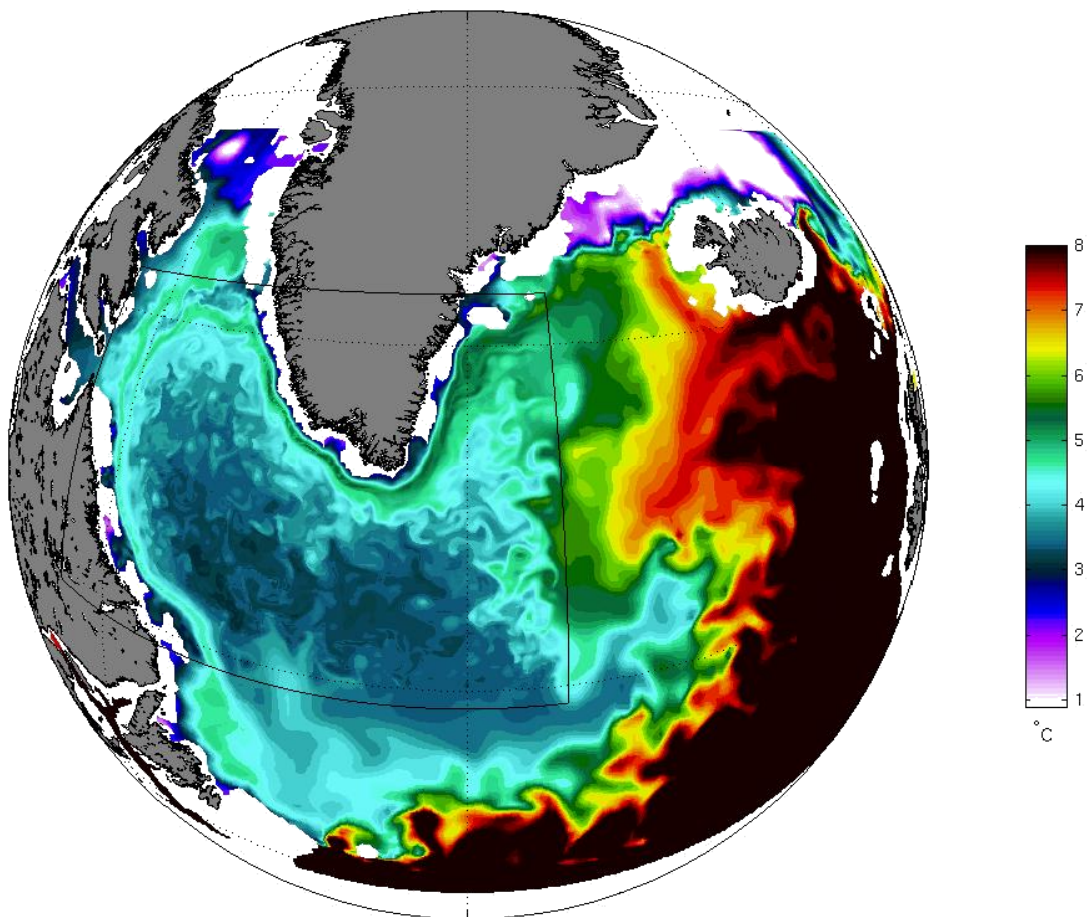


DRAKKAR project

**The ocean circulation in the North Atlantic and the Nordic seas:
Variability, processes and interactions with the global ocean.**



Impact of small-scale processes within the Labrador Sea on the surrounding ocean. This figure shows a temperature snapshot at 350m from a North Atlantic $1/3^\circ$ configuration of the OPA model, with a $1/15^\circ$ local refinement in the region of interest (Chanut, 2003). The AGRIF package (Blayo and Debreu, 1999) allows a dynamically-consistent two-way coupling of regional and basin-to-global scale model configurations at different resolutions. The package will be used in DRAKKAR which aims at studying remote interactions within the world ocean and large-scale effects of key local processes, as well as improving subgrid-scale parameterisations in ocean models.

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1 INTRODUCTION

This document presents the scientific objectives of the DRAKKAR project. The general framework is a European collaboration described in section 2. A detailed implementation plan for the French contribution is presented in part 3 for years 2003-2005. A new implementation plan will be written later for the last two years of the project (2006-2007).

DRAKKAR will implement community model configurations that will be used for the scientific purposes of the project team but also for the objectives of scientists associated with the project. The objectives of the French associated teams are only briefly mentioned in the present document (part 3.3).

2 European Collaboration

2.1 Motivations (from WOCE to CLIVAR)

The observations collected during the *World Ocean Circulation Experiment* (WOCE) program have clearly demonstrated that the state of the ocean is constantly changing at global and regional scales. In addition to an important year to year variability, these recent data show possible climate drifts over the last decades in many regions of the world ocean and strongly suggest that changes at every scales are tightly interconnected. The increase of anthropogenic CO₂ in the atmosphere may trigger even more dramatic changes in the future, as shown by the coupled model experiments conducted for the IPCC assessment (Intergovernmental Panel on Climate Change, IPCC 2001). One striking feature of these model results is that some (but not all) predict a collapse of the thermohaline circulation (THC) in the Atlantic, and the variations in strength of the Atlantic THC are thought to have a considerable influence on the exchanges with the other basins of the world ocean. An important aspect of the WOCE legacy, extensively discussed in the recently published book *Ocean Circulation and Climate* (2001), is that understanding the role of the ocean in climate requires, in addition to an accurate description of the general circulation, a full understanding of its variability, a topic embraced by its follow-on program *Climate Variability and Predictability* (CLIVAR).

The DRAKKAR project is motivated by open questions related to the variability of the circulation and water mass properties during the past and future decades, and its effects on climate through the transport of heat and the uptake of atmospheric anthropogenic CO₂. Our regions of interest are primarily (but not exclusively) the Atlantic Ocean and the Nordic Seas. To understand and predict global changes in the atmosphere-ocean-ice system, the carbon cycle, and marine ecosystems, and also to improve the outcomes of operational oceanography, require numerical ocean/sea-ice circulation models capable of realistically representing the physical ocean processes relevant to these multidisciplinary applications. To achieve the best possible scientific results, these model simulations require a wide spectrum of competence and important computational resources, which can be best found within a co-ordinated effort. The project proposes to join the efforts of several research teams in France, Germany, Russia and Finland to carry on a community modelling effort which will implement and manage a hierarchy of ocean model configurations, from which it will carry out co-ordinated realistic simulations of the ocean circulation at regional and global scales, at resolutions high enough to insure dynamical consistency over a wide range of resolved scales (from eddy to global, from day to decade).

2.2 Objectives

One primary concern of DRAKKAR is related to the circulation and the day-to-decade variability in the North Atlantic Ocean, as driven by the atmospheric forcing, by interactions between processes of different scales, by exchanges between basins and regional circulation features of the North Atlantic (including the Nordic Seas), and by the influence of the world ocean circulation (including the Arctic and Southern Oceans). Those scientific questions underlie the French contribution and the German SFB460 project. DRAKKAR is also concerned by the role of the changing ocean circulation in ecosystem dynamics, and in climate through the transport of heat and the uptake of atmospheric CO₂.

The scientific approach of the teams participating to DRAKKAR mainly relies upon numerical simulations. Therefore, the project is concerned by building a *state of the art* hierarchy of embedded model configurations, able to provide continued and systematic development and assessment of the ocean model components used in ecosystem, carbon cycle, and climate studies as well as in regional and operational oceanographic applications. With these concerns, the groups participating to the project have identified several priority objectives.

To build state of the art community model configurations.

A hierarchy of embedded model configurations of different grid resolution should make possible to carry out realistic, long term (several decades) simulations of the ocean and sea-ice circulation and variability at regional and global scale, and to perform sensitivity studies investigating key dynamical processes (requiring especially high resolution) and their impact at larger scales. The DRAKKAR model configurations will be used by the participating research teams to address their scientific objectives.

To provide a relevant, four-dimensional description of the atmospherically driven world ocean circulation and variability over the last 50 years and to extract dominant patterns and modes of variability.

Obtained from multiple-decades high resolution simulations carried out with various configurations, this description will allow (in the limits of model accuracy) to study the regional impacts of the global oceanic variability during this period, and to identify remote interactions between the North Atlantic and the World Ocean. It is also expected to contribute to the interpretation of the changes noticed in past and future ocean observations.

To improve the representation of key processes in ocean circulation models.

To achieve the best possible scientific results, ocean circulation models require a continuous improvement of numerical and physical parameterisations. The project will pursue continued development and sensitivity studies on atmospheric forcing fields and formulation of the surface boundary conditions, [representation] effects of topography and the bottom boundary layer, and sub-grid-scale parameterisation at medium resolution. One expects to achieve a significant improvement of the parameterisation of mesoscale and local key processes in future climate models.

To understand the role of regional [key] processes in the global oceanic circulation and variability.

Using either open boundary conditions or regional grid refinement within a global or basin scale model configuration, it will be possible to identify the impact of the dynamics of a critical ocean region on the circulation characteristics of the Atlantic or the World oceans.

Local grid refinement will provide dynamical consistency over a wide range of scales and allow to understand the underlying physics by studying scale interactions from eddy to basin or global. It will then be possible to establish dynamical links of variability between critical ocean regions and the general ocean. Priorities will be to understand the dominant mechanisms of the variability of the thermohaline circulation, of the basin-scale gyres, and of the most important regional circulation features in the Atlantic and the Nordic Seas. Special focus will be on the processes taking place within the North Atlantic and the Nordic Seas and their effect on the THC variability: freshwater and sea-ice cycles, intergyre exchanges, variability of mode waters, mesoscale features and transport, deep convection, deep water formation and export, boundary currents, deep overflows, exchanges across continental shelves, ...

To foster co-operative, multidisciplinary studies.

The high degree of realism and the dynamical consistency that our model simulations aim at are favourable to co-operative multidisciplinary studies. Priorities will be given to study the effects of mesoscale processes on the uptake and spreading of anthropogenic CO₂ and on the distribution of transient tracers, and to study the impact of the variability of the ocean circulation properties on the dynamics of large ecosystems (such as the upwelling of the Canaries or Benguela). Another specific objective of the project is to contribute to establish an integrated approach of marine studies, as the realistic prognostic simulations carried out in DRAKKAR appear complementary to the observing system which is presently being built up (ARGO, JASON) and to in-situ (sea-going) observation programs (SFB, OVIDE) with which a tight link will be maintained. Results from the project prognostic simulations relative to the last decade (1990's to present) will also complement the reanalyses from oceanic operational systems (MERSEA, MERCATOR) by providing dynamically-consistent, high-resolution descriptions of the circulation suitable to investigate key mechanisms and scale interactions.

2.3 Methodology

To permit participating research teams to achieve their scientific objectives, DRAKKAR proposes to carry out co-ordinated realistic simulations of the ocean circulation at regional and global scales, with pertinent atmospheric forcing and resolutions high enough to insure physical consistency over the range of scales which are dynamically important (i.e. from eddy to global, from day to decade).

The DRAKKAR model configuration system (Figure 1).

As first objective, the project will build or improve a hierarchy of numerical model configurations, from global to regional scale, each based on the primitive equation ocean circulation code OPA (Madec et al, 1998) coupled to the multi-layered sea-ice code LIM (Fichefet et al, 1997). This system will include :

- Global ocean/sea-ice model configurations at the coarse resolution of $\frac{1}{2}^\circ$ (ORCA05), and at the eddy-permitting resolution of $\frac{1}{4}^\circ$ (ORCA025). Those configurations have been developed in France at LODYC and in the MERCATOR project, respectively.
- Eddy-permitting resolution ($\frac{1}{4}^\circ$) configurations of the Atlantic Basin (ATL4) and of North-Atlantic/Nordic-Seas (NATL4) suitable for regional sensitivity studies.
- The two-way local grid refinement tool AGRIF, developed at LMC in Grenoble (Blayo and Debreu, 1999), which permits to increase significantly the horizontal and vertical resolutions over a specified region. This tool is of central interest to the project. With AGRIF, ocean key regions where a higher resolution (from $\frac{1}{12}^\circ$ to $\frac{1}{18}^\circ$ for example) will be used to accurately

represent the relevant physics, can be included in and can interact with the larger-scale (basin or global) model configurations. It is particularly well suited to study the impact of the dynamics of specific regions on the large scale circulation.

- An eddy-resolving configuration (between $1/12^\circ$ to $1/20^\circ$) of the North-Atlantic/Nordic-Seas (NATL12).
- A global atmospheric forcing data base for the ocean and sea-ice, suited to the bulk formulation of the ocean/sea-ice surface boundary condition, and representative of the atmospheric variability for the period 1950 to present.
- A specific high quality global atmospheric forcing data base from 1990 to present, mostly issued from satellite products.

The DRAKKAR simulation strategy.

The project will define and co-ordinate series of model simulations:

- Global ocean/sea-ice model configurations (ORCA05 and ORCA025) will be integrated for several decades driven by the atmospheric forcing defined by the project, to provide a relevant, four-dimensional description of the atmospherically driven world ocean circulation and variability for the past 50 years. Additionally, those experiments will provide time-varying boundary conditions for basin scale model configurations.
- A series of sensitivity experiments with the Atlantic ATL4 and the North-Atlantic/Nordic-Seas NATL4 configurations, with and without AGRIF grid refinement in key regions, to quantify the general impact of specific regional dynamics on the Atlantic circulation, to improve parameterisation, and to prepare the definition of the eddy resolving configuration NATL12.
- Two-way AGRIF coupling of fully eddy-resolving regional models with global model configurations ORCA05 and ORCA025 to study the sensitivity of the global circulation and its variability to the dynamics of critical areas.
- A high-resolution (between $1/12^\circ$ and $1/20^\circ$) ocean/sea-ice model experiment of variability of the North Atlantic and the Nordic Seas over the past decades.

2.4 Project Organisation

During the last decade, the DRAKKAR participating scientists fostered co-operative scientific activities within the Mast3 European project DYNAMO (Dynamics of North Atlantic Models), and between their national projects, CLIPPER in France and FLAME (Family of Linked Atlantic models) in Germany. The expertise gained through projects such as these also helped to build their capability to make significant contributions a the variety of modelling needs. However, the challenge of developing realistic ocean models required for the diverse range of applications can only be met by an effective integration and co-ordination of the activities and complementary expertise of every member of the group. This fact yielded the DRAKKAR concept.

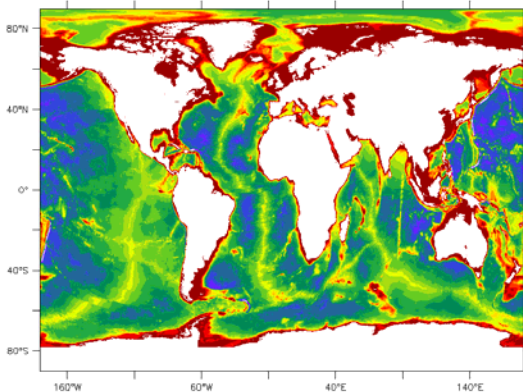
The structure proposed for DRAKKAR is inspired from the one successfully implemented in the CLIPPER project. An international project-team conducts the project activities. It has the charge to define details of the model configurations, to implement and to validate their various components. This team also defines model experiments to run, co-ordinates their execution by the participating groups, and organizes the sharing of model results. To complement the role of the project-team, associate scientists from various laboratories are solicited to help define the experiments and to analyse the results. Their role is especially important to construct the multidisciplinary reach of the project, and to enhance the scientific value of the simulation outputs.

Figure 1: DRAKKAR Embedded Model Configurations

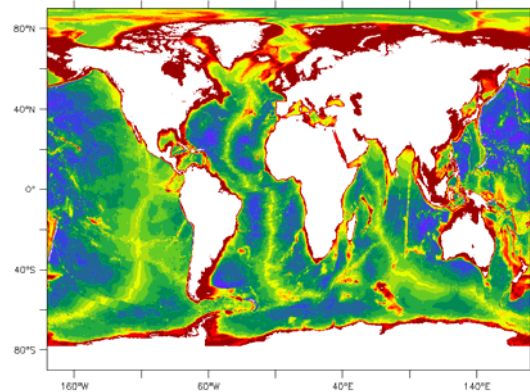
Used by the FLAME Group

Used by the French group

Global Configurations



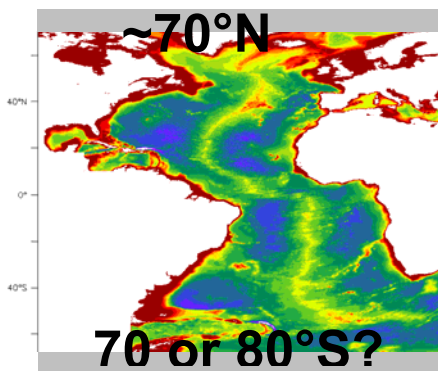
ORCA $\frac{1}{2}$ ($\frac{1}{2}^\circ$ resolution)
Global, non eddy permitting configuration,
with sea-ice



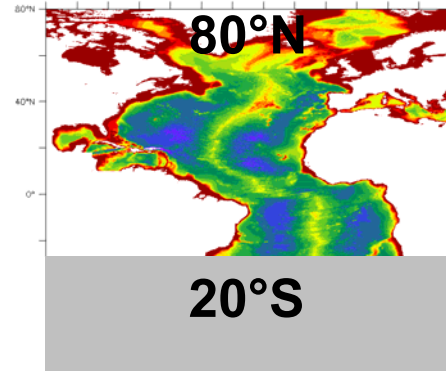
ORCA $\frac{1}{4}$ ($\frac{1}{4}^\circ$ resolution)
Global, eddy permitting configuration,
with sea ice.



Embedded in a global configuration or driven at open boundaries



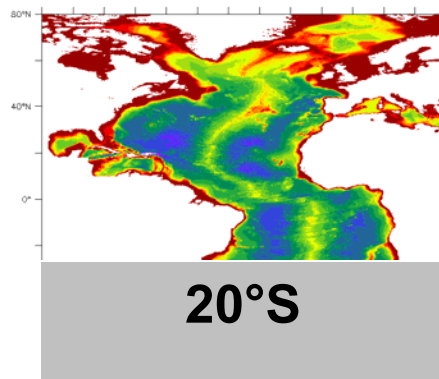
ATL4 ($\frac{1}{4}^\circ$ resolution)
Atlantic, eddy permitting configuration
no sea ice.



NATL4 ($\frac{1}{4}^\circ$ resolution)
North-Atlantic/Nordic-Seas configuration
eddy permitting, with sea-ice.



Eddy-Resolving North Atlantic Configuration



NATL12/20: High resolution (between $1/12^\circ$ to $1/20^\circ$) North-Atlantic/Nordic-Sea configuration with sea ice, embedded in a global configuration or driven by Open Boundaries.

The DRAKKAR project team is composed of the French former CLIPPER team and of the German FLAME team, both having a significant expertise in all the aspects of eddy resolving modelling of the ocean general circulation. The project team also includes individual research scientists at the Shirshov Institute of Oceanography (SIO) in Moscow, Dr. Gulev, who brings an essential expertise in air-sea fluxes and atmospheric marine boundary layer, and at the University of Helsinki, Dr. Beckmann, who brings an additional expertise in modelling of the high latitude ocean/sea-ice/ice-shelves system.

The French DRAKKAR team:

Name	Activity	Laboratory
Bernard Barnier	Co-ordinator	LEGI, Grenoble
Christian Le Provost	Scientist	LEGOS, Toulouse
Gurvan Madec	Scientist	LODYC, Paris
Thierry Penduff	Scientist	LEGI, Grenoble
Anne Marie Treguier	Scientist	LPO, Brest
Jean Marc Molines	Research engineer	LEGI, Grenoble
Sebastien Theetten	Research engineer	LPO, Brest
Elizabeth Remy	Research engineer	LEGOS, Toulouse

The German FLAME Team:

Name	Activity	Laboratory
Claus Böning	Co-ordinator	IFM Kiel
Arne Biastoch	Scientist	IFM Kiel
Joachim Dengg	Scientist	IFM Kiel
Jens-Olaf Beismann	Scientist	IFM Kiel

Individual Scientists:

Name	Activity	Laboratory
Aike Beckmann	Scientist	University of Helsinki
Sergei Gulev	Scientist	IOS Moscow

2.5 Links with respective national projects.

The concept of DRAKKAR is to integrate the skills and means of several research teams whose scientific objectives significantly overlap, in order to enhance their capabilities to develop state of the art numerical ocean circulation models. Such a collaborative effort, which requires an important commitment from each team, is expected to last longer than the typical duration of a scientific project such as DRAKKAR (2004-2007) or the German SFB460 (2002-2006), and is intended to serve the needs of new scientific projects in the future.

2.5.1 French contribution:

General scientific concern: The recent changes in the North Atlantic Ocean at basin and regional scales: response to the atmospheric forcing, interactions between basin scale and regional

circulation features of the North Atlantic (including the Nordic Seas), and influence of the world ocean circulation on the variability of the North Atlantic.

Objectives:

- To reach a realistic description of the atmospherically-driven variability of ocean currents and water masses in the North Atlantic and Nordic Seas from the 1950s to present.

- To understand i) the mechanisms responsible for the generation and propagation of this variability, and ii) the remote interactions between the North Atlantic and the world ocean, iii) the interactions between gyres and/or regional circulation features within the North Atlantic and the Nordic Seas.

- To complement and enhance, with realistic model simulations, the value of past and future observations, and document regional aspects of the ocean variability.

Approach: High resolution model simulation of the ocean circulation and sea-ice at the world scale, and very high resolution model simulation of the circulation and sea-ice in the North Atlantic and the Nordic seas, over the period of most recent atmospheric re-analyses (i.e. from 1950 to 2000 and longer).

2.5.2 Summary of FLAME activities:

General scientific concern: The circulation in the Atlantic Ocean, its variability from days to decades, its role in the ecosystem dynamics, and its effect on climate through the transport of heat and the uptake of atmospheric trace gases such as anthropogenic CO₂.

Objectives:

- To study deep water formation and circulation in the subpolar North Atlantic, and to develop an understanding of i) the Greenland-Iceland-Scotland overflows and their impact on the large scales, ii) the freshwater budget of the Labrador sea and its variability, iii) the deep western boundary current and the export of deep water to the subtropics.

- To study mesoscale ocean processes and to understand their effect on deep convection and its connection with boundary currents, on mode water formations and the uptake and spreading of anthropogenic trace gases, particularly CO₂.

- To understand the various mechanisms driving i) the interannual to decadal variability of the Atlantic thermohaline circulation, and ii) the interactions between the tropical and the subtropical Atlantic and the interannual variability of the equatorial Atlantic.

Approach: Development and application of a hierarchy of models, involving model versions of different resolution and geometry, with a range of different parameterisation concepts best suited for the variety of the scientific objectives. The presently available FLAME configurations are based on the MOM code. The one with the highest resolution is the 1/12° North Atlantic that should be integrated for years 1990-2003 in 2004. All new model configurations will be developed using the OPA code within DRAKKAR.

2.5.3 Shirshov Institute of Oceanography:

General scientific concern: The physics of the interactions between the ocean the atmosphere, the links and feedback between the ocean and atmosphere climates.

Objectives:

- To continuously improve the representation of the atmospheric forcing of ocean models.

- To study the dominant spatial and temporal patterns of variability of the ocean circulation in the North Atlantic.

Approach: Statistical analysis of high resolution model simulations representative of the ocean variability in the last 50 years. Evaluation of the various estimates of air-sea flux fields and

surface atmospheric variables, test and evaluation of atmospheric forcing parameterisation in ocean models.

2.5.4 University of Helsinki:

General scientific concern: Circulation and variability of the high latitude coupled ocean/ sea-ice system.

Objectives:

- To study the role of sea-ice and ice-shelves on the circulation and freshwater balance of the high latitude oceans.
- To improve the modelling of sea-ice and the representation of the bottom topography in ocean circulation models.
- To investigate the interconnection of high latitude oceans with the global ocean on interannual and interdecadal time scales.

Approach: Development and application of coupled ocean/sea-ice models, parameterisation of the effect of ice-shelves in the freshwater budget of the Antarctic Ocean and the inclusion of tidal effects in large scale climate models.

2.6 Complementarity of the investigations and methods

Scientific issues addressed by the German and French teams overlap most strongly in the Subpolar Gyre. The German FLAME project will more particularly investigate the connections between this gyre and the rest of the Atlantic through the export of NADW to the Southern Hemisphere, the Pacific and Indian Oceans. The French team concerns are complementary since they extend the interest to the interactions between the Subpolar Gyre and the Nordic Seas. The FLAME team will pay great attention to the processes which control the Atlantic meridional overturning. This focus is complemented by the interest of the French project team in the processes that govern the horizontal [gyre] circulation within the North Atlantic and Nordic seas. The simulation of sea-ice is essential to DRAKKAR objectives and will be performed in every global configuration. Time-varying, dynamically-consistent and hopefully realistic fresh-water fluxes will thus be available from global simulations to force the FLAME regional configurations along their northern boundary. This is an important requirement in order to study the freshwater balance of the subpolar oceans. The FLAME approach relies on a succession of sensitivity numerical experiments that aim at understanding the remote impact of various local physics at larger scale. The french project is more devoted to the realisation of a few continuous, long-term (global and regional) experiments to reproduce the observed evolution of the ocean over the last decades. Sensitivity studies performed by FLAME will be useful for designing and tuning the DRAKKAR experiments, and reciprocally, the latter will provide FLAME scientists with model trajectories suitable to extend the results of their process-oriented studies to continuous multi-decadal simulations.

Time Table of DRAKKAR activities:

March 2003: First DRAKKAR meeting at IFM Kiel. Definition of the scientific objectives, of the modelling system to be implemented and of the task of the various partners for 2003.

April 2003 – December 2003: Begin the implementation of the various model configurations of the DRAKKAR modelling system by partner teams, definition and validation of the atmospheric forcing functions.

January 2004: Second meeting in Grenoble. Discuss the latest progresses in the implementation of the DRAKKAR model configurations, definition of the co-ordinated work-plan for 2004.

3 French contribution to the DRAKKAR project:

**The ocean circulation in the North Atlantic and the Nordic seas:
Variability, processes and interactions with the global ocean.**

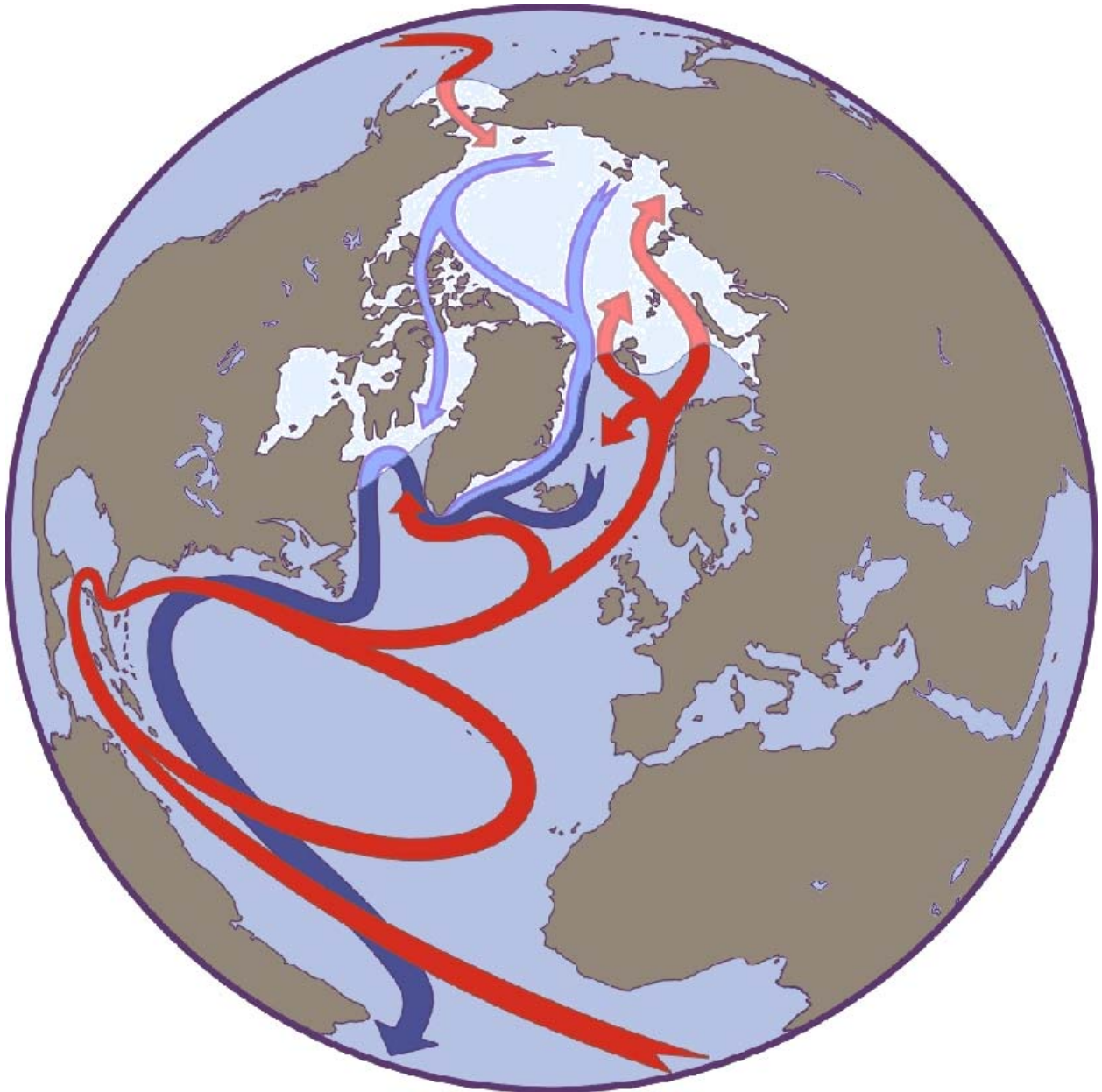


Figure courtesy of G. Holloway, Institute of Ocean Sciences, Sidney, British Columbia

3.1 Motivation and general presentation

3.1.1 The North Atlantic: A Key Region for Climate Changes

The Atlantic meridional overturning circulation (MOC) is forced in the sub-polar gyre partly by overflows from the Nordic Seas and partly by deep convection in the Labrador Sea, both processes contributing to the formation of the North Atlantic Deep water (NADW). The variations in strength of the Atlantic MOC are thought to largely control the variability of the heat transport toward the high latitudes, and to have a considerable influence on the exchanges with the other basins of the world ocean. The sub-polar North Atlantic thus stands out as a key region to study climate changes at the global scale, especially as recent analyses carried on with the WOCE data points-out many example of possible climate drifts over the last decades in the North Atlantic, a warming (Levitus et al, 2000) and a freshening (Dickson et al, 2002), and reported important year to year changes in the properties of the Labrador Sea waters (Houghton et al, 2002). Changes occurring in the climate of the North Atlantic Ocean can have drastic impact at regional scale, in particular on the evolution of regional marine ecosystems and fish stocks. A sensitivity of the upwelling of the Canaries to a NAO-related weakening of the Trade Winds in the North Atlantic has been detected by Roy et Reason (2001). A consequence of a weakening of the Canaries upwelling has been observed to increase the temperature of the upper ocean and to reduce the stock of pelagic fishes (Hilmi et al., 1998). This basin thus also stands out as a key region for the economical development of all waterside countries which requires clever preservation and management of its resources. To understand which mechanisms are driving the variability of the ocean properties (thermo-dynamical and bio-geo-chemical) and circulation at regional scales is therefore a high priority.

The leading mode of atmospheric variability in the region is the North Atlantic Oscillation (NAO, Hurrell, 1995). The NAO is now recognized as the dominant component of the climate variability in Europe and around the Mediterranean Basin. Links between NAO and fluctuations in sea surface temperature (SST) at decadal scales have been unambiguously established from many observational studies (Wallace et al. 1990, Cayan 1992, Kushnir 1994, Battisti et al., 1995). Such links indicate that NAO influences the ocean variability at the surface on time scales ranging from seasonal to decadal. But this influence has also been detected at depth in the characteristics of water masses (Lazier 1980, Levitus and Antonov 1995, Joyce and Robin, 1996, Dickson et al., 1996, Curry et al., 1998), and also in transports (Roemmich and Wunsch 1984, Read and Gould 1992, Sy et al. 1997, Koltermann et al. 1999). In the subpolar gyre, variability in water masses is manifested by the development and propagation of anomalies in salinity (Dickson et al, 1988; Belkin et al, 1998) and temperature (McCartney et al., 1997) and by the variability of subpolar mode water formation and deep convection. An important year to year variability has also been observed in the temperature of the subtropical mode waters of the North Atlantic. In particular, the formation of colder waters related to the severe winter of 1988 was followed by the formation of warmer waters after the mild weather of 1989 (Klein and Hogg, 1996). The variability of forced ocean models is also dominated by the response to NAO atmospheric forcing (Eden and Jung, 2001; Beismann et al, 2002; Gulev et al., 2003) with the interannual variability primarily forced by the wind stress and decadal variability also influenced by heat and freshwater fluxes (Eden and Willebrand, 2001; Gulev et al., 2003). The distribution of eddy kinetic energy in the ocean also varies with the NAO index, as shown in Figure 2.

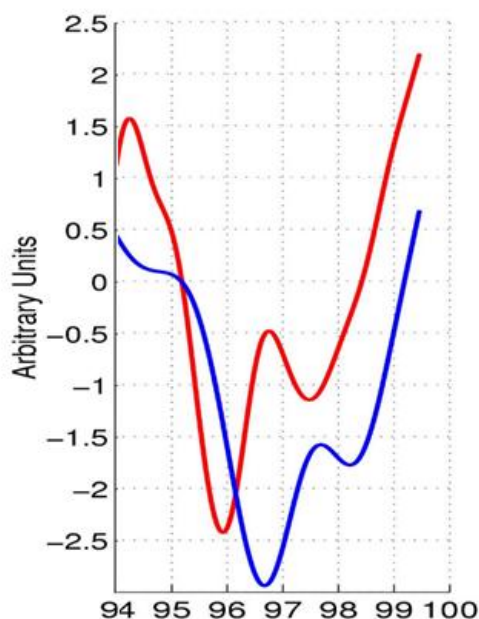


Figure 1. Red: NAO index. Blue: anomaly of the meridional contrast of surface eddy kinetic energy (EKE_{subpolar} - EKE_{subtropical}) from the CLIPPER 1/6° Atlantic Ocean model between 1994 and 1999. Both time series have been low-pass filtered and normalized by their 1994-1999 average. The EKE contrast visibly follows the NAO index fluctuations with a lag close to 10 months (Penduff et al, 2003).

Although our knowledge of the North Atlantic has progressed in the past decade, we still do not understand enough the connections between the variability of the atmosphere, the ocean circulation and the water mass properties. This is mainly because key processes happen at very small scale and are dominated by relatively high frequency variability, which obscures the long term trends. Examples are the mesoscale eddy flow, overflows from the Nordic Seas, the deep convection, and the transport of boundary currents subject to large barotropic high frequency variability (Dickson and Brown, 1994). This motivates a large number of observational programs in the area in the framework of CLIVAR (repeat hydrography sections like OVIDE, ARGO floats, German SFB460, U.K. "RAPID" program). Because of the width of the spectrum of time and space scales involved (from an overflow a few kilometres wide, with daily variability, to the global ocean circulation, with variability over decades and centuries), numerical models are needed to reconcile observations and theories in a four-dimensional picture of the circulation. Numerical models will also help identify the physical mechanisms at work, a necessary step to be able to predict future climate change.

3.1.2 Scientific questions

In the context of the science issues identified in DRAKKAR, we intend to address a series of open questions related to the variability of water mass properties and circulation in the North Atlantic and the Nordic Seas during the past decades.

- The North Atlantic and Nordic Seas variability in relation with the world ocean. Time scales of interest for DRAKKAR range from eddy to season and decades.
- Circulation and variability processes within the North Atlantic and the Nordic Seas, and interactions between processes of different scales.
- Improvement of representation and parameterisation of key processes in ocean models, including atmospheric forcing, representation of bottom topography and eddy effects.

These issues are presented in more detail in section 3.2. Other scientific questions will be addressed by other teams in the context of projects presented to French national programs (PNEDC, PATOM). Those scientific questions are listed in section 3.3 of this document; the corresponding actions will be presented in more detail in the documents submitted to PNEDC and PATOM at the end of 2003.

3.1.3 Numerical models and the DRAKKAR project

In the past decade, high resolution numerical models of the North Atlantic have demonstrated considerable progress, for example in terms of the representation of the Gulf Stream and the Azores current, or the eddy kinetic energy (Smith et al, 2000; Paiva et al., 1999; Eden and Böning, 2002). However, they still show major flaws in the sub-polar gyre, notably a tendency for excessive convection in the Labrador Sea and a considerable increase in salinity (Treguier et al., 2003). One aim of the DRAKKAR project is to work towards improvement of those models, in order to be able to study the mechanisms of variability in a context as close as possible to observations. To that end, the possibilities offered by the DRAKKAR modelling configurations and local grid refinement (Blayo and Debreu, 1999, Chanut, 2003) will be exploited to better represent or parameterise the mesoscale in key areas.

Contrary to most previous high resolution models the DRAKKAR configuration will be forced without artificial relaxation to surface climatological salinity (a flux correction will be added if needed) and will include a fully prognostic ice model. This will allow a more complete investigation of the freshwater budget. Special attention will be given to the representation of bottom topography: because of the low stratification, the subpolar circulation is steered by topography even in the upper layers (Reverdin et al., 2003) and regional models have shown great sensitivity to bottom topography (Käse et al., 2001; Penduff et al., 2002; Myers and Deacu, 2003).

Previous modelling studies of the North Atlantic circulation at medium and high resolution have generally concentrated on the variability forced locally (inside the computational domain) and neglected the variability which may be forced by interactions with other parts of the world ocean. In order to reach more definitive conclusions about the mechanisms of variability at the regional scale in the North Atlantic, it is necessary to take into account the interaction with the Nordic Seas, the Arctic Ocean, but also the subtropical and tropical Atlantic. The meridional exchanges essentially occur in the highly turbulent frontal regions marking the limits between the large scale circulation patterns. Those gyre scale interactions are important issues in the DRAKKAR project.

The model hierarchy planned within the DRAKKAR project is presented in Figure 1. Those configurations are based on the latest release of the OPA code, with sea ice, and including new developments like partial step topography. The global $\frac{1}{2}^\circ$ model (ORCA05) has been designed at LODYC to be used in climate studies in the framework of PNEDC and in European projects. The global $\frac{1}{4}^\circ$ configuration is being developed by the MERCATOR project to serve as the basis for the next global forecasting system POG (Prototype Ocean Global). We will use this configuration in research mode, thereby contributing to its future evolutions. We anticipate that most coupled models will be run in eddy permitting mode in the near future: the DRAKKAR project will thus help prepare the next generation of coupled ocean models. DRAKKAR plans include regional model configurations of the Atlantic and North-Atlantic/Nordic Seas at eddy permitting (ATL4 and NATL4) and eddy resolving (NATL12/20) resolutions. The development of this latter very high resolution model will be co-ordinated with MERCATOR in order to prepare the next generation of operational models for the North Atlantic.

3.1.4 National context

DRAKKAR is related to several national programs:

1. PNEDC (*Programme National de l'Etude de la Dynamique du Climat*). In this context, DRAKKAR will address scientific issues relevant to Science Theme 1 (The European Climate and its links with the North Atlantic and the Arctic Basin), with contributions to the understanding of the dynamical links existing between the horizontal (gyre) and meridional (thermohaline) circulation, the response of the ocean to the NAO forcing, and on the heat and freshwater budget of the North Atlantic and the Nordic Seas.
2. The PATOM (*Programme Atmosphère Océan à Multi-échelles*). In this context, DRAKKAR will address scientific issues related to the understanding of mesoscale ocean processes and of interaction between processes of different scales.
3. Finally, DRAKKAR will contribute to the objectives of the international project GODAE and to the scientific issues relevant to GMMC (MERCATOR/CORIOLIS) in several ways: firstly by using common model configurations (like ORCA025), and making prognostic runs to help validate and improve the model; secondly by comparing the variability of prognostic models with the re-analysis (with data assimilation) produced by MERCATOR over the last decade (1992 to present); and finally by producing simulated data such as ARGO-like profiling floats at a high sampling ($1^\circ \times 1^\circ$) useful to qualify the representativeness of the CORIOLIS data set at global and regional scale.

3.2 Scientific objectives of the French DRAKKAR project team

3.2.1 North Atlantic and Nordic Seas variability in relation with the world ocean.

The scientific questions at the core of DRAKKAR are focussed on the North Atlantic, but of course the North Atlantic communicates with the other oceans. The Arctic Ocean has perhaps the largest influence on the North Atlantic variability at the inter-annual to decadal time scale. It exports low salinity surface freshwater and sea-ice through the Fram Strait and through the Arctic archipelago into the Labrador Current. This freshwater export creates salinity anomalies in the subpolar gyre (Belkin et al, 1998) and plays an important part in the gyre salinity balance (Bacon et al, 2002). A feedback of the subpolar gyre salinity on the Arctic Ocean is also possible: the freshwater budget of the Arctic Ocean is largely positive and creates at the top of the water column a thin layer of cold and low salinity water. The water below, from Atlantic origin, is significantly warmer and saltier, and contains enough heat to melt most of the Arctic sea-ice. Therefore, small changes in the salinity of the top layer, by modifying the stability of the water column could have a strong impact on Arctic sea-ice and consequently on the freshwater export to the Atlantic.

The influence of changes occurring in the Antarctic and Indian oceans is expected to act over longer time scales but may still be felt over a 50 year period. We will investigate which type of connections exist between those basins and the North Atlantic (warm/cold routes through the South Atlantic, propagating waves along the Atlantic boundaries), and the role of eddies (such as Agulhas and North Brazil current eddies) in these connections. One special focus will be the importance of upwelling of North Atlantic Deep Water in the Antarctic Circumpolar current (ACC) as a means of closing the Atlantic THC. Such an influence is demonstrated in the time-mean by prognostic models (Toggweiler and Samuels, 1998), inverse models and data (Rintoul

et al, 2002). However, the extent to which this mechanism also plays a part in the variability of the THC is not known.

The above questions will be addressed by experiments performed with the global eddy permitting $\frac{1}{4}^\circ$ model ORCA025, with the ice model LIM. Two experiments will be performed: one over 50 years forced by NCEP data, and one over the last 10 years using forcing fields from satellite when available (see section 2.2.3 for the forcing fields).

A less expensive, limited-area model configuration of the North Atlantic and Nordic Seas at $\frac{1}{4}^\circ$ (NATL4) will be used (among other purposes) to quantify the influence of interbasin exchanges on the interannual variability of the North Atlantic, compared with the local influence of time-varying atmospheric forcing. A series of 50 year long experiments will be performed with the NATL4 configuration, driven by various surface forcing and various conditions at the limits of the domain. Above global experiments will provide the time-varying boundary conditions at the southern (20°S) and northern (Fram Strait) limits of this model. Comparing the local area model solution with that of the global ORCA $\frac{1}{4}$ model will help validate the prescription of boundary conditions both for the ocean and the sea ice. The boundary conditions will then be analysed and degraded to a climatology by averaging in time. Sensitivity studies with climatological forcing conditions except at one boundary (surface, southern or northern), will allow to quantify individual contribution of each type of forcing to the variability inside the basin.

Statistical and correlation analyses will be performed to study the aforementioned connections between the North Atlantic and the surrounding oceans (as well as within the basin, see the next section). The simulated patterns of seasonal to interannual variability will be studied from EOF analyses applied to the de-trended anomalies of various model variables. These multivariate, three-dimensional leading modes are expected to provide some information about the subsurface and dynamical part of the main propagating features that have been observed in the real ocean. Lagged correlation computations along the paths of the main water masses will help better quantify the propagating time-scales of these signals. More generally, these statistical investigations will make use of the tools developed by S. Gulev (Gulev et al., 2003) to describe the remote impact of variable surface fluxes within the Labrador Sea.

3.2.2 Processes within the North Atlantic and Nordic seas

Variability of the subpolar gyre: global and local description, models and data.

In-situ observations of the ocean are often local (mooring arrays and hydrographic sections). A large number of observational programs have been carried on in the last decade, aimed at key processes within the North Atlantic Subpolar gyre. Transports at Denmark straits and over the Iceland Scotland Ridge have been measured (Hansen and Osterhus, 2000 provide a recent review). Mooring arrays have followed the deep overflow downstream of Denmark Straits (Dickson and Brown, 1994). An extensive observational program has been aimed at monitoring Labrador Sea convection (Pickart et al, 2002). Observations show large interannual variability and point out the importance of small scale and eddy processes (convective plumes, preconditioning of convection through cyclonic recirculation cells, role of eddies and interactions with the boundary current during the restratification period, importance of atmospheric mesoscale forcing...). However, in the Labrador sea as well as in other parts of the subpolar regions, there are few observations that can help quantify the connections between those localised phenomena. Transient tracers (Rhein et al, 2002) help provide a global picture, but their interpretation is not always straightforward. Lagrangian measurements (Reverdin et al., 2003;

Lavender et al., 2001; Bower et al, 2002) offer a good qualitative view but the data density at depth is not large enough to provide a full three dimensional view of the velocity fields, and even less so of its variability (figure 3).

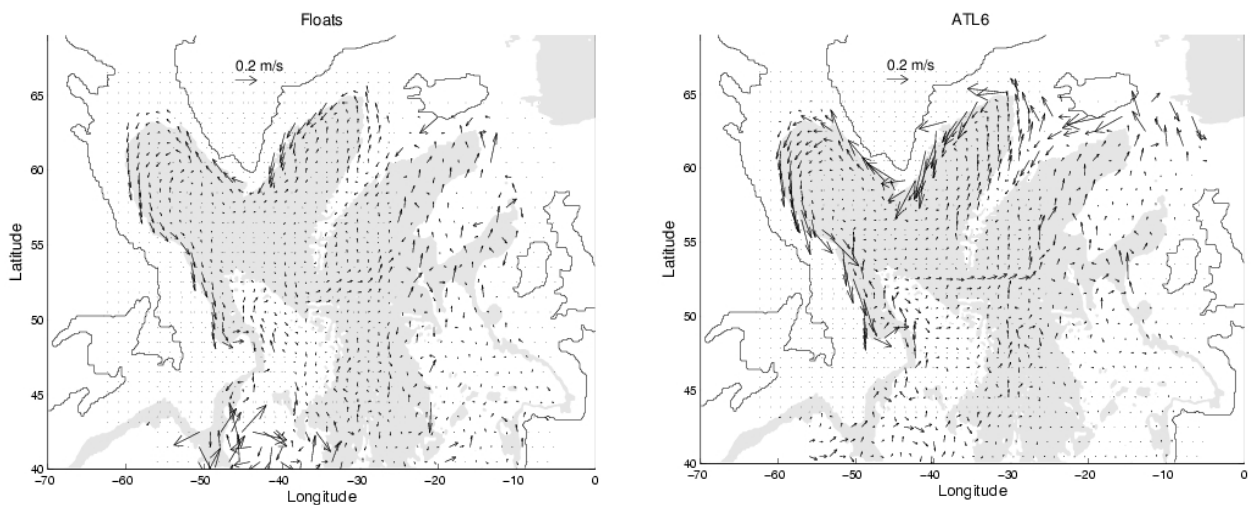


Figure 3: a) Velocities at 700m estimated from floats (in the western part, Lavender et al., 2000; in the eastern part, Bower et al, 2002). b) Velocities from the 1/6° CLIPPER model, averaged in the same boxes. Velocities in the subpolar gyre boundary current are underestimated by the floats (the model boundary currents seem in better agreement with eulerian estimates of transports). The underestimation is probably due to insufficient sampling of the thin boundary current.

DRAKKAR model configurations will help quantify and interpret the link between sources of variability at different spatial scales: overflows, deep convection, wind driven currents, surface fluxes of heat and freshwater. Examples are the link between the variability in the Nordic seas and the strength of the overflows; the importance of the various overflow contributions versus convection in the Irminger and Labrador Sea to the variability of deep water export to the rest of the world ocean; the exchanges between the western and the eastern side of the subpolar gyre. Some of those questions are best addressed by performing idealised sensitivity experiments. This approach has been used extensively by the FLAME group (e.g., Biastoch et al, 2003): when necessary, sensitivity experiments regarding the above issues will be co-ordinated within the DRAKKAR project.

The strategy for the DRAKKAR model experiments will be adapted so as to allow the best possible model-data comparisons, in order to help understand local observations. The database of model results will be organised to make possible off line calculation of float trajectories and tracers (with outputs as frequent as one day, over a few years). Very frequent (hourly) outputs will be performed at a few grid points to simulate moorings. Transient tracers (CFCs) will be calculated on line during the long experiments (50 years), following the OCMIP protocol (Dutay et al, 2002). ARGO floats (extracting profiles along a trajectory) will also be simulated.

Mechanisms forcing the variability: atmospheric freshwater fluxes and surface salinity.

One main source of variability is the atmospheric forcing. Contrary to most previous high resolution models (Smith et al, 2002; Paiva et al, 1999, Treguier et al, 2001) the DRAKKAR configuration will be forced without artificial relaxation to surface climatological salinity and will include a fully prognostic ice model. Even though we may have to add to the forcing a prescribed flux correction, this strategy will allow a better assessment of the relative role of

atmospheric freshwater fluxes, those resulting from ice melt, and transport by the eddies and thin boundary currents (like the East Greenland Coastal Current, Bacon et al, 2002).

The salinity of the warm waters carried by the North Atlantic current plays a key role in the behaviour of the thermohaline circulation (THC) in models, because a higher salinity can compensate an increase in temperature and avoid a collapse of the THC in global warming scenarios (Latif et al, 2000). Owing to the highly turbulent character of the North Atlantic Current, variability of the salinity field in non-eddy resolving models may be biased. Biases also arise when relaxation to climatological salinity is used. The DRAKKAR models will allow to study the connection between the high salinity waters generated in the subtropical gyre and the regions of deep water formation. This study will build upon the results of the project "Surface salinity in the Atlantic and thermohaline circulation" funded by PNEDC for years 2003 and 2004 (Reverdin and Colin de Verdière).

Variability and propagation of the subpolar mode waters (SPMW).

In the subpolar gyre, warm waters brought by the North Atlantic current are converted into different varieties of subpolar mode waters (Mc Cartney and Talley, 1982) which feed the regions of deep water formation (Norwegian Sea, Labrador Sea) or recirculate in the North East Atlantic. Modes of variability characterising the subduction of SPMW towards the subtropical gyre have been identified in idealised models (Hazeleger and Drifjout, 1999; Nurser and Zhang, 2000). The propagation of anomalies from the Labrador Sea to the Gulf Stream region occurs through advection by the Labrador current or topographic wave propagation. The DRAKKAR high resolution model will be specially suitable to study those mechanisms, as well as the coupling between low frequency variability of the Gulf Stream and Labrador Sea water formation (Joyce et al, 2000). The spatial and temporal variability of the formation of SPMW is one of the objectives of the observational program OVIDE. A specific contribution of DRAKKAR will be the evaluation of the role of eddies in the transformation of the warm waters. The method of de Miranda et al (1999b) will be used to calculate instantaneous subduction rates and their spatial structure, and correlate it with the distribution of eddy activity.

Modes of variability and propagation of anomalies.

Until the beginning of the ARGO program, observations of variability were concentrated at the surface. They indicate that the temperature and salinity anomalies propagate around the subtropical and subpolar gyres along the Gulf Stream/North Atlantic current system. However their vertical and multivariate structure is still largely unknown. Detailed diagnostics of those anomalies in the high resolution DRAKKAR models should provide a better understanding of the respective role of advection, planetary and topographic Rossby wave propagation, surface fluxes and turbulent diffusion in the mechanism of propagation.

Understanding the variability of intergyre exchanges.

One key objective of the observational programs in the subpolar gyre (like OVIDE) is the monitoring of meridional transports of heat, freshwater, nutrients and anthropogenic CO₂ from the subtropical to the subpolar gyre, and from the subpolar gyre to the Nordic Seas. By producing numerical solutions directly comparable with observations, DRAKKAR will allow to evaluate the role of changes in water mass properties vs changes in current systems. The fully eddy resolving configuration planned for 2006 will allow a systematic investigation of scale interactions and the role of eddies and narrow boundary currents in the meridional transports.

Water mass exchanges between the subpolar gyre and the Nordic Seas are known to vary on different time-scales (e.g. Orvik et al, 1999, VEINS project). These connections occur within localised and relatively shallow regions (Greenland-Iceland-Scotland Ridge). We will investigate

the impact on the Atlantic-Nordic Seas interaction of the mixing that occur within overflows south of this ridge

Barotropic transport and vorticity balance

One important question is the role of the barotropic circulation in the inter-gyre transports. Barotropic currents are very difficult to estimate from observations, because strong barotropic flows are concentrated in thin boundary currents, that are not correctly sampled by available float data (Figure 3). Those currents are subject to high frequency variability of large amplitude, so that LADCP measurements taken during a hydrographic cruise are not representative of the seasonal mean. Numerical models are needed to evaluate the contribution of barotropic flows to the transports, and to understand their dynamics. To that mean, we will estimate vorticity balances in DRAKKAR model configurations: the vorticity balance is especially well suited to investigate the dynamical origin of barotropic currents (wind forcing, bottom stress coupling, non-linear rectification, JEBAR effect...)

DRAKKAR model configurations will also be used to study the interannual variability of the barotropic flow. The pattern of surface currents has recently been shown to change in response to the NAO, from an analysis of surface buoys (Flatau et al, 2003): part of this variability is certainly barotropic.

Strategy

During the first phase of the project (2004-2005) the above scientific questions will be addressed using the eddy permitting NATL4 model configuration (North Atlantic and Nordic seas) with areas of refined resolution using the AGRIF tool. For instance, a refinement in Denmark Straits or over the Iceland-Scotland ridge will be used to investigate the role of overflows in the export of dense water and the sensitivity of the meridional overturning circulation to small scale instabilities. Horizontal refinement (to $1/12^\circ$) in the region of the Flemish Cap will allow to investigate the effect of the topography (coastline and bottom) of this region on the path of the North Atlantic Current, and on its interactions with the deep western boundary current. However, many objectives (meridional transports, inter-gyre exchanges, freshwater budgets) will be best addressed by a high resolution model with homogeneous, eddy-resolving grid in the whole domain: this is the NATL12/20 model configuration planned for 2006.

3.2.3 Improvements of key processes in ocean models

Forcing

The forcing function for the long-term numerical experiments with different ocean model configurations should be based on up-to-date parameterisations of air-sea exchange processes to be applied to the basic variables available from numerical weather prediction systems (like air temperature, humidity...). In order to develop such a set of parameterisations, ideally the following steps are required:

1. Formulation of the basic requirements expected for the model forcing. In particular, requirements for the global and regional closure of the heat and freshwater balances should be formulated on a quantitative level and include assessments of the accuracy needed.
2. Several series of pilot computations, with different data sets (NCEP, ERA, satellite products) for the period of overlap of those products are necessary to evaluate different parameterisations of surface flux components (bulk formulae), to identify those which better fit the model requirements, and, if necessary, to develop new schemes for particular fluxes. Those computations can be performed using observed sea surface temperature (without actually running the ocean model).

3. The actual implementation of the forcing function (bulk formula) in the numerical model must be cost-effective and modular.
4. Series of experiments with different model configurations should be undertaken in order to test the forcing function, identify problems, and perform fine-tuning of the parameterisations.

During this development, it is clear that the following questions should be addressed:

- The quality of individual variables in National Weather Prediction (NWP) centre products, such as NCEP, should be revisited to provide the possibility to set up parameterisations of air-sea interaction which will largely rely on the most accurate parameters and be to a lesser degree dependant on the most problematic parameters (e.g. cloudiness, humidity).
- The bulk formulae used in the models must be a simplified version of the state-of-the-art flux production algorithms, but they must still account for the key sea-air interaction processes.
- Interplay of bulk formulae with sea ice must be analysed, especially in the (relatively new) context of eddy resolving configurations,
- Synoptic and sub-synoptic variability of fluxes should be adequately represented, and thus comprehensive analysis of the time scales should be provided.

Such a strategy is clearly a long-term one. A “first-guess” of the forcing function will be estimated in 2003 for the first model runs, with minimal changes from available forcing data and available bulk formulae. Continuous improvement and assessment of this “first guess” forcing will be sought to reach an updated forcing function in 2006 for the high resolution North Atlantic and Nordic Seas model configuration. Our strategy will be discussed and co-ordinated with the work proposed in the framework of GMMC by A. Bentamy et al (LOS, IFREMER).

Flow-topography interaction

Many studies have been conducted on this theme at LEGI during the DYNAMO project (Willebrand et al, 2001, Barnier et al., 2001) and CLIPPER (Penduff et al, 2001 and 2002). Many aspects of flow-topography interaction are represented best using a vertical "s" coordinate, like rectification due to eddies (de Miranda et al, 1999a). On the other hand, the "s" coordinates does not systematically improve the representation of overflows (Willebrand et al, 2001).

During the first phase of the project, the DRAKKAR team will investigate in more details the partial step representation of the topography. Käse et al. (2002) and Myers and Deacu (2003) show a large sensitivity of the subpolar gyre circulation when the topography is represented by partial cells instead of the classical "full cells". Recirculations seem to improve, but the stronger boundary current can worsen the problem of salinity increase. Although the partial step topography is a priori more accurate than full cells, results vary with each model's horizontal, vertical resolution, and parameterisations. Partial step topography must thus be validated in detail in each DRAKKAR model configuration.

Investigations in the context of FLAME (Beckmann and Doscher, 1997, Dengg et al, 1999) as well as ongoing work at LEGI (GMMC proposal, years 2002-2003), have shown that bottom boundary layer parameterisations improve some aspects of the overflows (mainly the overflows from the Nordic seas) but not others (the Mediterranean Sea outflow). Those studies must continue in the context of DRAKKAR, for instance to render the bottom boundary layer parameterisations compatible with the partial step topography.

Eddy representation and parameterisation

DRAKKAR will use model configurations at resolutions from non-eddy resolving to eddy permitting to fully eddy resolving (especially as allowed in small regions by the AGRIF tool). It

is thus necessary to develop our understanding of how to parameterise subgrid scale effects at different resolutions. Even taking into account only the most widespread parameterisations around (isopycnal/horizontal harmonic/biharmonic mixing, Gent and McWilliams eddy-induced velocity, Smagorinsky shear-dependent mixing...), there is no consensus about which parameterisation is the most adequate according to the dynamics and model resolution. Work is currently under way on that topic at LEGI (GMMC proposal, 2002-2003) building on the results of J. Chanut's PhD thesis, and focussing on the Labrador sea and convection regions. The DRAKKAR team will pursue the investigation of this problem in collaboration with Nick Hall (LEGI) and Y. Morel (CMO), considering a variety of dynamical regimes throughout the North Atlantic. We will use a very pragmatic approach based on comparison of experiments with increasing spatial resolution, using the AGRIF grid refinement software.

3.3 Collaborations with associated scientists

This part of the project is still being elaborated. Contributions from associated scientists have been solicited, and more propositions for collaborations are arriving as the project begins to be better known in our community. The following list is not exhaustive, and is restricted to DRAKKAR. At present, we mention these associated projects very briefly, but a summary of the objectives will be included in the near future.

Global sea level variability. C. Le Provost, A. Cazenave and collaborators at LEGOS.

Variability of the Antarctic circumpolar current (ACC) and its carbon cycle.

- Eddy kinetic energy variability in the ACC (R. Morrow, LEGOS).
- Eddy variability and its effect on the carbon cycle (O. Aumont - LODYC, P. Rivière - LEMAR).
- Description of the circulation and water masses of the Austral ocean, and understanding the mechanisms generating their (seasonal to interannual) variability (BILBO project scientists).

Pacific and Indian Oceans

- Contacts have been made with T. Delcroix (IRD), Y. Du Penhoat (LEGOS) and with B. Ferron (LPO). Contact with LODYC scientists is being established (R. Molcard, J. Vialard, , C. Menkes, etc...).

Atlantic Ocean

- Variability of the transports and water masses in the subpolar Atlantic (OVIDE project participants).
- Response of the Gulf Stream and the subtropical gyre to atmospheric forcing, propagation of anomalies along the western boundary, variability of the sea-surface salinity in the North Atlantic (C Frankignoul).
- Yucatan Channel and the Gulf of Mexico (J. Candela and E. Pavia - CICESE Ensenada, Mexico, M. Crépon - LODYC).
- Dynamics of the Equatorial Atlantic and currents in the Gulf of Guinea (IRD scientists - EGEE project, and A. Vangriesthem IFREMER - BIOZAIRE project).
- Dynamics of the subpolar latitudes, variability of sea surface salinity (J. C. Gascard, G. Reverdin, LODYC).
- The melt of the Greenland Icecap in recent years and its impact on the fresh water budget of the subpolar gyre (H. Gallée, LGGE and X. Fettweis, UC Louvain-la-Neuve).

- Natural variability of the upwelling and ecosystem of the Canaries (P. Marchesiello, IRD Brest).
- Low frequency variability in the Nordic Seas and the Arctic (M.-N. Houssais and C. Herbaut, LODYC).

Advanced data assimilation in eddy resolving models.

- Development of assimilation tools for nested grids (P. Brasseur and J. Verron - LEGI, in collaboration with E. Blayo and L. Debreu - LMC).
- Evaluation of coupled physical/bio-geo-chemical assimilative systems: (P. Brasseur - LEGI, in collaboration with Patrick Monfray - LEGOS and Olivier Aumont - IPSL).
- Model configurations implemented and validated by DRAKKAR partners will be used by N. Ayoub at LEGOS.

Multidisciplinary studies :

- Contacts are currently going on to build up a collaboration with J. Orr - LSCE on CFCs and C₁₄.
- Bio-geochemistry: Collaborations with M. Levy (LODYC).

Sea-Ice:

- Evaluation of the ice-model in high resolution configurations (T. Fichefet - UCL Louvain La Neuve).

Numerical Modelling

- Development of grid refinement tools, coupling of models and numerical methods (E. Blayo, L. Debreu and E. Kasantsev, LMC).

3.4 Implementation plan and calendar

The first phase of the project (2003-2004) is dedicated to global and regional simulations at eddy and non eddy permitting resolutions, with for some experiments, a local refinement to full eddy resolving resolution. Results from these latest experiments will be used by the DRAKKAR group to define in 2005 the high resolution model on the North Atlantic and the Nordic Seas (NATL12/20), with a resolution better than 1/12° (between 1/12° and 1/20°). The high resolution model will be run in 2006 and analysed in 2007 (a separate implementation plan will be submitted later for those experiments). The implementation plan and calendar plan will be updated annually by the DRAKKAR project team to foster the co-ordination between the partners. The planing of the major tasks that will be carried out in 2003 and 2004 is presented in Table 1.

For the choice of forcing data and eventual improvements of the bulk parameterisations, specific validation studies on the atmospheric variables to be used will be conducted at SIO-Moscow (S. Gulev) and also in collaboration with the GMMC proposal of Bentamy et al. Model experiments will be performed at LPO using the global ORCA05 (1/2°) configuration with the LIM ice model. This configuration will have the same vertical resolution as the global 1/4° configuration (45 layers) and a partial step topography. This version will also be implemented at IFM (A. Biastoch) in particular for data assimilation studies, and for local refinements (AGRIF) sensitivity experiments.

The NATL4 (North-Atlantic/Nordic-Seas 1/4°) configuration will allow various tests (partial step topography, parameterisations, sea-ice model in eddy permitting mode) before running the

global $\frac{1}{4}^\circ$ model. It will have the same grid, topography, and forcing fields as the global $\frac{1}{4}^\circ$ model, and at first will use boundary conditions taken from the global $\frac{1}{2}^\circ$ model. NATL4 will be a useful tool after 2004 for process-oriented studies and to evaluate the respective role of local and remote forcing in the North Atlantic variability, and a support for AGRIF zooms in key regions. Developed at LPO, its use will be shared by LPO, LEGI, and IFM.

The ATL4 (Atlantic $\frac{1}{4}^\circ$) configuration is similar to NATL4 but its northern limit will be located at the sills of the Nordic Seas and it will include the South Atlantic. It will be developed and used for sensitivity studies by IFM.

Table 1: Planning of the various tasks and numerical experiments carried out for the DRAKKAR objectives during the first three years of the project (2003-2005).

2003		2004		2005 and beyond
Definition of forcing fields (SIO, LPO, LODYC)		Continuous improvement of forcing fields and forcing parameterisations for the very high resolution model at SIO.		
Implementation of the $\frac{1}{2}^\circ$ global model ORCA05-LIM at LPO and IFM	Test of forcing fields in ORCA05-LIM by LPO, LODYC and IFM	50 year long experiment with ORCA05-LIM by LPO	Analysis of the results by the EG group	
		Sensitivity experiments with ORCA05-LIM with and without high resolution AGRIF at IFM		
	Implementation of the Research Version of the global $\frac{1}{4}^\circ$ model ORCA025-LIM at LEGI co-ordinated with Mercator R&D	50 year long experiment with ORCA025-LIM by LEGI.	Analysis of the results by the EC group	
Implementation of the $\frac{1}{4}^\circ$ North Atlantic Nordic Sea model NATL4 at LPO	Validation of the NATL4 configuration with open boundary for sea-ice by the EC group	Experiments with NATL4 and AGRIF at high resolution in key areas co-ordinated between LPO and LEGI	Series of 50 year long experiments with NATL4 and various boundary conditions from the ORCA05 50-year experiment	
			Experiments with NATL4 and AGRIF at high resolution in key areas co-ordinated between LPO and LEGI	
	Implementation of the $\frac{1}{4}^\circ$ North Atlantic model ATL4 at IFM	Validation of the ATL4 configuration with open boundary for sea-ice by the EC group	Sensitivity experiments with ATL4 with and without high resolution AGRIF grid refinements at IFM	
Implementation of global test configurations for the sigma coordinate at the University of Helsinki and local configuration at LEGI.			Begin implementation of the very high resolution North Atlantic / Nordic Seas Model by the EC group	

We propose to carry out a 50 years long model simulation (1950-2000+) with the ORCA025-LIM configuration driven by an atmospheric forcing derived from the NCEP/NCAR re-analysis. This simulation will include the oceanic spreading of CFCs since 1950, following the OCMIP protocol (Dutay et al, 2002). We shall attempt to include C_{14} as well. Another, shorter experiment (1992 to present) will be carried out using more accurate forcing fields available only for the recent years (satellite winds and precipitation, for instance). It will also include CFCs initialised from the previous experiment. The model will be implemented in 2003, the main experiments run in 2004 by LEGI, and the analysis of the results will begin in 2005.

The implementation of the very high resolution North Atlantic/Nordic Seas model will likely begin in 2005, after a first assessment of the first phase of the project.

Analyses of this ensemble of experiments will be co-ordinated by the EC project team, giving rise to many joint scientific studies between EC and associated scientists. These analyses will heavily rely on the PhD students and the Postdocs that will be able to join the project (applications for assistantships are indicated in Table 3).

Table 2: Relevance of the scientific objectives of the French DRAKKAR project team for the different national programs.

Themes	GMMC	PATOM	PNEDC
North Atlantic and Nordic Seas variability in relation with the world ocean	- NATL4/ ORCA025 model configurations development and validation. - Open boundaries with sea ice - In-depth evaluation of ORCA025.	- Role of eddies in interbasin exchanges	- Variability of the North Atlantic. - Quantification of interbasin exchanges. - Variability of heat and freshwater budgets
Processes within the North Atlantic and Nordic Seas	- Tests and improvements of AGRIF tool. - Preparation of a high resolution North Atlantic configuration. - Understanding (by direct simulation) trajectories of ARGO floats	- Role of local processes in the variability of the circulation. - Vorticity balance of the subpolar gyre. - Mechanisms of variability of water masses.	- Role of local processes in the variability of the thermohaline circulation. - Role of eddies and thin boundary currents on the regional heat and freshwater balances. - Enhanced understanding of ongoing observations (OVIDE, ARGO). - Modes of variability and propagation of anomalies
Improvement of key processes in ocean models	- validation of bulk formulae and forcing data in high resolution models. - Test and validation of partial step topography - Combining partial steps with bottom boundary layers	- Flow topography interactions. - Subgrid scale parameterisations and eddy representation.	- Forcing fields: improvement and validation. - Subgrid scale parameterisations for climate models

3.5 Budget, human and computer resources

3.5.1 Requested funding

European collaboration:

An application to a PICS (Programme International de Coopération Scientifique) will be made to CNRS to support the co-operation between the French and the German teams. The amount requested will be 15 000 € per year for the next three years.

French contribution:

The project has objectives relevant to the 3 following national projects: PNEDC, PATOM and GMMC. The estimated level of funding is the following (a funding request on the proper form will be provided to the relevant scientific committees in due time).

- GMMC : 20 000 €/year for the next 3 years (funding for the first 2 years obtained).
- PATOM : 9 500 €/year for the next 3 years.
- PNEDC : 9 500 €/year for the next 3 years.

High resolution NATL15/20:

For the high resolution phase (2005 and beyond) the DRAKKAR project will be fully established, and the funding of the project will be updated.

3.5.2 Human resources

Personnel presently working on the project:

Table 3: Permanent and non permanent scientists working on the project in 2003.

Name	Activity	% time	Laboratory
Bernard Barnier	Co-ordinator	60	LEGI, Grenoble
Christian Le Provost	Scientist	20	LEGOS, Toulouse
Gurvan Madec	Scientist	20	LODYC, Paris
Thierry Penduff	Scientist	60	LEGI, Grenoble
Anne Marie Tréguier	Scientist	80	LPO, Brest
Jean Marc Molines	Research engineer	75	LEGI, Grenoble
¹ Anne de Miranda	Research engineer	50	Réseau bleu
Sebastien Theetten	Research engineer	80	LPO, Brest
¹ Elisabeth Remy	Research engineer	50	LEGOS, Toulouse
Sylvain Cailleau	PhD thesis	15	LEGI-LMC, Grenoble
Josiane Brasseur	Project secretary	20	LEGI Grenoble
Total : About 8/10 full time researchers and engineers should be working on the project in 2004/2005			

¹In a co-operation between DRAKKAR and MERCATOR-OCEAN,

Post-docs and PhD students will be requested to work on the project starting in 2004.

3.5.3 Computer resources:

A simulation of 50 years with the global $\frac{1}{4}^\circ$ model will represent about 17 000 of NEC CPU hours. Tests will be performed to see if this model configuration can run efficiently on the parallel IBM machine, when the new version of the connecting network is available.

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- Penduff, T., B. Barnier, W.K. Dewar, J.J. O'Brien, 2003: Impact of the North Atlantic Oscillation on the eddy flow: dynamical insights from a model-data comparison. Submitted to J. Phys. Oceanogr.
- Valdivieso da Costa, M, H. Mercier and A.M. Treguier, 2003: Effects of the mixed layer time variability on kinematic subduction rate diagnostics. submitted to J. Phys. Oceanogr.
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4.3 Other recent publications of the DRAKKAR team (2001-2003):

- Barnier, B., T. Reynaud, A. Beckmann, C. Böning, J.-M. Molines, S. Barnard and Y. Jia, 2001: On the seasonal variability and eddies in the North Brazil Current: Insights from model intercomparison experiments. *Progress in Oceanography*, Vol. 48, 195-230.
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4.4 List of acronyms:

ARGO: Global array of profiling floats, part of the GOOS

DOE : Dynamics of Overflows and Entrainement.

DYNAMO (MAST3 European project): DYnamics of North Atlantic MOdels.

FLAME : a Family of Linked Atlantic Models

GMMC: Groupe Mission Mercator-Coriolis

GODAE: Global Data Assimilation Experiment

GOOS: Global Ocean observing System

IPCC: Intergovernmental Panel on Climate Change

PATOM: Programme ATmosphere-Ocean à Multi-échelles

PNEDC: Programme National de l'Etude de la Dynamique du Climat