes, this idea of contribution from a wider community is intrinsically related to the use and promotion of idealized demonstration cases in NEMO.

Two groups of actions have been identified for respectively (i) fostering the emergence of a community of process-oriented users of NEMO and (ii) fostering contributions to NEMO ocean dynamic component from projects led outside the consortium.

Obviously, a key requirement for the actions described below to be implemented is that they should not result in a large burden on NEMO system team. The cost versus benefits trade off should be carefully examined before any action is undertaken.

Actions for fostering the emergence of a community of process oriented users of NEMO could involve:

- Implementing a limited series of idealized demonstration cases in NEMO reference that could serve as material for increasing NEMO's online visibility and for pedagogical purposes in summer schools; these idealized demonstration cases should come with tutorials and diagnostics suites in line with current practice in other communities to increase visibility (github, markdown, jupyter notebooks);
- Providing a technical environment for a web based user community to grow; in practice this could involve providing a demonstration as to how external users can implement and distribute demonstration cases not to be supported NEMO reference.

Actions for fostering more contributions to NEMO ocean dynamic component from project led outside the consortium could involve :

- Advertising publically for NEMO priorities in terms of the representation of oceanic physical processes; this could for instance be achieved through NEMO web site; this communication could also come with a description of how external contribution could flow within NEMO reference (see below);
- Establishing a clear endorsement process for science projects that could lead to important developments that could eventually be integrated fun NEMO reference; this could for instance involve writing letters of support in the name of NEMO developers committee;
- Defining how users external to NEMO system team and NEMO consortium institution could contribute to NEMO development; this involves clarifying the criteria for a development to be considered and defining precisely the decision and review processes for the code.

List of acronyms

BBL : Bottom Boundary layer
LES : Large Eddy Simulation

Chapter 6 – Towards locally higher effective resolution: AGRIF

6.1 Scope

Geophysical fluid modelling covers a wide range of scales obviously truncated by limited computational resources. Refining the solution only over a selected geographical area provides an alternative to push the explicit computation of the turbulent cascade further, resolve complicated geometries and design ad-hoc parameterizations to be used with coarser resolution grids. This chapter describes the strategy followed in NEMO to that end, points out current limitations and provides directions for further developments.

6.1.1 Possible refinement strategies

We briefly recall the two common approaches to reach locally higher resolution:

- Grid deformation. Unstructured grids models naturally offer this feature (e.g. MPAS, Ringler et al 2013). Stretching an orthogonal curvilinear structured grid is possible too (see for instance the BLUElink Australian prediction model grid in Brassington et al. 2005), though with likely more constraints on the grid deformation properties. In any of these cases, ping stability is however dictated by the smallest grid element, which substantially increases the computational problem. Another issue is that sub-grid parameterizations have to be valid throughout the domain, whatever the grid size and eddy resolution regime are (Hallberg, 2013).
- Step wise change of resolution. Different grids and possibly different models are abruptly connected in space. This easily circumvents the aforementioned problems of time stepping and parameterization choice. One has however to deal in that case with an (ill posed) open boundary problem and possible reflections near boundaries (Harris and Durran, 2010). The abrupt transition also raises the problem of spin up of turbulent scales from the boundary, a situation encountered in the first approach also, but probably easily handled by a smooth grid transition (Danilov and Wang 2015). The transfer of information can either be “one-way”, i.e. only the parent grid model transfers information to its child grid domain or “two-way” if a feedback from the fine grid is performed. In practice, connections between grids can be implemented through an external coupler (with OASIS in HYCOM, Baraille personal communication) or through dedicated libraries such as AGRIF for NEMO (Debreu et al. 2008) or SAMRAI (https://computation.llnl.gov/projects/samrai, Herrnstein, 2005).

It would be difficult to find a clear advantage for one method compared to the other. These are not exclusive of each other also. Transition of NEMO kernel towards unstructured grid is not discarded (see section 4.2.2) but it is likely that the second path will remain the preferred choice to obtain local refinement in the coming years.

6.1.2 The AGRIF library

The practical nesting implementation in NEMO is based on the AGRIF library (AGRIF: Adaptive Grid Refinement in Fortran, Debreu et al. 2008). AGRIF allows grid refinement to be implemented in any structured grid, finite-difference model written in FORTRAN. The embedding methodology considers an arbitrary number of refined grids (refined by any integer factor) of the original grid and these are time integrated in a serial way (parent first, successively refined grids after, according to the Berger and Oliger 1984 algorithm). These can have several level of embedding (telescoping nesting) as long as they do interact with a unique parent level (this restriction relates only to the current implementation, see issues below). Memory sharing between grids is handled thanks to pointers, detected during the code preprocessing stage. This leaves to the user very few modifications to implement information transfer between grids.

Since grids are logically defined from each other, they share coincident cells, so that interpolation and updates are facilitated and conservation properties are easily obtained. Combined with high frequency temporal exchange (at each baroclinic time step), the overall procedure has proven to be numerically robust. Such a level of robustness and computational efficiency is probably difficult to

obtain with an external coupler approach though this has still to be formally demonstrated.
The code preprocessing step has been for years the Achilles' heel of AGRIF to ensure its sustainability in NEMO. Great progress has been made in the past 10 years so that this does not seem to be the case anymore. Two-way grid nesting is now possible with all prognostic components of the NEMO platform: Ocean, Passive tracers and Sea-Ice (LIM3).

6.2 Issues and limitations

6.2.1 Overlapping Grids

Nested grids are defined over rectangular regions and must have a single parent level. It means that grids having the same level of refinement cannot transfer data with each other, which precludes from defining overlapping grids (as currently implemented, overlapping nested regions only get boundary conditions from their parent grid - the same holds for updates). Allowing for overlapping grids would facilitate following complex geometries, hence getting closer to the possibilities offered by unstructured grids. This however requires that grid exchange is performed at the smallest time increment in the code (at the barotropic or ice rheology sub-stepping) to render the overlap transition transparent. More generally, solving the 1:1 imperfect nesting issue described below is a prerequisite to have overlapping grids.

6.2.2 MPP flexibility

Current implementation does not allow allocating separate mpp resources to each refinement level. It could also be more computationally efficient (in the case of small nested regions in particular) to allocate separate resources and integrate grids concurrently (see Harris and Lin 2013). External couplers are often used in that way so that the load can be balanced between coupled components. The Berger and Oliger (1984) algorithm on which AGRIF is based is however a serial algorithm: the parent grid level has to be updated first to provide time interpolated data. The concurrent nesting approach would on the other hand require some kind of time extrapolation of boundary data. If this is a strong requirement not to change the overall time stepping order in the library, it should at least be made possible to dispatch mpp resources at the same grid refinement level.
In addition, when it comes to HPC, NEMO-AGRIF needs to be compatible with new developments done in NEMO itself. Especially as it is, it won't be able to deal with the on-going OpenMP implementation. Compatibility can be achieved at minima, but more generally, we have to keep in mind that such developments in the NEMO code may require additional work, testing and manpower to be used with AGRIF.

6.2.3 Imperfect 1:1 nesting

1:1 nesting means that neither time nor spatial refinement is used. Ideally, in such a case, grid nesting should not change the overall solution. This test, although hard to pass with success, is a good indicator of the nesting implementation robustness and a necessary step to solve 6.2.1. The present implementation fails on that aspect on several points that should be addressed:

- Coupling is performed at baroclinic time step. Coupling at barotropic time step as in Debreu et al. (2012) should be envisioned at the expense of designing a compliant time stepping structure (4.3.3). A similar issue is raised by the ice rheology solver (ice variables are exchanged at each baroclinic step also).
- Provision of boundary data should be extended for higher (>2) order numerical schemes.
- Cyclic east-west or north fold boundary conditions are not compatible with refinement. This is a strong requirement to use AGRIF for BGC coarsening at the global scale (see below).

6.2.4 Conservation issues

Nesting can give rise to lack of conservation in particular of volume and tracers. Corrective methods (refluxing, see discussion in Debreu et al 2012) exist but are hard to implement with Leap Frog time stepping. Change for a two-time level time stepping should allow perfect conservation to be ensured.

6.2.5 Usability and pre-processing

Use of AGRIF, even though it is almost transparent for users since the modified code can be used in the standard way, requires an additional step of pre-processing to create adequate input files. Pre-processing tools are existing but we have to keep in mind that:

- They are strongly connected to any change done in the definition of the vertical coordinate definition in NEMO.
- They make the assumption on a few numbers of child grids with a given (square) geometry.
- There is no clear articulation between the standard pre-processing tools and the AGRIF pre-preprocessing tools.

The later point constitutes an obstacle to the dissemination of the use of AGRIF.

6.2.6 Vertical coordinate change

Vertical refinement or more generally vertical coordinate change (nesting of s coordinate model into a z-coordinate model) has to be implemented. Use of horizontal refinement over overflow regions for instance is likely to be efficient only if associated with a vertical coordinate change.

6.2.7 BGC coarsening

AGRIF has the capacity to define coarsened “grand mother” grids with associated operators to properly “degrade” parent grid variables. This would greatly simplify the implementation of BGC coarsening, which is for time being code intrusive and hard to maintain.

6.3 Plans

The different issues listed above can be grouped in the following three tasks, mostly according to the expertise needed. Impact and effort (Low/Medium/High) are given under brackets.

6.3.1 Expanding library mpp capabilities (mpp)

Items 6.2.1 and 6.2.2 above are, to some extend, specific to the library so that expertise from AGRIF developers is mandatory. Some of the reported issues are also of concern in coastal/regional applications of AGRIF for which it is primary developed today (for the CROCO-AGRIF model in particular).

Issue 6.2.1 has been already solved in CROCO-AGRIF model so that changes should be available in the library. Issue 6.2.2 is more complex to solve since the needs of the large scale global and regional communities appear to differ. The NEMO community has expressed the need for refinement on small selected domains in global models on massively parallel computers. A concurrent nesting approach is likely to be more efficient in that case but unlikely to be possible with AGRIF.

- T6_mpp.1 (M/L) => Transfer latest versions of AGRIF library in NEMO in particular to allow inter-grid communications (i.e. interpolations and updates) at the same refinement level.
- T6_mpp.2 (H/H) => Clarify if using separate mpp resources for parent and child grids is possible in AGRIF framework. Design changes in the library and the nesting flow chart.
- T6_mpp.3 (H/M) => Implement load balancing among several child grid domains.

Possible people involved: Debreu, Benshila

6.3.2 Improving Robustness (rob)

This concerns items 6.2.3 and 6.2.4 for which tasks are well identified. Note that reaching perfect 1:1 nesting is not only a verification test, it will help to increase the overall implementation robustness for other refinement factors. For instance, fixing ghost cells problem is all the more important that higher order advection schemes become more and more used.

The priority for this task is high since other developments rely on its completion. Having the new two level time stepping implementation (see §4.3.3) would be preferable before starting coupling at barotropic time step as well as solving conservation issues (see §6.2.4). Strong coordination is needed here since proper integration of AGRIF requires some adaptation of the time stepping structure.

We recommend that quantitative assessment of the progress made should be detailed in idealized experiments. An additional SETTE test should be added to check these developments.

- T6_rob.1 (H/M) => Coupling at barotropic time step.
- T6_rob.2 (H/L) => Implement parametrable ghost cells provision.
- T6_rob.3 (M/M) => Allows for cyclic East-West / north fold boundary conditions in nested grids.
- T6_rob.4 (L/L) => Implement fixes for perfect tracer conservation.

Possible people involved: Madec, Chanut, Benshila, Rousset

6.3.3 Expanding use of AGRIF in NEMO (use)

- T6_use.1 (H/M) => Nesting tools have to merged with the configuration manager (see section 11.2.3). In order to simplify this, we recommend that what is specific to AGRIF i.e. the volume matching near grid interfaces, to be performed with the library functions (this could alternatively be done during initial mesh creation stage - ie DOMAINcfg step).
- T6_use.2 (M/L) => Vertical coordinate change between nested grids. Conservative vertical remapping schemes to be implemented. Testing in idealized setups. This task i s well advanced but needs additional testing as well as adaptation of the preprocessing package.
- T6_use.3 (M/M) => BGC coarsening at the global scale. Needs cyclic East-West bcs to be solved from task (6.3.2). Transpose existing coarsening procedure to the AGRIF "grand-mother" grid concept. This task should be performed after testing of the existing coarsening procedure by the community.
- T6_use.4 (M/L) => Demonstrate new concepts in a global configuration.

Possible people involved: Graham, Bricaud, Chanut, Debreu

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Chapter 7 - The NEMO data interface

7.1 Scope and background

This chapter describes the strategy related to the observation, assimilation increments and ensembles interface code in NEMO. Comparison of model runs to observations is important for a number of applications including assessment of the model and for input to data assimilation schemes. NEMO contains code (in the OBS module) which reads in observations, interpolates the model values to the observation locations at the nearest time-step during the model run, and outputs the location, time, observation value, equivalent model value and quality control information to a netCDF file. A number of common observation types are currently included. The input observations and output “feedback” information are in the feedback format. Tools are provided for converting some standard observation file formats into feedback format, and for visualising the output feedback information.

Data assimilation systems (external to NEMO) estimate changes to the model state required to bring it closer to the observations, called “increments”. NEMO includes code (in the ASM module) which reads netCDF files containing these increments and adds them instantaneously to the model at the start of the run, or adds them slowly during the run using a method called Incremental Analysis Updates (IAU). The ASM module also contains code to output information on the model grid which is needed for some data assimilation algorithms. The ASM module can also be used by applications other than data assimilation where perturbations to the model’s initial state are needed.

The NEMO-ASSIM working group has been set up to coordinate the work of groups using NEMO in data assimilation systems. Plans for changes to the OBS and ASM modules are discussed with the members of NEMO-ASSIM, and reviewers of code changes are normally expected to come from the NEMO-ASSIM group. The Met Office uses the OBS/ASM interface for data assimilation; CMCC and Mercator-Ocean intend to move towards the use of that interface in the future.

The strategy for the components described in this chapter is related to the strategy described in other chapters. The chapters on sea-ice and biogeochemistry are related as comparison of model counterparts of observations for variables in those model components may also be required, and assimilation increments may need to be applied to variables in those model components. The application of increments dealt with here also relates to the chapter on the model kernel, in the sense that changes to the structure of the kernel may affect the application of the increments. There is also a requirement for user support for aspects of the code dealt with here, particularly for the observation interface. The use of the observation interface and increments application code has not been tested with Agrif, so there is also a link with that chapter.

7.2 The main issues for NEMO strategy related to observations, assimilation increments and ensembles

7.2.1 Maintain assimilation interface code within NEMO

The OBS and ASM modules in NEMO provide a very useful utility for groups running data assimilation systems with NEMO, and other users who wish to compare the model with observations or add changes to the initial state of a model run. Their inclusion within the main NEMO code enables good configuration management of the interfaces, and allows assimilation systems to be applied to new versions of NEMO more easily than if they were outside the main NEMO system. It is therefore recommended that these modules be maintained in future NEMO versions.

7.2.2 Make it easier to include new observation types

Only certain common observation types are currently included in the observation interface code. These are temperature and salinity profiles; velocity profiles; satellite altimeter sea level anomaly data; in situ and swath satellite sea surface temperature data; and satellite sea-ice concentration. There is a requirement to make it easier to add new observation types. In order to facilitate this, code was written at NEMO3.6 which generalised the OBS code so that profile and surface observation types would be dealt with in a more generic manner. It was decided by the NEMO systems team not to implement this code at NEMO3.6, but a branch has been carried forward and it is planned to be implemented in NEMO4.0. Further developments may be required to improve this aspect further. It is planned in the short term to include satellite sea surface salinity data, and this development will provide an opportunity to further improve the generic nature of the OBS code.

7.2.3 Provide examples of input data for running the OBS code.

In order to make it easier for users of NEMO to make use of the observation interface code, some example observation inputs should be made available to users. A SETTE test has been included for OBS which has some example observations, and the NEMO book describes how to convert some existing observation input files to the feedback format required by NEMO. However, there hasn't been much user uptake from modelling groups, so the recommendation is that some more comprehensive examples should be developed.

7.3 Strategy to address the main issues

7.3.1 Maintain assimilation interface code within NEMO

In order to maintain the OBS and ASM modules within NEMO at future versions, there are no specific work items required. The existing SETTE tests should ensure that the code continues to work in future versions. The Met Office plans to maintain these modules to ensure they work in future versions, with inputs from others encouraged. Developments will be agreed with the NEMO-ASSIM working group.

People involved: Matt Martin, Daniel Lea, and members of NEMO-ASSIM working group.

Date for progress: on-going maintenance.

7.3.2 Make it easier to include new observation types

The new simplified version of the OBS code, which was written relative to NEMO3.6 will be implemented in NEMO4.0. Improvements to the code to make it even easier to include new observation types will also be made then. The Met Office plans to make these updates, with review from other NEMO-ASSIM members. Any further improvements to OBS will be implemented as business-as-usual.

People involved: Matt Martin, Daniel Lea.

Date for progress: Dec 2017.

7.3.3 Provide examples of input data for running the OBS code.

In order to encourage modelling groups to use the OBS code to provide inputs for assessment, it is recommended that an end-to-end test case is used, and some examples from that case are then provided with NEMO. Working with the data assimilation group at the Met Office, a model assessment study should be carried out with a modelling group (either in the Met Office or from another group), to demonstrate the use of the OBS code. The experiment design will need to be clarified, input observations provided, and the model run carried out. Utilities for the assessment of the outputs will be developed based on the existing tools provided with NEMO, and any additional tools included in future versions of NEMO. This work is not urgent, but progress during 2018 is expected.

People involved: Matt Martin, Daniel Lea, Tim Graham.

Date for progress: Dec 2018.

7.4 Additional issues:

7.4.1 Allow for satellite observation types where the satellite footprint is larger than the model grid size

The existing code in OBS carries out bi-linear interpolation in the horizontal to estimate the model counterpart of the observations. This method assumes that the observations represent point estimates. Some observation types (particularly satellite data) represent estimates which are spatial averages. The OBS code therefore needs to be updated so that the model equivalent of these satellite footprints can be estimated more accurately. This issue is becoming more important as model grid resolutions become finer.

People involved: Matt Martin.

Date for progress: Dec 2017.

7.4.2 Ensure the profile observation operator deals correctly with general vertical coordinates

The OBS code can be used to estimate the model counterparts of vertical profile observations in model configurations, which have spatially and temporally varying vertical coordinates. Updates were made to make sure the calculations worked correctly with the non-linear free surface and in sigma-coordinate configurations of NEMO. Further assessment and improvements to this aspect of the code should be carried out to address any outstanding issues.

People involved: Robert King.

Date for progress: Dec 2017.

Chapter 8 - The ice component of NEMO

The sea ice strategy is currently under revision (2017-2019), which is why this chapter stands out of this document, and will be revised by 2019.

8.1 Scope

The different ice forms of the marine cryosphere have an important and diverse influence on the ocean (Holland, 2013). Most NEMO applications including at least some polar component must consider the marine cryosphere carefully. Therefore, the development of NEMO involves significant work on the representation of the marine cryosphere.

The marine cryosphere includes **sea ice** and its snow cover, **icebergs**, and **ice-shelves**.

Sea ice is white, reflecting most of the incident solar radiation from space. The formation of ice releases salt to the upper ocean, whereas the melting of the ice releases freshwater, affecting the vertical ocean density structure and inducing a net export of salt to depth. Sea ice also reduces the transfer of atmospheric momentum to the ocean and acts as a physical barrier to the transfer of freshwater, gases and aerosols. There presently are several sea ice components interfaced to NEMO (LIM (as NEMO sea-ice component today), CICE and GELATO), but the sea ice working group recently proposed to move towards a single, **European sea ice model**, sharing the best aspects of the three aforementioned components. The transition to the new NEMO sea ice model will occupy most of the resources from March 2017 until mid-2019, after which a specific strategy will be developed.

Land ice builds up through the accumulation of snowfall over Greenland and Antarctica. Seen from the ocean, land ice takes the form of melting **ice-shelves** at the edge of the continents which, in turn, calve **icebergs** that slowly drift at the ocean surface. Although land ice and sea ice bear some physical similarities, the modelling components to handle them are usually drastically different, because the scales of the problem are fundamentally different.
Icebergs in NEMO are handled through the ICB module and under ice-shelf melt is handled through the ISF module both within the Surface Boundary Condition (SBC) code. Both of these are relatively new developments within NEMO.

The strategy on sea ice is led from a specific working group, whereas the strategy on icebergs and ice-shelves is not specifically addressed, which may promote duplication.

8.2 Sea Ice

The transition towards a European sea ice model and the subsequent long-term strategy for sea ice in NEMO

The choice of the sea ice component varies among the different projects using NEMO. Because of the many duplications that this involves at the expense of scientific activities, the sea ice working group (SIWG) has recommended to merge the different sea ice components into a European community model for sea ice modelling in NEMO, which has been approved by Developer's Committee and endorsed by the Steering Committee. At this stage, the SIWG includes members from Met Office, CNRS, NERC, MERCATOR, CMCC, UCL (Louvain-la-Neuve) and CNRM-

GAME, but this composition will likely evolve.

The development strategy for sea ice has been split into two phases. **Phase 1** contains all the key physics and capabilities required for all groups to be able to use a unified NEMO sea ice model and, at the least, closely approach their current level of sophistication. In practice the development of a new European sea ice model will be achieved by taking the existing LIM3 source code and adding the necessary physics and functionality from the CICE and GELATO models. The transition phase will involve porting the following into the NEMO trunk:

- The C-grid version of the CICE linear remapping scheme (Lipscomb and Hunke, 2004) developed for GELATO
- The JULES surface exchange scheme developed for CICE within HadGEM3 motivated by Best et al., (2004) and described further in West et al., (2016)
- The elastic-anisotropic plastic (EAP) rheology (Wilshinsky et al., 2006) developed by the Centre for Polar Observation and Modelling (CPOM) and implemented in CICE by Tsamados et al., (2013)
- CPOM's Flocco and Feltham (2007) topographic melt-pond scheme implemented in CICE by Flocco et al. (2012)
- CPOM's prognostic form-drag scheme implemented in CICE by Tsamados et al., (2014)

Phase 1 is planned to last until mid-2019. One key requirement for inclusion in phase 1 is that the functionality in question needs to be already fully tested and implemented within one of the existing sea ice model code bases by end summer 2017.

Phase 2 presently contains a wish list for the longer-term development of a communal sea ice model, on which there is no consensus, only open questions. The development strategy will only emerge once Phase 1 is over, by the start of Phase 2 in mid-2019. Hence, by the time of writing this chapter, what can be outlined is only **a provisional skeleton of what needs to be discussed in the framework of the future sea ice prospective exercise**, on the base of which the SIWG will develop the strategy in the next two years. A first preliminary meeting confined to the SIWG is planned to take place in early 2018, and a second one, open to the wider sea ice community, would happen in 2019.

The sea ice sections of this strategy document therefore will be further updated in the course of 2019. Here below, we propose a basis to develop this strategy.

NEMO applications involving sea ice

An important preliminary step to develop a sea ice long-term strategy is to identify the upcoming NEMO applications involving sea ice, which a priori include: global and regional climate projections, forecasts (short-term, seasonal, decadal) and ice-ocean global re-analyses. We should also question whether specific idealised test cases are desired. Scales would roughly span the 1 km (effective) – global range.

An overarching aspect that is not settled is to disentangle what are the key model features that are required for each of these aforementioned applications. The required model ingredients are not fully identified.

Development principles for sea ice in NEMO

We should also agree on a small series of principles that would govern the development of sea ice within NEMO. The following guiding principles were applied to the development of LIM:

- Robustness: the sea ice component needs to be numerically stable and to conserve energy, water and salt.
- Versatility: the sea ice component must be compatible with all NEMO functionalities (BDY, AGRIF, HPC, SAS, …)
  Consistency between ice and ocean: the sea ice is frozen seawater, and as such must be consistent with the ocean code, scientifically (e.g. thermal properties), numerically (C-grid), but also in terms of coding style.
- It is convenient for the sea ice code to be independent of whether the atmospheric component is forced or interactive.
- It is also desirable for the parameters to be roughly independent of resolution, so that as much as possible, no big change in parameters is required when moving from 2° to 1/12°.

Representation of sea ice

The general representation of sea ice that was adopted in CICE, GELATO and LIM follows from the ideas developed during AIDJEX (Coon et al, 1974). This framework is based on a quasi-3D continuum approach, where sea ice processes are split between horizontal dynamics (in particular rheology), vertical halo-thermodynamics and the representation of the subgrid-scale ice thickness distribution. Our long-term strategy would need to be positioned with respect to this framework: should we keep it, improve it or change paradigm?

A few items to be discussed would be to consider the advantages and short-comings of:

- Continuum versus discrete element approaches;
- Lagrangian versus Eulerian approaches;
- Introducing floe size as a prognostic variable in various fashions (mean, maximum, distribution?);
- The present handling of sea ice thickness distribution, in the context of high-resolution simulations;
- Providing simple and computationally cheap sea ice representations for e.g. palaeoclimate applications.

Sea Ice Dynamics

Horizontal dynamics are fundamental to transport ice equator-wards, to dynamical thickening of ice during ridging and rafting, and to open and close leads, which in turn drastically improve the representation of seasonality of sea ice coverage and ice-ocean freshwater & salt exchanges. Among the different terms of the horizontal momentum sea ice equation, the rheology, is dominant in most cases, and it is accepted that the viscous plastic (VP) family of rheologies has the best performances today (Kreyscher et al, 2001). The CICE, GELATO, and LIM codes are all based on the elastic-viscous plastic (EVP) approach of Hunke and Dukowicz (1997), which satisfactorily resolves the horizontal sea ice velocity.

Recent works by Weiss and co-authors have stressed that the evaluation of **sea ice rheologies** should not only consider velocity but also deformation, in particular the scaling laws and intermittency properties of deformation. The ability of VP/EVP to represent these last two metrics has been questioned or confirmed depending on authors, which has been used as a basis to revisit or propose new approaches for sea ice rheology. These include, among others, the elasto-brittle (EB: Rampal et al., 2016), Maxwell Elasto-Brittle (MEB: Dansereau et al., 2016), elastic-anisotropic plastic (EAP: Wilchinsky et al., 2006; Tsamados et al., 2013) and the improvement of VP-solvers (Lemieux et al., 2014). These different approaches are potential futures for NEMO and should carefully be examined in terms of physics and numerics. The EAP rheology should be implemented in Phase 1 and there already are ongoing developments on the MEB.

Another important criterion to account for is the formation of **land-fast** sea ice (the immobile sea ice fastened to coasts). Adding a basal stress term helps to generate a large part of Arctic land-fast sea ice regions, where the ice is attached to the ocean floor (Lemieux et al., 2016), but this does not fully work everywhere, in particular where land-fast sea ice is not grounded but presumably driven by the formation of ice arches, where adding tensile strength or increasing shear strength can help. How land-fast ice is captured by all rheological formulations is an active topic of research. There is a bottom stress option in the current code, but this need to be proofed scientifically.

The **ridging-rafting schemes** and the **ice strength formulations** could also be re-evaluated and questioned. Recent research (Ungermann et al., 2017) suggests that the Rothrock (1975) ice strength formulation systematically deteriorates model results and could be dropped out. The functional dependence of ice strength on brine volume available in NEMO should be tested as well.

Regarding **the horizontal advection scheme**, the different options available from CICE, GELATO and LIM (Prather, UM5, linear remapping) should be compared and assessed in terms of precision, cost and compatibility. Based on this evaluation, a recommendation on what should be kept in the model should be done. Prather and UM5 are already in the code, whereas linear remapping (Lipscomb and Hunke, 2004) in C-grid should be implemented during Phase 1.

Sea ice thermodynamics

Ice thermodynamics are the fundamental core of a sea ice model, deciding how sea ice grows and melts as a function of forcing and ice properties. In the early times, thermodynamic processes solely referred to sea ice growth and melt. Nowadays, with the increase in complexity of sea ice models, thermodynamic processes refer to a wider range of processes. LIM and GELATO were pretty close in terms of thermodynamics, whereas CICE had somehow more advanced and diverse options for sea ice thermodynamics.

At the base of sea ice thermodynamics is the **enthalpy equation**, an equivalent to the state equation for seawater, which non-linearly relates the internal energy to the sea ice state variables, namely salinity and temperature. CICE, GELATO and LIM all base on the Bitz and Lipscomb (1999) formulation as a function of S and T, which considers brine inclusions, assuming constant ice density, gas-free ice and linear liquids. Whether these hypotheses should be re-considered should be examined. We also may consider, if useful, to offer the possibility to activate the Semtner (1976) 0-layer approach, with pure ice and no sensible heat storage. The enthalpy equation decides the form of the **heat diffusion** equation, and affects how all thermodynamic sea ice processes can be parameterized. Introducing **air fraction** as an additional state variable could be considered, as it would enable to treat snow with varying density, together with sea ice within a single framework.

Next to temperature, salinity is the other important state variable and is driven by **brine uptake and drainage** processes. LIM and GELATO treat bulk salinity as with an empirical equation and retrieve a salinity profile as a function of the bulk salinity. The most advanced CICE version solves a vertical salt dynamics equation (Turner et al., 2015). There are several approaches to treat brine dynamics available in the literature (Vancoppenolle et al., 2010; Griewank and Notz, 2013; Rees-Jones and Worster, 2015, Turner et al., 2015). These are potential future directions for NEMO and should be carefully examined to find the most suitable choice.

Radiative transfer affects the rate of internal warming and the light supply to the upper ocean - with impacts on ice algal and under-ice phytoplankton communities. Radiative transfer is traditionally formulated based on the exponential decay of light on its way downwards (**Beer-Lambert law**), which is what is presently done in LIM and GELATO. In such schemes, the attenuation coefficients and surface transmission coefficients are specified and the albedo must be parameterised, which is done as a function of surface state (ice thickness, snow depth, surface temperature, melt ponds). In CICE, a two-stream **Delta-Eddington** scheme has been implemented. Such schemes are a priori much better suited for scattering media such as snow and ice and require the specification of the absorption and scattering coefficients, whereas the albedo derives directly from upwelling and downwelling radiation fluxes, which reduces empiricism. A final aspect to consider is the connection between subgrid-scale distribution of surface properties (snow depth, ice thickness, melt ponds) that many field studies underline as important. Recent under-ice observations provide new opportunities to evaluate these two general types of schemes, objectify how they perform and help the selection of the best choice, if any.

The representation of surface characteristics such as snow depth and melt ponds have a significant impact on the surface albedo. **Snow on sea ice** suffers from the paucity of reliable large-scale observations. Ideally, snow density profile should be prognostic and should be used to compute thermal conductivity and optical parameters. Yet snow on sea ice is highly complex and spatially variable. Lecomte et al. (2011, 2013) show that multiple layers improve the representation of temperature and propose a simple treatment of vertical density variations, both are to be rewritten for inclusion in the sea ice code. Another approach to consider is to take a snow model from the shelf, such as CROCUS (Vionnet et al., 2012) and to adapt it to sea ice.

Melt ponds. Several model representations for melt ponds on sea ice have been proposed. Level-ice melt ponds fill up ponds with surface melt water and prescribe a depth-area ratio. Ponds cannot expand beyond level ice area, which limit their horizontal extent. Such a scheme has been implemented in GELATO and CICE. The topographic melt pond parameterization developed for CICE (Flocco and Feltham, 2007) and implemented in NEMO during Phase 1 progressively fills up the sea ice thickness category with surface melt-water. Potential progress regarding the representation of melt ponds includes modelling the latent heat impact of melt-water refreezing and consideration of the melt ponds within the vertical thermodynamic solver.

Ice-ocean and ice-atmosphere interfaces

Interfaces of sea ice with atmosphere and ocean are another important aspect to consider. Evolving on interfaces often involves work in the sea ice component and as well as work in the corresponding atmosphere/ocean component.

The ice-ocean interface. Using the **three-equation** approach (McPhee et al., 2008; McPhee, 2008) to represent ice-ocean heat and salt exchanges and their coupling with the freezing point would enable to better resolve the fresh layers below sea ice in summer. Ice state-dependent skin and form **ice-ocean drag coefficient** formulations for momentum transfer have been proposed by Tsamados et al. (2014) and should be implemented during Phase 1. These go together with the introduction of level / ridged ice tracers and a semi-implicit treatment of the ice-ocean stress in the ocean component. The capacities of bi- or multi-column ocean physics, soon available in the trunk, should also be re-evaluated. We should also consider to implement a standalone slab or mixed-layer ocean through SAS.

The ice-atmosphere interface. State dependent ice-atmosphere drag coefficients of Tsamados et al (2014) should be introduced during Phase 1, next to the Lüpkes et al. (2012) Lüpkes and Gryani (2015) already available today. Proposing alternative coupling fields and methods will start during Phase 1 with the introduction of the method of West et al (2016) and should be further examined.

Recent works have introduced **sea ice-wave coupling** and we should call experts of the domain to examine which of this need to be retained as far as sea ice is concerned. It seems clear that a representation of floe size and floe breaking must be introduced, to introduce the key dependence of wave attenuation on floe size. More exotic effects, such as pancake ice growth, or impacts on ice-ocean heat and momentum transfer will also be considered.

Sea Ice Biogeochemistry

The first step to introduce biogeochemical tracers is to introduce a **generic tracer interface**, in the line of TOP for the ocean, using a single tracer array and various tracer statuses (dissolved, particle, volumetric, areal, …).

Recent modelling work has provided means to simulate various aspects of **sea ice**

biogeochemistry. A first step would be to introduce a simplified skeletal layer NPD model for living and detrital organic carbon and nutrients, following the works of Hayashida et al in Canada, based on Lavoie et al. (2005) approach. A second step would be to generalize this approach to multiple layers and couple that with brine dynamics and radiation, as done in the 1D model of Vancoppenolle and Tedesco (2017). Further steps could be to improve the carbon budget (Moreau et al 2015) or iron dynamics (J. Janssens Phd thesis).

8.3 Icebergs

The iceberg scheme in NEMO is described in Marsh et al. (2015). The scheme is relatively new and there are a number of areas for potential future development – many identified within Marsh et al. (2015). These include the following:

- No interaction between icebergs and near-surface winds
- No interaction between icebergs and sea ice (including fast-ice)
- No interaction between icebergs and shallow bathymetry (including iceberg grounding)
- Advection of icebergs only uses surface ocean current rather than using vertically integrated ocean velocity over the full iceberg draft
- Iceberg melting only dependent on SST rather than using temperature over thickness/depth of iceberg

Let us also note that icebergs are at this stage not compatible with AGRIF. In addition, once the coupling interface with continental ice sheets is done, icebergs should ideally carry a temperature-dependent enthalpy, for heat to be conserved.

There are currently no plans to develop the iceberg scheme further with regard to the above functionalities. The relative importance of each of these processes will need to be better understood before such work is undertaken.

8.4 Ice-shelves

Ice-shelf functionality in NEMO is a relatively recent development and is described in Mathiot et al. (2017). At present the functionality exists to model the ocean within ice shelf cavities of fixed size with interactive melt determined by ocean temperatures. There is also additional functionality to use prescribed ice-shelf melt and to run with closed cavities with melt water added at depth along the mouth of the ice-shelf cavity.

Planned improvements to the ice-shelf module include:

- Adaption of the ice-shelf cavities to use terrain-following (sigma/s) coordinates
- Improved coupling to continental ice sheet models
- Modifications to NEMO to allow the sub-surface geometry of the ice-shelf cavity to vary in time – in a manner that is computationally robust and conserves energy, salt, and mass
- Allowing grounding-line movement to simulating the retreat or advance of ice-shelves (possibly making use of the NEMO wetting and drying scheme developed for use in tidal estuaries)

Further developments to the ice-shelf functionality that are not yet planned within the NEMO consortium include:

- Allowing changes to the surface geometry including the calving point and the land-sea mask
- Use of realistic calving schemes in the continental ice-sheet models as inputs to the iceberg module

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Chapter 9 – Air sea interactions and boundary layers

9.1 Scope

Gravity-driven tidal forces (and geothermal flux) put aside, the circulation of the ocean is entirely driven (directly or indirectly) by the exchanges of momentum and buoyancy (heat + freshwater) with the atmosphere.

The turbulent components of these air-sea fluxes, namely the wind stress, evaporation and sensible heat flux are dependent on both the sea surface state (SST and the "aerodynamic roughness") and the near surface atmospheric parameters such as the wind, humidity and temperature.

Other air-sea fluxes include the radiative components of the heat flux (solar and longwave) and precipitation. The net solar flux to the ocean, and its penetration in the water column, depend on the surface albedo (that depends on whitecapping and so on breaking waves) and the turbidity of the surface layer (that depends on phytoplankton). The net radiative longwave flux depends on the SST through its upward contribution. Precipitation is therefore the only air-sea flux that can be considered independent of the surface ocean and atmospheric state.

In order to better represent these exchanges of momentum, heat and freshwater between the ocean and the atmosphere, and to capture the complex coupling between the ocean and atmospheric boundary layers, and thereby to improve the forcing of NEMO, attention is focused on four different fronts:

- A/ more realistic representation of the coupling between the atmospheric boundary layer (hereafter ABL) and the ocean surface boundary layer (hereafter OSBL); e.g. the action of the ABL on the OSBL, and the response of the ABL to the evolving prognostic ocean surface properties, must be better accounted for.
- B/ better representation of subgrid-scale vertical physics through improved turbulence closures in the OSBL and below.
- C/ more accurate estimation of turbulent air-sea fluxes through the use of more sophisticated bulk algorithms/parameterizations to compute exchange coefficients in use in bulk formulae (i.e. consideration of wave information, skin temperature, salinity, etc.)

- D/ include representation of relevant wave-current interaction processes

Note: all these aspects are strongly interconnected / interdependent to one another, and the inclusion of wave prognostics/diagnostics would benefit each of them.

9.2 Main issues

9.2.1 Representation of the ABL

Background

Recent studies have highlighted the substantial thermal and dynamical coupling that exists between the sea-surface and the ABL, typically at horizontal scales corresponding to ocean mesoscale eddies (Oerder et al., 2016; Renault et al., 2016; Chelton, 2013; Frenger et al., 2013). SST fronts and (sub)mesoscale SST anomalies (such as in old/warm eddies) can have a non negligible impact on the surface wind field, and hence, in return, on the surface wind stress that modifies, sustains or weakens these fronts/anomalies in the ocean. This highlights the ability of the ocean to impact on its own atmospheric small-scale forcing. To be able to capture this type of interactive coupling between the wind stress and the SST, the horizontal resolution at which the ABL is represented must be roughly the same as that of the ocean (the height of the ABL must also be free).

Benefits and improvements from having an interactive ABL coupled to an OGCM are various:

- better representation of surface currents and the mixed-layer
- forcing of the tropical dynamics (e.g. better initialization of seasonal forecasts)
- consideration of wind-SST interactions (e.g. impact on biogeochemistry)

Issue

Currently, in NEMO, the action of the ABL onto the ocean is crudely represented through the use of the traditional bulk approach. As such, surface fluxes are computed based on prescribed near-surface air properties, obtained from reanalyses or NWP operational data, and the prognostic SST of NEMO. This bulk approach is showing its limits for a variety of reasons:

- The ABL has an infinite heat and moisture capacity
- The ABL, and in particular surface winds, are not influenced by the (sub)mesoscale SST oceanic features (fronts, eddies), this becomes a problem as the horizontal resolution of NEMO keeps on increasing
- Underestimation of the thermal coupling (absence of downward mixing)
- Overestimation of the dynamic coupling (absence of re- energization by the atmosphere)
- Atmospheric data is generally too coarse w.r.t. the horizontal resolution at which NEMO is run

The bulk approach has been the default "ocean-only" forcing approach used in NEMO for more than a decade. Moreover, the bulk algorithm/parameterization used to estimate the transfer coefficients has not evolved at all during the last decade: it is the NCAR algorithm of Large & Yeager developed for CORE (2004, 2009).

9.2.2 Wave-mixed layer interactions

Background

In order to improve the prediction of sea-state estimates, reducing errors due to unresolved nonlinear feedbacks between currents and waves that affect the oceanic circulation (also on shelf and coastal waters) as well as the sea level, mixing, bottom stress, surface temperature, and upwelling, a series of issues are considered.

Wave-current interaction processes influence the momentum and energy exchange between the atmosphere and the ocean and within the OSBL. Enabling NEMO to explicitly include the effect of waves will provide an improved forecast of the upper ocean dynamics since most of the wind energy and momentum are first transferred to waves, and are then indirectly passed to the ocean, and also because the wave induced currents (Stokes drift), although rapidly attenuated with depth, strongly affect the currents in the surface ocean.

The NEMO-WAVE Working Group was established in 2013 to identify required actions and model developments related to Atmosphere-Wave-Ocean exchanges processes and their roles in driving the ocean circulation at both coastal and global scales.

The WAVE WG decided to follow the “vortex force” (VF – Ardhuin et al., 2008) formalism presenting a more rigorous mathematical derivation and a larger range of applicability than the “radiation stress” (RS – Mellor 2011) formulations and has produced a code implementation of meso-to large-scale processes including:

- Use of the neutral drag coefficient evaluated from the wave model
- Computation of vertical profiles of Stokes Drift according to Breivik et al. (2014)
- Computation of the Stokes-Coriolis Force
- Generalization of the surface boundary condition for momentum accounting for the wave effects
- Wave enhanced vertical turbulence: implement the Qiao (2010) formulation as an option
- Inclusion of the Stokes drift components in the tracer advection term

Wave fields can be obtained in FORCED mode or in COUPLED mode through OASIS.

In order to improve the prediction of sea-state estimates, reducing errors due to unresolved nonlinear feedbacks between currents and waves that affect the oceanic circulation (also on shelf and coastal waters) as well as the sea level, mixing, bottom stress, surface temperature, and upwelling, a series of issues are considered.

Issue 1

Improve and consolidate the surface wave coupling development already included in NEMO, related to meso-large scale wave-current interaction processes following the vortex force representation in the momentum equation. This implies: an improved Stokes-Drift profile computation, an improvement of the representation of the enhanced mixing due to wave breaking and the addition of a better Langmuir turbulence parameterization (see section 9.2.3).

Issue 2

Include coupling with sea-ice and with icebergs. There is a large variety of sea ice states: frazil & pancakes, floes broken by waves, near-continuous pack ice (with floes much larger than the wavelengths). At present there is no seamless parameterization that covers all, and the general questions are:

- The attenuation rate of waves (e.g. Kohout et al. 2014, Rogers et al. 2016, Ardhuin et al. 2016)
- Under-ice and near-ice mixing (this is a wave-ice-ocean-atmosphere coupled problem with multiple scales from a single floe, to current jets, and wind stress gradients that force near-inertial motions)
- The breakup of ice floes by waves
- The consequences on dynamics (rheology) and thermodynamics (freeze / melt) of having fractured ice in the MIZ

Issue 3

Providing a standard for the exchange of fields between wave models and NEMO will be beneficial since several wave models are being used for this (WaveWatch III, WAM and ECMWF's version of WAM). It is important to define the exchange of fields in order to allow various wave models to provide forcing to NEMO. It is also important to know of relative biases of the different models for the different exchange parameters.

Issue 4

Conduct a second phase of model development to include wave effects at small and coastal scale in order to achieve a full wave coupling in NEMO. To achieve this objective, a series of processes should be investigated and additional terms should be included in the momentum equation.

9.2.3 Improving the vertical turbulence closure in the OSBL

Background

The sub-grid parameterization is considered in order to improve the representation of the physical processes taking place in the upper ocean influencing the transfer of momentum and tracers between the atmosphere and ocean interior. Here the focus is on the role that surface waves and Langmuir turbulence play in setting upper ocean stratification. The energy flux by surface wave breaking affects the upper-ocean mixing up to a depth of the order of the wave height. Work against the shear in the Stokes drift generates Langmuir turbulence that can penetrate down up to a depth about ten times the typical wavelength of the wave field.

Different approaches to represent sub-grid scale turbulence are available. However, offering too many options may give rise to an excessive maintenance load, so the number of different implementations needs to be limited.

Issue 1

The CVmix software repository in the US provides a suite of Fortran vertical mixing parameterizations for use in numerical ocean models. This might allow diversity (e.g. KPP, Hallberg) without too high a maintenance cost, but this approach may not be computationally efficient.

Depending on the computational efficiency of the CVmix interface, there is the need also to have a number of fully coupled NEMO vertical-mixing modules. Should these include TKE, GLS and possibly the OSMOSIS-OBL scheme?

Issue 2
There is a need to provide wave information for OSBL schemes such as CVmix-KPP and OSMOSIS-OBL that can benefit from it.

Issue 3
How can the OSBL models be combined with the energy-budget-aware models of internal waves driving thermocline and deep mixing that are being developed?

Issue 4
The ice-covered OSBL: do we require subgrid-scale physics to represent the effects of leads, ice inhomogeneity etc.? How far do we need to go in coupling waves and ice?

9.2.4 Turbulent air-sea fluxes via bulk formulae

Background
Regardless of the approach chosen to mimic the action and response of the ABL on/to the OSBL (9.2.1), turbulent air-sea fluxes (hereafter TASF) have to be estimated by means of the bulk formulae. As such, improvement of the bulk formulae would not only benefit the current traditional bulk forcing approach, but all potential approaches chosen to replace the traditional bulk approach.

Until the merge-party 2016, the NCAR algorithm of Large & Yeager (2004, 2009) was the only option, with the so-called "sbcblk_core" interface. This NCAR bulk parameterization is less sophisticated than for instance the COARE (3.0, 3.5 and soon 4.0) and ECMWF parametrizations (Brodeau et al. 2017). The COARE and ECMWF parameterizations were coded from scratch in a NEMO-friendly way and tested in the framework of the AeroBulk[1] initiative (Brodeau et al. 2017) and are now available in the new generalized bulk interface "sbcblk" of the code as alternative to the old NCAR parameterization (trunk version). This new "sbcblk" interface also includes various refinements of the generic bulk formulae.

Issue

TASF estimated with the COARE and ECMWF bulk parameterizations need to be made more realistic thanks to:

- Consideration of the cool skin and warm layer effects (rather than the bulk SST)
- Use of wave information (e.g. sea surface roughness) in the estimation of the bulk transfer coefficients.

9.3 Plan for issues development

9.3.1 Representation of the ABL
Currently, two types of forcing approaches that can guarantee a coupling between the ABL and the OSBL have been identified:

- Coupling to a simplified ABL model (approach 1)

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[1] https://github.com/brodeau/aerobulk

- Coupling to a full AGCM driven via spectral nudging (approach 2)

These two approaches are retained because they are both compatible with the requirements identified as important for forcing NEMO. These requirements are:

- Allow properties in the lower region of the ABL to vary with the prognostic sea surface properties (mainly the SST)
- Conserve the ability to force the ocean and perform hindcasts, e.g. by taking advantage of atmospheric reanalysis and operational analysis data. In this respect, reanalyses should provide:
    - Approach 1 & 2: *upper boundary conditions* or *spectral nudging reference* at a given altitude above the ABL (typically above 1000m)
    - Approach 1: non turbulent air-sea fluxes such as radiative heat fluxes at the surface and precipitation
- Use a horizontal resolution comparable to that of the ocean in the ABL

Approach 1 (ABL model)

Concept: couple NEMO to a simplified model of the marine ABL which allows representation of key processes associated with air/sea interactions at the characteristic scales of the oceanic mesoscale.

- Dynamical downscaling through a simplified ABL model run on the same horizontal grid as NEMO
- Driven from above (top of ABL) by reanalysis data
- Thickness of ABL is variable (allows proper wind-stress - SST interaction, which is not the case in CheapAML (Deremble et al., 2013))
- Radiation, clouds, precipitation prescribed from reanalysis data (“transparent ABL”)

Such an ABL model, SIMBAD[2], is currently being developed in the framework of the ALBATROS project (Mercator Ocean, CNRM, Inria, CNRS). SIMBAD is meant to be a model of intermediate complexity between the traditional bulk forcing approach and a full three-dimensional atmospheric model (approach 2). It is currently being developed and tested at different levels of complexity:

- 1D approach: mono-column. A one-dimensional version of SIMBAD forced by large-scale atmospheric real-time data from ECMWF operational models has been integrated into the NEMO surface module and appropriate preprocessing tools have been developed. Increase in numerical cost w.r.t. NEMO alone is 8% (Lemarié, personal communication).
- "Approach N+1", multi-column (considerations of sea-ice, open ocean, leads, ice categories, etc.)
- "Approach N+2", full 3D (advection lat., etc.)

It is important to emphasize that the future success of this type of approach, will be partly linked to the numerical/scaling performance of this type of ABL model. In particular, the relative numerical cost of the ABL model should remain "small" w.r.t. the cost of a full AGCM and NEMO.

Pros:
A coupled and "drivable" ocean-ABL system, without paying the cost of a full AGCM.
Atmospheric forcing at the same horizontal scale as that of the ocean (no coupler needed)
Same grid as NEMO □no coupler-related issues, exact conservation
Cons:
Full adequacy of the approach to perform ocean hindcasts has yet to be demonstrated

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[2] SIMplified Boundary Atmospheric layer moDel for ocean modeling purposes

Approach 2 (coupled to AGCM with spectral nudging)

NEMO is coupled to a given AGCM via a coupler, typically in the same way as it is done in already existing CMIP-type of climate models (EC-Earth IFS, MetOffice HadGEM3, IPSL LMDZ, CNRM Arpège, etc). The main difference is that large-scale horizontal features of the atmospheric circulation in the AGCM are restored to their reanalysis data counterparts above the ABL. Typically at horizontal synoptic scales and above, hence the designation of spectral nudging, a it allows smaller-scale atmospheric circulation features to remain "free".

Note: the cost of coupling to an AGCM is still considered prohibitive in the context of performing ocean hindcasts and forecasts, which has been encouraging the exploration of the feasibility of approaches such as approach (ii). However, recent numbers from fully coupled simulations with EC-Earth (NEMO coupled to IFS of ECMWF) at various horizontal resolutions suggest that the relative cost of the atmospheric component, with respect to the total cost, decreases as the horizontal resolution of the coupled system increases. As such, in recent simulations with EC-Earth ORCA12-T1279 (~15km global in the ocean and the atmosphere) the relative cost of IFS (without spectral nudging) is 40% (L. Brodeau, personal communication).

Pros:
The full coupled system!
Only the spectral nudging to implement, which is already a feature available in most AGCMs
Cons:
Radiation, clouds, precipitations are “too free” + known coupled model biases likely to emerge...
Coupling, conservation issues, interpolation-coupler...
Cost ? (constraint of similar resolution in ocean and atmosphere components)

The NEMO Working group in charge of these subjects will propose the approach by end 2017.

9.3.2 Wave-Current interactions

Issue 1

In order to improve and consolidate the surface wave coupling development already included in NEMO at meso-large scale some code improvements are needed. The work has been discussed within the WAVE WG and includes:

- Add the new vertical profile formulation from Breivik et al., 2016 to the present one (Breivik et al., 2014) and provide it as a namelist option. This option will be included in 1 year.
- Enhanced mixing due to wave breaking. The Qiao 2010 formulation already implemented will be possibly maintained and a modification involving the flux (rather than a surface value) of turbulent kinetic energy from breaking waves in the TKE scheme will be included. This work will be included in 2 years.
- Langmuir turbulence parameterization (see section 9.3.3)

Issue 2

Include coupling with sea-ice and with icebergs. Some work is in progress considering the analysis of the waves impact on sea ice and upper ocean and the implementation of the collisional sea ice rheology along with floe size distribution evolution. This issue requires further specific discussions and more than 2 years time to be addressed.

Issue 3

A coupling interface between NEMO and WWIII model is available and provided through OASIS. A standard for the exchange of fields between wave models and NEMO will be considered in order to allow a range of wave models to provide forcing to NEMO.

Issue 4

In order to include wave effects at small and coastal scale and to achieve a full wave coupling in NEMO, a series of model developments have to be considered. This includes: the vortex force term, the sink of wave momentum due to bottom friction, and the force linked to the wave induced mean pressure. Further discussions within the WAVE WG and external experts are needed to start the model developments that will be carried out after the finalization of issues related to large-meso scale wave-current interaction processes, vertical mixing enhancement due to waves and wave-ice interaction.

9.3.3 Improvement of vertical turbulence closures in the OSBL

Issue 1

Following the need to reduce the number of mixing schemes but taking in consideration that this is an important part of the code, the strategy is to select two fully-coupled schemes: the KPP-OSMOSIS which is an opportunity to showcase a scheme where Europe is leading, and a GLS module that can be specified in the namelist to run as a simple TKE model.
A NEMO interface to CVmix will also be written so that a wider variety of externally maintained schemes can also be run.

Issue 2

Much of the code to permit wave information (such as fields of Stokes drift) to be passed to vertical mixing modules such as OSMOSIS-OBL and CVmix-KPP is now in trunk, but there is a need to make wave data fields available that are as consistent as possible with the other forcing.

Issue 3

Links will be developed with the German team working on the IDEMIX scheme.

Issue 4

In order to address the different issues it is suggested to create an “investigation team” involving experts on waves, ice and ocean.

9.3.4 Turbulent air-sea fluxes via bulk formulae

Implement the use of the warm-layer and cool-skin parameterizations (skin temperature) in the computation of surface heat fluxes (latent, longwave upward, and sensible) with the COARE and ECMWF algorithms. These warm-layer and cool-skin parameterizations are already coded, tested and validated in AeroBulk (Brodeau et al., 2017). [Brodeau & Madec have volunteered to do this.]

Wait to know more about the strategy of the "wave implementation" (see 9.3.2) to know what type of wave information should be used to improve the the estimations of bulk transfer coefficients (CD, CE and CH) within the bulk parameterizations.

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Chapter 10 – The biogeochemical component of NEMO

TOP interface for tracers and biogeochemistry

10.1 Scope

TOP (Tracers in the Ocean Paradigm) is the NEMO interface that provides the physical constraints and boundaries conditions for oceanic passive tracers transport. It also handles a seamless, hardwired coupling with biogeochemical (BGC) models.

In this chapter the NEMO-TOP evolution is addressed by considering the need i) to improve the orthogonality between physical processes and oceanic tracers dynamics, ii) to consolidate the modularity of the interface sub-components and iii) to foster the code readiness to handle future evolution of biogeochemical models (e.g., interactive benthic and sea-ice biogeochemical models, increased number of pelagic tracers).

The description of overlapping issues between TOP and other NEMO components is detailed within the specific chapters. In a nutshell, these will focus on the efficient implementation of computational algorithms (Chapter 3), a flexible method to adapt grid resolution over the oceanic domain (Chapter 6), and the interface with the forthcoming sea-ice model (Chapter 8).

10.2 Main issues

10.2.1 Tracers vertical sinking

Despite the large variety of advection and diffusion schemes made available through the OPA engine, the current NEMO code is still lacking a general scheme to deal with the vertical sinking of tracers in the pelagic environment. This is a key physical process that directly affects the spatio-temporal distribution of particulate suspended matter and the dynamics of phytoplanktonic groups, like e.g. diatoms. Among the large ensemble of approaches available from literature (Yool et al., 2013; Aumont et al, 2015; Vichi et al., 2015; Buthenschön et al., 2016) it is here necessary to identify the most suitable and up-to-date scheme to be included in TOP that will ensure an adequate balance between accuracy and computational efficiency. Furthermore, current schemes are mainly derived from typical advection schemes that were developed to handle transport by fluids. The potentially very high sinking speeds of particles (which can reach hundreds of meters per day) puts very high constraints on the timestep to respect the CFL criterion, especially where the vertical resolution is very high. To circumvent this constraint, time-splitting methods have been adopted by some biogeochemical models embedded in NEMO (Aumont et al., 2015). Yet, this can become very CPU intensive. Alternative solutions have been proposed in other modeling systems such as CROCO. These solutions will be investigated with care and if satisfying, the most appropriate one will be implemented in TOP.

10.2.2 Vertical light penetration scheme

Vertical penetration of visible light depends on the optical properties of seawater. It is mainly controlled by the content in pigments (i.e., chlorophyll), colored dissolved substances and particles. Computation of the vertical attenuation of light is required for the upper heat budget of the ocean and by various biogeochemical processes, the most well known being photosynthesis by phytoplankton (but all photochemical processes depend on the amount of light). Currently, in NEMO, modules performing this computation are developed separately for each biogeochemical model as well as in the dynamical core of NEMO (Lengaigne et al., 2007; Hernandez et al., 2017). The development of a standalone module to compute the vertical distribution of shortwave radiation (including visible light) would help rationalizing the treatment of light and would avoid the existence of multiple, sometimes redundant, modules. Furthermore, it will be useful for scientists interested in modeling photochemical processes in new biogeochemical schemes.

10.2.3 Carbonate System module (CSM)

The pelagic carbonate system has become a pillar of ocean sciences spreading from the biogeochemistry up to the climate studies through Earth System Models. In the last decade a strong effort was spent in the consolidation of scientific and modelling knowledges (Zeebe and Wolf-Gladrow, 2001; Dickson 2007; Orr et al., 2015) and, nowadays, a generalized and common approach for carbonate system simulation is well established (Orr et al., 2016). The inclusion of a state-of-the-art standalone module for the pelagic carbonate system in NEMO-TOP represents a community-based evolution of the interface and it will offer an easy-to-use tool for ocean scientists who want to deal with the CO2 problem.

10.2.4 Air-sea gas exchange module

At present, the different modules of TOP interface dealing with both inert chemistry components (e.g., CFCs, SF6) and biogeochemistry (mainly oxygen and CO2) use internally defined routines to solve the air-sea gas exchange. Given the wide variety of inert tracers used to perform the tracking of water masses and deep ocean ventilation studies, the development of a common air-sea gas transfer scheme (see e.g., Orr et al., 2016) will generalise the workflow of TOP existing modules, by ensuring also an easier maintenance of the code. In addition, this will simplify the inclusion of new inert chemistry tracers and the coupling with biogeochemical models.

10.2.5 Implementation of new BGC components

The overall structure of TOP is focused on the marine pelagic component (arrays for state variables, time integration, etc.) and only few elements are available to enable the treatment of additional dynamical components. Given the emerging interest in modelling both benthic (Capet et al. 2013) and sea-ice (Tedesco and Vichi, 2014) systems, the implementation of a new set of generalized routines to facilitate the coupling with complex biogeochemical models is a strategic issue. This will be achieved by following the modular layout available for the pelagic system, by including for these components the definition of 2D/3D state variables, time integration schemes, and I/O handling.

10.2.6 Implementation within PISCES biogeochemical model

Since PISCES is the marine biogeochemical model embedded in NEMO, this model will serve as a basis to test and validate the developments described in this chapter as well as in others chapters (see section 10.1). This task will require to modify the architecture of PISCES to redefine its perimeter : Currently, the modules that are planned to become part of NEMO-TOP are embedded within PISCES. Furthermore, Task 10.2.5 plans to implement a set of generalized routines to couple new BGC components with NEMO. This includes benthic models. Such a benthic model is already existing within PISCES and will be used as a basis to develop and validate the generalized routines. As for the oceanic part of PISCES, this activity will require to redefine the architecture of the sediment module of PISCES and its interfaces within NEMO.

10.3 Plan for issues development

The development of previously described issues is here addressed by including the prioritization over the NDS time window, the expected person(s) in charge of each activity, and a brief summary of the technical implementation to be done.

Tracers vertical sinking (10.2.1)	
Priority	High
Responsible	TOP Discussion Group
Technical	Collect informations on available sinking schemes; evaluate costs and efficiency of implementation within NEMO; build a generalized and flexible routine to provide sinking for tracers.

Vertical light penetration scheme (10.2.2)	
Priority	Moderate
Responsible	TOP Discussion Group
Technical	Collect informations on available light penetration schemes; evaluate costs and efficiency of implementation within NEMO; build a generalized and flexible routine to provide optical properties of the water column and light propagation.

Carbonate System module (10.2.3)	
Priority	Moderate
Responsible	TOP Discussion Group
Technical	Adopt the CMIP6 exercise consensus on best practices for carbonate system solution; implement carbonate system routines following the general modular approach; design an easy-to-plug memory interface for biogeochemical models.

Air-sea gas exchange module (10.2.4)	
Priority	Moderate
Responsible	TOP Discussion Group & External experts
Technical	Evaluate available approaches for defining the air-sea gas exchanges; create a data module containing the required set of parameters to simplify maintenance.

Implementation of new BGC components (10.2.5)	
Priority	Low
Responsible	TOP Discussion Group & External experts
Technical	Implementation within the MY_TRC template/demonstrator; select best way to activate memory layout for sea-ice and benthic system; create 2D (or 3D) memory arrays and time integration subroutines; develop I/O support; create a test case for general coupling.

Implementation within PISCES BG model (10.2.6)	
Priority	High
Responsible	TOP Discussion Group & Christian Ethé
Technical	Modify the architecture of PISCES to account for the new modules planned in this chapter. Test and validate the planned activities with PISCES.

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Chapter 11 – NEMO validation and range of user support

11.1 Outline

The NEMO system team is a team of developers mostly employed by the various consortium members. Its work is focused on NEMO platform development with the following remit:

- To adopt changes and improvements in natural (ocean) and computer sciences
- To prepare for future changes by the simplification and redesign of key modules and algorithms.
- To use sustainable development methodologies which ensure quality control and traceability
- To fix reported bugs and keep documentation (reference manual, wiki pages, code comments) up to date.

The core of the team consists of the NEMO officers from each consortium member and therefore has not grown significantly in size despite a growing user base.

Maintaining a wide user base for NEMO remains a priority because of the many benefits to both the consortium and wider community including:

- Maintaining a high level of awareness of NEMO in the community and amongst funding

agencies
- Enabling community-based testing of new releases.
- Developing new scientific options in advance of consortium needs
- Providing collaborative opportunities for consortium members

However, the user base, outside the consortium organisations, is not tied to NEMO and will use NEMO only when there are clear advantages in terms of ease of use, reliability, robustness, scientific capability, and efficiency. Much system team effort is concentrated on the last four categories but it is the first two that are essential to attracting and retaining new users.

This chapter summarises the discussions that have taken place during the perspective process regarding the targeted range of user support and the proposals for providing this in the future. Firstly, the related topic of model validation is discussed together with the future role and nature of the reference configurations. It should be noted, however, that an active user base places demands and expectations on the consortium-based development team that often conflict with consortium priorities.

11.2.1 Validation

The NEMO development process is formalised into 5 phases designed to maintain quality and reliability of developments. Briefly, these phases are:

1. Description in the yearly work-plan
2. Implementation plan and preview
3. Coding and validation
4. Review
5. Merge into the NEMO reference

Adhering to this process requires more time and effort than individual developments for one-off purposes but greatly reduces the possibility of unintended side-effects whilst maintaining coding standards, structural integrity and code readability.

The key validation stage includes testing for basic properties such as restartability and reproducibility and these tests are run in a variety of configurations designed to cover all the common options in NEMO. These tests do not, however, assess or validate the physical and dynamical behaviour of the models.

Recent changes to the user interface provide options for setting up test cases more simply. Test cases such as a classical lock exchange simulation can be used to compare options such as the choice of advection schemes.

These changes are broadly welcomed by the community but some evolution of the new user interface is likely once users actually begin to try it for themselves. Keeping configuration settings open and transparent transfers more responsibility to the user to provide external inputs. The system team will look to maintain guides and recipes explaining how standard tools and packages can be used to generate these inputs with the explicit aim of enabling the community to be largely self-supporting in this respect.

New test cases that usefully illustrate or validate aspects of NEMO will be considered for inclusion in the general release providing the originator can provide code and documentation that meets required standards. Maintaining such contributions in future releases will be done on a best endeavour basis but cannot be guaranteed by the system team. Again a strong and active community will have a role to play in this effort. This should be especially true if test cases are used for pedagogical purposes.

To ease the burden of testing and validation on the development team there should be investment in more automated methods. There has been useful work done in this area beyond the basic SETTE tests with the development of the ‘TRUSTING’ system which can be scheduled to run tests regularly and highlight suspected problems via a web interface. The complexity of such systems (which often require lower level access to web server settings) limit their widespread use but the consortium should be looking to establish services on at least two distinct HPC platforms (preferably covering a range of architectures and compilers). Consortium partners with ready access to computational support services are needed for this role.

11.2.2 User Support

User support encompasses a wide range of activities. Development working practices help to ensure the reference manual is updated with each release and the system team developers endeavour to respond to user issues in a timely manner. However system resources are limited and it is hoped that the community can, to some extent, be self-supporting. Note also that many users work with older releases whilst the developers who try to respond to their queries are working on the trunk.

A new web site is now available with updated resources and new facilities such as user forums . New material illustrating NEMO’s capabilities will, most likely, arise from the development and implementation of new test cases (both by the system team and from community contributions). Recipes, tutorials and resources will be hosted on the new service as they become available and will form a new point of entry for novice NEMO users.

The Wiki provision of the new service now provides clearly defined, separate areas for developers and users. This separation should allow more accessible and coherent support material for users to be added over time (by both system team and users themselves) whilst maintaining the specialist TRAC services required in the development process.

Essential elements such as AGRIF and XIOS are external to NEMO but their use within NEMO needs to be supported in two ways:

1. Maintenance of interfaces and compilation methods within the NEMO framework

2. Provision of ancillary resources (nesting tools, xml files etc.) and accurate, relevant documentation specific to application within the NEMO framework.

This latter requirement is particularly challenging since the expertise and forward perspective on the external packages lies outside the system team

11.2.3 Configuration Manager

One area of user support where others (MITgcm, ROMS) are perceived to offer more support is in setting up and configuring new models; especially small regional models. To address this, system team effort has been directed towards a configuration manager. The Working Group charged with this has released a set of tools and documentation (SIREN) which satisfies the basic needs for deriving a regional model

The SIREN tools satisfy the requirements for building a regional model derived from an existing NEMO configuration (by subsetting and interpolation). More generic solutions that could build configuration files and boundary conditions from any sources have been considered and prototyped by the WG but taking these further will require resources beyond the system team. External funding opportunities to support such work will be considered as they arise but the immediate priority will be to provide guide material for users explaining how existing tools can be used to build all the necessary components.

The WG has questioned various groups known to be using NEMO in regional set-ups and gathered information on how they derived their configurations. From this survey, a clear set of recipes, suggested methods and recommended tools will be distilled. Some groups have also offered bespoke scripts (python, matlab etc.) for general use. This work should provide a useful and timely resource and stand as an example of how the community can be encouraged to help itself.