Excerpts from a proposal for a Concerted Research Actions (ARC) programme

Taking up the challenges of multi-scale marine modelling

by

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Acknowledgements
Wanderer, there is no road,
walking makes the road.

Antonio Machado
I. The Project

The use of such [numerical] simulation in scientific research (numerical experimentation, sensitivity study and process studies, etc.) is thought by many to represent the first major step forward in the basic scientific method since the seventeenth century. Science is now a tripartite endeavour, with Simulation added to the two classical components, Experiment and Theory.


I.1. Introduction: the need for multi-scale modelling

Ecosystems are changing fast. One of the main findings of the Millennium Ecosystem Assessment, released in 2005 after the first four years of study, is that “over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fibre and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth” (Millennium Ecosystem Assessment, 2005). The report further indicates that “the degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to reducing global poverty”. Recent ecosystem degradations have been principally driven by demographic pressure and economic development, which in turn have led to changes in land-use, increase in resource consumption, environmental pollution and climate change. Among these drivers, climate change is expected to become the dominant driver of changes in ecosystem services globally. The resulting ecosystem changes will have dire consequences for human well-being and represent a significant cost to Society (Stern, 2007).

Ecosystems are intrinsically multi-scale. The scientific community needs to develop a thorough understanding of the functioning of ecosystems in order to be able to predict their evolution under increasing anthropogenic pressure, assess potential impacts on Society and evaluate the efficiency of mitigation measures. Ecosystems being complex systems characterised by a hierarchy of levels interacting among each other in a non-linear manner, such an endeavour will be intrinsically multi-scale. As such, it will require methods to transfer information between scales and account for cross-scale interactions. The need for a multi-scale approach is further justified by the differences between scales at which ecosystems degradation is driven, scales at which the resulting changes to ecosystem functioning have most impact, scales at which ecosystems are managed and scales at which we have got the best understanding of the physical and biological processes driving ecosystems.

Climate is changing fast and is intrinsically multi-scale. The Intergovernmental Panel on Climate Change (IPCC\(^1\), 2007) has established that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea

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\(^1\) IPCC: Intergovernmental Panel on Climate Change (http://www.ipcc.ch), also known as GIEC (Groupe d’experts Intergouvernemental sur l’Evolution du Climat).
level”. Furthermore, “most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations”. The climate system is made up of several components (atmosphere, hydrosphere, cryosphere, lithosphere, biosphere) that are functioning and interacting over a wide range of time and space scales. In the ocean, for instance, deep convection (e.g. Killworth, 1983) occurs over a few days in a small number of areas a few kilometres in size, and yet this process is crucial for the formation of water masses and the oceanic uptake of carbon dioxide — and other gases.

**Ecosystems and climate interact with each other.** Their functioning and interactions take place over a wide range of space and time scales. The inherently multi-scale nature of the abovementioned phenomena is one of the motivations for the present proposal. We are not planning a comprehensive study of the World's ecosystems and climate. Instead, we will focus on the processes transporting matter, momentum and energy in the hydrosphere², i.e. ubiquitous and inherently multi-scale phenomena. There are three reasons why we have decided to focus on the hydrosphere:

1. **More than half of the World's population lives within 60 km of the coast**, hence the crucial importance of coastal seas and the land-sea interface region, or the so-called land-sea continuum.
2. **Aquatic ecosystems are among the fastest deteriorating ecosystems**. For instance, over the last two decades, about 20% of the World's coral reefs have become barren due to the combined effect of an increase in sea temperature, nutrient pollution and overfishing.
3. **Sea ice** — with its high albedo and the associated high-latitude feedback processes — and the **World Ocean** — with its enormous heat capacity and the very long timescales of its interior — are key players of the climate system.

Today, numerical models and computer simulations are the only tools available to understand in detail and predict the evolution of the abovementioned complex systems. However, even the most powerful computers cannot explicitly represent all of the existing phenomena, for their spectrum of space and time scales is much too wide (e.g. from millimetres to thousands of kilometres and from seconds to thousands of years in the World Ocean). Ignoring the smallest time-space scales is not an option, for the systems dealt with are non-linear, implying that the smaller-scale processes interact with the larger-scale ones. The only feasible approach consists in simulating explicitly only the largest-scale phenomena, while taking into account the smaller-scale ones by means of makeshift formulas — usually termed “physical parameterisations”.

Since the 1950's, computer power increased steadily, which progressively allowed for an increase in model complexity and a widening of the range of explicitly-resolved phenomena. This trend, which is unlikely to come to a standstill, caused spectacular improvements in models' skills. Unfortunately, further increasing the resolution³ is far from easy, as doubling

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² Herein, for the sake of simplicity, sea ice is assumed to be part of the hydrosphere rather than the cryosphere.
³ The concept of resolution may be loosely defined as the inverse of the distance between points where the computer estimates the value of the state variables, i.e. velocity, pressure, temperature, etc.
the resolution might multiply the computer time by as much as sixteen\textsuperscript{4}. Therefore, the best strategy probably consists in enhancing the resolution only when and where this is needed. Doing so may prove difficult in most of today's models, for the structured grids they are based on markedly lack geometrical flexibility (Figure 1). To remove this stumbling block, a new generation of models is emerging. Seeking inspiration in developments pioneered essentially in mechanical engineering, these models will offer an almost infinite flexibility for adapting the resolution to the features of the processes under study, leading to multi-scale simulations.

**Figure 1.** Structured (left) and unstructured (right) meshes of the Irish and Celtic Seas. The former grid was generated by Jones and Davies (2005), while the latter was built by means of Gmsh (see Section I.2.b). The geometrical flexibility of the unstructured mesh is clearly illustrated, for it allows for a better representation of the coastlines and an enhanced resolution over dynamically-important bathymetric features.

To perform multi-scale simulations, having recourse to unstructured-mesh techniques is not the only option; grid nesting is the most obvious and best-known alternative as it can be implemented in structured-mesh models (e.g. Zavatarelli and Pinardi, 2003; Barth et al., 2005; Debreu and Blayo, 2008, and references therein). However, it is our conviction that unstructured-mesh modelling is the most promising option. The present proposal is based on this hypothesis.

\textsuperscript{4} Strictly speaking, this applies only to a doubling of the resolution in a three-dimensional model using an explicit time stepping.
One of the teams leading the development of unstructured-mesh marine models is based at the Université catholique de Louvain (UCL). Over the last decade, this group worked out the first prototype of the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM), and has been heavily involved in the dissemination of the findings ensuing from these novel model developments and applications. For instance, Emmanuel Hanert and Eric Deleersnijder participated in the edition of special issues of Ocean Modelling on unstructured-mesh marine modelling (Pietrzak et al., 2005; Hanert et al., 2009). Eric Deleersnijder was instrumental in assembling a special issue of Ocean Dynamics devoted to multi-scale modelling (Deleersnijder and Lermusiaux, 2008). A somewhat similar initiative has recently been announced, in which Vincent Legat is due to play a leading role. The latter was a key speaker at the scoping meeting on Multi-scale Modelling of the Atmosphere and Ocean that was held on 25-26 March, 2009, at Reading University, and was placed under the auspices of Cambridge's Isaac Newton Institute for Mathematical Sciences. All the promoters of the present proposal were involved in the organisation of the 8th International Workshop on Unstructured Mesh Numerical Modelling of Coastal, Shelf and Ocean Flows, that was held on September 16-18, 2009, in Louvain-la-Neuve. Finally, Eric Deleersnijder will lead the preparation of a special issue of Environmental Fluid Mechanics entitled Integrated Studies of the Land-Sea Continuum, in which multi-scale model developments and results are likely to be reported on.

In the next section, the state of the art in this rapidly-developing domain is outlined. Our intention is not to provide a review of all of the existing models and numerical methods. However, we believe that the main types of approaches will be mentioned, with a certain emphasis on SLIM.

I.2. A brief account of the state of the art

I.2.a. Ocean models

Numerical ocean simulation started in the sixties, when the first models were developed, with, in particular, the seminal paper of Bryan (1969). These models used finite differences on structured grids. Over the years, many improvements have been achieved, regarding all the aspects of the models, i.e. the equations, the numerical methods and their computer implementation. Flexible vertical coordinate systems (see White and Adcroft, 2008; White et al., 2009; and references therein), advanced subgrid-scale and neutral physics (e.g. Griffies et al., 2000; Griffies, 2004; Griffies et al., 2005), and high-order monotonic advection schemes are amongst the many improvements that ocean models have benefited from (see also Griffies et al., 2009).

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5 SLIM belongs to the second generation of geophysical and environmental fluid flow models because it is based on an unstructured mesh, as opposed to first-generation ones that rely on structures meshes.
6 http://www.climate.be/slim
9 https://www.newton.ac.uk/events/iniw90/iniw90.html

I-4
Most of mainstream models still rely on conservative finite differences on structured grids. Such algorithms are very fast. They also have inherent limitations. Coastlines have a staircase representation, which may generate spurious effects (Adcroft and Marshall, 1998). The grid is an image of the coordinate system. Therefore, varying resolution requires changing the metric, and this prevents highly-variable resolution to be easily achieved.

To handle a wide range of scales, structured grid models usually rely on nested grids. This allows to vary the resolution, and therefore, achieve local refinement in zones of particular interest. The main drawback of such methods is that resolution can exhibit large jumps in grid size at the grid interfaces. In addition, two-way nesting, where the large and small domains influence each other, needs advanced techniques to avoid wave reflections and ensure high order time and space accuracy (e.g. Debreu and Blayo, 2008). Mainstream regional models, such as ROMS\textsuperscript{12}, rely on such nesting procedures (e.g. Warner et al., 2008).

Unstructured grids nicely circumvent most of the drawbacks of structured models. Coastlines can be smoothly represented; resolution can vary smoothly from hundreds of kilometres to tens of meters. However, due to the complexity of unstructured topology, implementation can hardly be as efficient as structured models. Unstructured mesh resolution of partial differential equations may resort to various types of methodologies.

A large family of models are built upon unstructured staggered low order discretisations. These can have finite-difference, finite-volume and finite-element interpretation. Walters and Casulli (1998) describe how to use the lowest order Raviart-Thomas finite element. Such an approach is used in RiCOM, a three-dimensional coastal model (Walters, 2006). Casulli and Walters (2000) describe a finite-volume approach on orthogonal triangular grids. Such an approach is used in Ham et al. (2005). An efficient semi-implicit wetting and drying algorithm can be integrated in such a model (Casulli, 2008). All these approaches can at best provide second order accuracy, but the actual order of accuracy is known to depend on the quality of the mesh.

FVCOM\textsuperscript{13} provides an implementation of a low-order staggered finite-volume method for the hydrostatic, primitive equations. The mesh is 2D unstructured on the horizontal with vertically-aligned nodes (Chen et al., 2003; Chen et al., 2006; Chen et al., 2007). The model equations can be expressed either in Cartesian or spherical horizontal coordinates in conjunction with generalized terrain-following vertical coordinates. The model allows for wetting and drying, and has a sea ice and biological modules. This model has many users, thanks to the robustness of its algorithms and the quality of its designers' team.

Stanford University's SUNTANS\textsuperscript{14} is a non-hydrostatic, primitive-equation, coastal-ocean model. The mesh is horizontally unstructured and vertically structured, with $z$ vertical levels (Fringer et al., 2006; Wang et al., 2008). A wetting and drying algorithm is available, as well as up-to-date subgrid-scale parameterisations.

\textsuperscript{12} ROMS: Regional Ocean Modeling System (http://www.myroms.org/).
\textsuperscript{13} FVCOM: Finite Volume Coastal Ocean Model (http://fvcom.smast.umassd.edu/FVCOM/index.html).
\textsuperscript{14} SUNTANS: Stanford University Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (http://suntans.stanford.edu/).
Finite-element models have advantages over finite-volume and finite-difference models in that they allow for higher order interpolation, and thus higher order accuracy. SEOM, the spectral element ocean model, was a first attempt to use high-order finite elements for oceanic flows (Iskandarani et al., 1995; Iskandarani et al., 2005). However, really high order discretisation needs high order representation of geometry and forcing, increasing the workload in the pre-processing stage.

Among finite-element models, many are built upon the P1NC-P1 discretisation, such as TsunAWI (Harig et al., 2008), one of the versions of FEOM\textsuperscript{15} (Danilov et al., 2008), or the Great Barrier Reef model of Lambrechts et al. (2008b). This finite-element pair attempts to mimic the staggering of the finite-difference C grid. However, its accuracy decreases to first order in the inviscid limit (Hanert et al., 2008; Comblen et al., 2009a).

The previously-cited finite-element models use no explicit stabilization term. In computational fluid dynamics, it is usual to resort to a stabilised formulation to obtain an efficient discretisation using element pairs that otherwise would be unstable. One model using such a formulation is FEOM (Wang et al, 2008a; Wang et al., 2008b). The main version of FEOM is a P1-P1 three-dimensional hydrostatic finite-element model, using unstructured 2D-horizontal meshes with vertically-aligned nodes and flexible vertical coordinate solutions. This model is designed for large-scale ocean modelling, and is therefore equipped with the relevant subgrid-scale and neutral physics parameterisations. It is coupled to a finite-element sea-ice module (Timmermann et al., 2009).

ADCIRC\textsuperscript{16}, the successor of QUODDY, is a coastal ocean model that solves either the two-dimensional, depth-integrated equations or the three-dimensional, primitive equations (Westerink et al., 2008). It uses both continuous, low-order, finite elements or discontinuous, high- and low-order finite elements (Dawson et al., 2006; Kubatko et al., 2009). The former have to be stabilised by means of a generalised wave continuity equation. The mesh is unstructured in the horizontal and structured in the vertical. Wetting and drying is implemented.

ICOM\textsuperscript{17} is a three-dimensional, non-hydrostatic model that employs fully-unstructured, dynamically-adaptive meshes (Ford et al., 2004a; Ford et al., 2004b; Piggott et al., 2008). This collocated method allows the existence of spurious oscillations and thus requires some stabilisation procedures to obtain acceptable solutions. The time-integration scheme is implicit.

Since the late nineties, there is a growing interest in the Discontinuous Galerkin (DG) method, mainly because this technique provides accurate results for hyperbolic conservation laws. Basically, it consists in a volume term built as in all finite-element methods, and an interface term built as in finite-volume methods. High-order shape functions can be easily incorporated and, at the interfaces, an efficient upwind flux calculation can be performed to tackle the treatment of wave phenomena. Thanks to the absence of continuity constrain on the inter-element boundaries, h-adaptivity (Hartmann and Houston, 2002; Bernard et al.,

\textsuperscript{15} FEOM: Finite Element Ocean circulation Model, from Bremerhaven's Alfred Wegener Institute for Polar and Marine Research (http://www.awi.de).
\textsuperscript{16} http://www.adcirc.org
\textsuperscript{17} ICOM: Imperial College Ocean Model (http://amcg.ese.ic.ac.uk/index.php?title=ICOM).
2007) and p-adaptivity (Burbeau and Sagaut, 2005) can be easily implemented. Efficient slope and flux limiters enable positive and shock-capturing versions of the scheme (Cockburn and Shu, 1998; Chevaugeon et al., 2005; Remacle et al., 2006). For atmospheric modelling, the high-order capabilities of this scheme are very attractive (Nair et al., 2005; Giraldo, 2006), and the increasing use of DG follows the trend to replace spectral transform methods with local ones. Coastal modelling also benefits from this method (Aizinger and Dawson, 2002; Kubatko et al, 2006; Bernard et al., 2009), and high Froude number flows are accurately captured by this kind of schemes (Schwanenberg and Harms, 2004; Remacle et al., 2006). However, the implementation of elliptic dissipative terms requires specific modifications, as is discussed in Arnold et al. (2002). The local-DG method (LDG) and the interior penalty method (IP) are among the most popular solutions. LDG introduces a mixed formulation for velocities and stress and can be difficult to handle with an implicit time stepping (Cockburn and Shu, 1998), while IP requires the introduction of a penalty parameter that worsen the conditioning of the discrete spatial operator (Riviere, 2008).

I.2.b. SLIM's liquid water component

There are one-, two- and three-dimensional versions of SLIM's liquid water component. The first one has been used principally to investigate vertical mixing processes in shallow seas and estuaries (Blaise and Deleersnijder, 2008), i.e. process studies. The model capitalises on both the geometrical and functional flexibility of the finite-element method to achieve the highest accuracy at the lowest computational cost. Geometrical flexibility is achieved by dynamically changing the grid resolution during the course of the simulation to track features of interest, like the pycnocline position (Hanert et al., 2006). Mesh adaptation is based on an error estimator that indicates where resolution should be increased. Currently, the error estimator depends on the distance to the surface, distance to the bottom and density gradient. Furthermore, the functional flexibility of the finite-element method allows us to locally modify or enrich the set of basis functions used to approximate the model solution. That feature, based on the X-FEM\(^{18}\) formalism, is particularly useful to improve the representation of the velocity field in the bottom boundary layer. The velocity field being asymptotically logarithmic near the bottom, we use that information to modify the set of basis functions and thus compute an accurate velocity field without having recourse to the so-called law-of-the-wall approach (Hanert et al., 2007).

The 2D module solves the depth-integrated shallow-water equations. Preliminary results were obtained in a number of domains: Lake Tanganyika (Gourgue et al., 2007), The Gulf of Mexico (Bernard et al., 2007), the Great Barrier Reef, Australia (Lambrechts et al, 2008b). For the first two applications, SLIM was used in a reduced gravity mode and, in the Gulf of Mexico, dynamic mesh adaptivity was — very successfully — resorted to (Bernard et al., 2007). Various flow instability cases were simulated, as a first attempt to demonstrate the capability of our model to represent meso-scale variability (White et al., 2006). Wetting and drying can be taken into account by means of a conservative, but computationally inefficient, algorithm (Gourgue et al., 2009).

\(^{18}\) X-FEM: eXtended Finite-Element Method (http://www.xfem.rwth-aachen.de/).
It is noteworthy that SLIM has a river network module that can be coupled easily to its 2D hydrodynamic module (de Brye et al., 2009). Each river has a one-dimensional representation, but as many confluences as is necessary can be implemented. This allowed us to carry out an exploratory, integrated study of the Scheldt River, tributaries, Estuary and the adjacent shelf sea (de Brye et al., 2009).

SLIM incorporates a local, element-based coordinate system (Comblen et al., 2009b), where a non-flat 2D mesh can naturally be taken into account. This is a key feature for large-scale geophysical simulations where taking into account Earth's curvature no longer is a problem. Also solved is the problem of the singularity at the poles arising when the mesh is based on a geographical coordinate system (see Robert et al., 2006, and references therein).

SLIM is flexible in terms of temporal integration as it is equipped with explicit, semi-implicit and fully implicit Runge-Kutta time marching algorithms providing a wide variety of tools to control the computational cost and/or accuracy of the solution. In the case of the fully implicit time marching, the numerical system of equations is being solved with a Newton iteration where the Jacobian is approximated numerically.

The spatial derivative operators are discretised with the Galerkin finite-element method for both the free-surface elevation and the velocity field. A key advantage of the finite-element formulation is that there is no restriction on the element type: both continuous and discontinuous elements of various polynomial orders can be used. In the case of Discontinuous Galerkin method (DG), the numerical solution is a piecewise polynomial function that is discontinuous at the element interfaces. The inter-element fluxes are solved with an approximate Riemann solver (Comblen et al., 2009a). The code is parallelised with MPI interface to allow efficient and seamless operation in large computing clusters.

Generating high-quality meshes tailored to suit the applications is essential for taking full advantage of the flexibility of the finite-element method. The meshes are generated with the Gmsh software (Lambrechts et al., 2008a), where the mesh size can be arbitrarily defined based on various criteria (Legrand et al., 2000; Legrand et al., 2006; Legrand et al., 2007) such as distance to the coastline, wave speed, curvature of the coastline, local refinement, error measures from previous simulations, etc.

SLIM incorporates a generic tracer equation that is consistent with the 1D, 2D and 3D modules. The tracers can be run off-line using stored hydrodynamical data, which reduces computational cost significantly in cases where the hydrodynamics is already available. The tracer module has a generic reaction term that can be adapted to model different tracers. So far, the tracer module has been used for simulating salinity, radioactive pollution, fecal bacteria (de Brauwere et al., 2009), and residence time (Blaise et al., 2009). A preliminary version of a sediment transport module is being developed and tested in the Scheldt Estuary.

SLIM's three-dimensional module solves the Boussinesq equations under the hydrostatic approximation. These equations are solved on a three-dimensional mesh, made up of prismatic elements built from the extrusion of a two-dimensional triangular mesh.

Early versions of the three-dimensional code were based on continuous-discontinuous formulations, in which strict conservativity was guaranteed (Blaise et al., 2007; White and

19 http://www.mcs.anl.gov/research/projects/mpi/
20 http://www.geuz.org/gmsh/
Deleersnijder, 2007; White et al., 2008a; White et al., 2008b; White and Wolanski, 2008). Then, the model has been profoundly modified so that it now largely relies on the Discontinuous Galerkin method, which has greatly improved the robustness of the code. The lateral interface terms were implemented bearing this objective in mind. Upwinding is used in advection terms. An interface stabilisation is performed, deduced from a Riemann solver for the gravity waves (Comblen et al., 2009a) and a Local-Lax-Friedrichs flux for internal waves.

![Figure 2](image)

**Figure 2.** Numerical simulation by means of the three-dimensional version of SLIM of the evolution of the baroclinic instability suggested by Tartinville et al. (1998) as a benchmark for marine models. Isohaline surfaces are displayed in 3D, while iso-contours of the sea surface elevation are represented at the bottom of each picture. That a “mode-two” instability progressively develops is in excellent agreement with the laboratory experiments of Griffiths and Linden (1981); the majority of the numerical simulations discussed in Tartinville et al. (1998) exhibited results of a lesser quality, i.e. a “mode-four” instability. This figure is reproduced from Blaise (2009).

The temporal discretisation is based on implicit/explicit Runge-Kutta time stepping schemes (Ascher et al., 1997), where stiff linear terms are treated implicitly while nonlinear terms are treated explicitly. The terms related to surface gravity waves, Coriolis, vertical advection and diffusion of tracers and momentum are treated implicitly, while horizontal advection and diffusion are explicit. The resulting linear systems to solve are “block diagonal”, each block corresponding to a column of prisms. It is then not necessary to build three-dimensional global matrices, and the memory usage is highly reduced. The parallel scaling is strong as each block system is solved independently.
Three different vertical discretisations are implemented in the model: sigma- and z-coordinate systems, and shaved cells. Different turbulence closure schemes are implemented to represent unresolved physics. The available vertical turbulence closures include the Mellor and Yamada level 2.5 model (Mellor and Yamada, 1982) and the formulation of Pacanowski and Philander (1981). Horizontal subgrid-scale phenomena are parameterised following the approach of Smagorinsky (1963).

The new version of SLIM_3D is still under development and validation. In this respect, various popular benchmarks are being resorted to. For the DOME, for instance, SLIM's results are comparable to those of other models (Ezer and Mellor, 2004; Wang et al., 2008a). The ability of the model to develop baroclinic instabilities was investigated with the benchmark developed by Tartinville et al. (1998), who sought inspiration in the laboratory experiments of Griffiths and Linden (1981) (Figure 2). Internal wave representation is examined on the basis of Chapman and Haidvogel (1993). Other test cases are or will be considered, including that posted on the web by the SLIM team.

I.2.c. SLIM's sea ice component

For more than a decade, UCL's G. Lemaître Institute of Astronomy and Geophysics has been at the leading edge of sea ice modelling. LIM (the Louvain-la-Neuve sea Ice Model) was originally a large-scale dynamic-thermodynamic sea ice model developed by Fichefet and Maqueda (1997), and coupled to the French ocean model OPA (Goosse and Fichefet, 1999; Timmermann et al., 2005). Recently, a new version of the sea ice model has been released (LIM3, see Vancoppenolle et al., 2009) with major improvements. In order to account for unresolved variations in ice thickness, several thickness categories have been included in the model. A new multi-layer halo-thermodynamic component incorporates an explicit representation of brine entrapment and drainage, as well as the impact of brine on sea ice growth and decay. LIM3 is part of the NEMO ocean modelling system and is used in numerous European laboratories involved in climate studies and operational oceanography.

Finite-element methods have been proposed at the onset of sea ice modelling. In the framework of the AIDJEX project (Arctic Ice Dynamics Joint Experiment), Mukherji (1973) was the first to make use of a finite-element method code for its aptitude to simulate the crack propagation in sea ice. A few years later, Becker (1976) introduced the guide lines of the method and asserted: “Because of their generality and widespread use, finite element techniques seem a worthwhile alternative to the difference scheme. [...] The ease with which finite element techniques can be used to model complicated shapes with arbitrary variation in the mesh spacing is likely to be the motivating factor leading to any such use.” In the early eighties, Sodhi and Hibler (1980) pioneered an unstructured grid along with a finite-element method in order to resolve the ice drift in the complex region of Strait of Belle Isle. Another work investigating the potential of the finite-element method in sea ice modelling was by Thomson et al. (1988). They performed a comprehensive comparison between

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21 DOME: Dynamics of Overflow Mixing and Entrainment (http://www.rsmas.miami.edu/personal/tamay/DOME/dome.html).
22 The Rattray Island benchmark (http://sites.uclouvain.be/slim/index.php?id=91)
23 NEMO: Nucleus for European Modelling of the Ocean (http://www.nemo-ocean.eu/)
different constitutive laws for Eulerian and Lagrangian descriptions in order to model the short-term ice motion in Beaufort Sea. Over the last decade, many efforts have been directed toward the implementation of unstructured meshes in sea ice modelling (Schulkes et al., 1998; Yakovlev, 2003; Wang and Ikeda, 2004; Sulsky et al., 2007). Recently, Timmermann et al. (2009) successively performed a run on a global configuration with a coupled ice-ocean model. However, although impressive progress has been made by Timmermann and his co-workers, a true breakthrough has probably not yet occurred.

The finite-element sea ice model developed in the framework of SLIM (Lietaer et al., 2008) uses two thickness categories to describe sea ice on a given area. The growth and decay of sea ice at the interfaces depend on heat budgets including radiations and turbulent heat fluxes from the atmosphere (Goosse, 1997) and from the mixed layer modelled as a slab ocean (Fichefet and Maqueda, 1997). Following Semtner (1976), the computation of heat diffusion within the thick ice neglects the storage of sensible and latent heat, resulting in a linear temperature profile. The momentum equation includes the viscous-plastic rheology (Hibler, 1979) and is forced by daily wind stress from NCEP/NCAR reanalysis data. The numerical resolution of the set of dynamical equations involves a standard Galerkin formulation and a linearisation procedure based on a Newton-Raphson scheme. The climatological sea ice drifts, thicknesses and concentrations computed by the model compare qualitatively well with the observations.

A clear advantage of unstructured grids is that they enable the resolution of the narrow straits of the Canadian Arctic Archipelago (CAA) while maintaining a reasonable resolution elsewhere. A numerical experiment has hence been performed to investigate the influence of resolving the narrow straits of the Canadian Arctic Archipelago on the sea ice features in the whole Arctic (Lietaer et al., 2008). Focusing on the large-scale sea ice thickness pattern, within our general framework and hypotheses, we have shown that the inclusion of those straits is not essential, the impact being merely local. However, we have shown that the local and short-term influences of the ice exchanges are non-negligible. In particular, depending on whether the straits are open or closed in the numerical experiment, the domain boundary and the associated boundary condition influence directly the numerical solution in the vicinity of those straits. Moreover, on average, the sea ice volume in the CAA represents a non-negligible 10% of the total sea ice volume in our model. Finally, the ice volume fluxes through the Archipelago represent a non-negligible freshwater flux towards Baffin Bay and the Labrador Sea. Though relatively small compared to the ice contribution of the freshwater outflow through Fram Strait (7%), this ice export, together with the North Water Polynya formation, might be important regarding the water stratification in Baffin Bay and the decay of the summer sea ice cover in Baffin Bay. All these features show how important the CAA is on the mass balance of the Arctic sea ice and point to the need for a better understanding of the complex processes and interactions taking place in this region.

Other recent numerical efforts include the development of a Lagrangian, adaptive sea ice model allowing the computational grid to move with the ice drift. In order to maintain a good quality of the mesh, the mesh has to be adapted during the simulation, involving particular mesh adaptation techniques. Different test cases have first been run to evaluate the mesh adaptation procedure and validate the Lagrangian sea ice model; simulations carried
out on the Arctic Basin are being analysed. This Lagrangian version of the model has several interesting applications, such as the dynamical mesh refinement in any region of interest (e.g., the ice edge), buoys tracking, or the inclusion of material properties in the sea ice rheology.

I.3. Numerical and physical challenges

In the previous Section, we made it clear that, over the last two decades, a wide variety of space-discretisations have been tested, with the Discontinuous Galerkin (DG) method potentially emerging as the most promising solution. DG is now implemented in most of SLIM's modules. Unfortunately, so far, a crucial element has been hardly ever discussed in the literature (Danilov et al., 2008; Griffies et al., 2009): in terms of computer time, unstructured-mesh models tend to be one order of magnitude slower than classical, structured-mesh models. Though the unstructured-mesh models (i.e. the second-generation models) can deal with problems that are out of reach for structured-grid models (i.e. first-generation models), the slowness of the new models is a vital problem that must be addressed successfully for these models to prevail within the next 10 to 20 years and be able to perform the multi-scale simulations they are designed for. Dealing with this issue is the most important objective of the present proposal. Accordingly, we must turn to time-marching procedures that are entirely novel or, at least, unheard of in the realm of oceanography. This will imply a very profound modification of the code. Related tasks will involve thoroughly revising the implementation of the code on massively parallel computers and the wetting and drying algorithm, which presently is the slowest part of the code.

During the last decade, we ran as few simplistic, highly-idealised test cases as possible. Instead, whenever possible, we tested the model against realistic flows, albeit often simple ones. This systematically presented the developers of SLIM with problems that would have gone unnoticed for a long time if we had preferred simplistic test cases. Therefore, dealing with as many realistic applications as possible is key for identifying the relevant fundamental numerical and modelling challenges to be taken up and avoid wasting time in trying to improve simulations of simplistic — and often unrealistic — flows\(^{24}\), even though the latter might, at first glance, appear as more “generic” than those taking place at a particular location of the seas of the world.

Therefore, the physical questions to be addressed must:

- be related to intrinsically multi-scale problems, otherwise a classical, first-generation model would be sufficient;
- be sufficiently generic and significant, in the sense that they are relevant to a number of marine or oceanic domains, rather than one specific location of a given sea;
- represent tough, multi-scale test cases for the model equations, the numerical methods and their computer implementation, prompting new and, hopefully, fruitful developments of SLIM.

\(^{24}\) That simplistic test cases may be misleading is an issue that has been addressed in an elegant — though provocative and controversial — manner, by Nihoul (1994) in an article entitled “Do no use a simple model when a complex one will do”.
The main objective of the present project is to

*increase SLIM's computational efficiency by at least one order of magnitude,*
*enabling it to perform multi-scale simulations at an acceptable cost.*

To do so, we will

*have recourse to novel time-integration procedures,* and
*profoundly revise SLIM's implementation on massively parallel computers.*

Physical questions will be addressed that are

*intrinsically multi-scale,*
*sufficiently generic/significant,* and
*represent tough test cases that will require further model developments.*

Accordingly we will study

*ice-ocean interactions in a complex-geometry region,*
*water and sediment fluxes in a tropical land-sea continuum,* and
*coral reefs: impacts of land-to-sea fluxes and physical aspects of connectivity.*

The abovementioned studies will focus on the *Canadian Arctic Archipelago,* the *Mahakam River, Indonesia,* and the *Great Barrier Reef, Australia,* respectively.

To perform these studies and enhance SLIM for present and future projects, we will

*improve the wetting and drying algorithm,*
*develop the sediment dynamics module,*
*complete the baroclinic module,*
*couple SLIM's solid- and liquid-water components,* and
*perform the developments imposed by unexpected issues.*

All aspects of the research work will be carried out in an

*open-source (C++) mode,*
*relying on the collaboration with partners outside UCL.*

The external partners, Profs Ton Hoitink and Eric Wolanski, have explicitly expressed their willingness to contribute data and expertise to the present project (See Appendix C). Improving the wetting and drying algorithm, developing the sediment dynamics module and completing the baroclinic module are also part of the tasks to be achieved in the framework of the ongoing Interuniversity Attraction Pole TIMOTHY\(^\text{25}\). However, the baroclinic flows to be addressed in TIMOTHY occur in shallow-water areas (see de Boer, 2009, and references therein), while those relevant to the study of ice-ocean interactions in a complex-geometry region are of a basin- or global-scale nature. Therefore, overlaps in development and assessment work are likely to be minimal. Other developments of SLIM are performed in the framework of TIMOTHY, which are related to contaminant transport, ecological

modelling and timescale-based diagnoses\(^{26}\). Whether or not the latter will prove to be useful herein has yet to be determined. Finally, developments of diagnostic tools have been made, are being made and will continue to be made in the framework of all the SLIM-related projects, for the structured-mesh tools are not adapted to second-generation model results (e.g. Cotter and Gorman, 2008).

Most of the data needed for calibrating, validating and forcing the model are or will be available (free of charge), as is summarised in Appendix A. The computer format and the time/space scale resolution of the data sets are all different. In addition, most data sets present gaps due to various types of instrumental failures or physical problems. Handling these difficulties is no trivial task (see Sorjamaa et al., 2009, and references therein). Fortunately, there exist freely-available softwares for addressing these issues, the potential of which will need to be evaluated. A good candidate may well be DIVA\(^{27}\), for it is widely-used and well-documented. Hereinafter, there will be hardly any other explicit discussion about data.

The work to be done will be described in Sections 4 and 5, while Section 6 will outline the synergy between the promoters.

I.4. Multi-scale model developments

I.4.a. Novel time-integration procedures

As stated above, it is vital that the computational speed of SLIM be increased by at least one order of magnitude. To perform this daunting task, many aspects of the code will be profoundly modified, i.e. the way it is implemented on parallel computers and the core of the numerical method.

Over the last decade, we have compared various types of finite-element approaches for geophysical and environmental fluid flow simulations, i.e. continuous, partly continuous, and discontinuous techniques. For space discretisation, the Discontinuous Galerkin (DG) finite-element method has become our workhorse. The reasons that led to this choice are as follows:

- **Accuracy**: DG discretisations are able to deal with a number of geophysical and environmental flow regimes (e.g. Comblen et al., 2009a). In fact, DG can be seen as a method that lies somewhere between standard continuous finite elements and finite volumes, enjoying some advantages of both methods (Remacle et al., 2003). DG turns out to be appropriate for advection, waves and diffusion. DG can also be easily extended to higher order of accuracy, keeping both the same computational stencil and the same formulation.

- **Stability**: DG can be applied to unstructured, curvilinear and/or non-conforming meshes (Remacle et al., 2005; Bernard et al., 2009). Finite-volume techniques can also be applied to such meshes. Yet, the main advantage of DG over standard finite volumes is that DG is highly robust with respect to the quality of the meshes (Bernard et al., 2008).


\(^{27}\) DIVA: Data-Interpolating Variational Analysis ([http://modb.oce.ulg.ac.be/projects/1/diva](http://modb.oce.ulg.ac.be/projects/1/diva)).
In other words, DG schemes provide accurate and stable solutions to flow problems even for meshes of suboptimal quality.

There are however controversies about the supposed inefficiency of DG with respect to Continuous Galerkin (CG) or finite volumes. Indeed, a mesh simulation on a given mesh with linear elements has about 6 times more degrees of freedom in DG than in CG. Making DG computationally efficient is thus an important problem to be tackled. For this, we contemplate three options. In theory, each of them is capable of reducing the computational cost by one order of magnitude, which is exactly what we are looking for.

**Route 1: Exploiting single precision BLAS\(^\text{28}\)/LAPACK\(^\text{29}\) libraries for the efficient implementation of the explicit and implicit Discontinuous Galerkin methods.** DG methods have excellent accuracy and stability properties. But equally important is their high data locality, which allows for an efficient computer implementation. There is some controversy over the latter issue, for the number of required unknowns is largely superior to any other method, and the coupling between the degrees of freedom leads to a large number of operations per unknown for assembly and system solution. In a recent work (Hillewaert et al., 2009), we have shown that the locality of the data structures associated with DG allows for efficient implementations of the core operations needed for both explicit and implicit iterative strategies, namely residual computation, tangent matrix assembly, decomposition, and solution. Efficiency can be achieved by using appropriate data structures, reformulating the basic operations appropriately in terms of BLAS and LAPACK functionality, and using appropriate prestored parametric influence matrices. Standard finite-element implementations are able to achieve only about one tenth of the peak performance of computers. With some clever reformulation, it is possible to reach very high and sometimes near-peak performances, especially for linear algebra steps such as matrix decomposition; in any case, near-optimal performance has been obtained with respect to the relevant basic operations, thus taking direct advantage of the efficiency of the particular implementation of BLAS and LAPACK. We are now convinced that we could gain one order of magnitude in terms of CPU time without degrading at all the accuracy. It has been seen that using specific iterative strategies, namely flexible GMRES (Saad, 1993), was enabling to reach “double precision machine precision” in a linear solver using a preconditioner computed in single precision.

**Route 2: Multi-methods for multi-physics and multi-scale time integration.** No single time-discretisation can work well for all physical processes in a complex marine model, as different subsystems have widely different characteristics in terms of time scales, dynamic behaviour, and accuracy requirements.

The primitive equations for ocean flows allow for the existence of phenomena exhibiting a wide spectrum of propagation speeds. Typically, external gravity waves propagate at \(10^1 - 10^2 \text{ ms}^{-1}\) and internal gravity waves at a few metres per second, whereas advection is characterised by speeds ranging from \(10^{-3}\) to \(1 \text{ ms}^{-1}\).

Traditionally, a time-splitting approach is employed, where processes are solved using methods that take into account their stiffness. Many models rely on explicit splitting, where

\(^{28}\)http://www.netlib.org/blas/
\(^{29}\)http://www.netlib.org/lapack/
the two-dimensional mode is advanced with a small time step, whereas the three-dimensional dynamics is treated with a much larger time increment (see Shchepetkin and McWilliams, 2005, and references therein). A alternative solution is to use an implicit method for the free-surface equation (e.g. Dukowicz and Smith, 1994). Then, the same time step is used for all the components of the model.

Here, we will go beyond the operator splitting paradigm. Specifically, we will consider the general framework of additively partitioned time-integration methods; time-splitting is just a particular instance of such methods (Bujanda and Jorge, 2002). We propose a “multi-method” approach where different time discretisations will be resorted to for different processes; the set of discretisations will be constructed such that the overall time-stepping multi-method has the specified accuracy and stability properties.

The first class of multi-methods we will study are implicit-explicit (IMEX) schemes to integrate systems driven by both non-stiff and stiff terms (Ascher et al., 1995). IMEX applies an explicit method to the non-stiff part (e.g., advective terms) and an implicit method to the stiff part (e.g., reaction terms, strong diffusion, fast waves phenomena) or mesh-induced stiffness for adaptive grids (Kanevsky et al., 2007). We will consider IMEX schemes based on linear multi-step methods (Crouzeix, 1980; Ruuth, 1995; Hundsdorfer, 2001; Kanevsky et al., 2007) and on the so-called ARK\(^{30}\) methods (Cooper and Sayfy, 1983; Zhong, 1996; Ascher et al, 1997; Kennedy and Carpenter, 2003; Carpenter et al., 2005; Pareschi and Russo, 2005). We will combine implicit schemes with good linear stability properties for stiff terms (Gjesdal, 2007) with strong stability preserving schemes for the hyperbolic terms (Gottlieb et al., 2001). Nonlinear properties, like total variation diminishing, maximum principle, or monotonicity, are required in order to preserve the favourable characteristics of the DG spatial discretisation.

The second class of multi-methods we will study are multirate schemes, which use different time steps on different grid cells, and therefore address elegantly the greatly varying cell sizes between adapted elements. In the context of adaptive mesh refinement, local time stepping allows for the satisfaction of linear and nonlinear stability conditions under local CFL restrictions (Sandu and Constantinescu, 2007). The methods will be designed to maintain numerical stability (Skelboe, 1992), a high order of accuracy at the global synchronisation step and conservation of system invariants (Sandu and Constantinescu, 2007). We will build upon our strongly stable multirate method restrictions (Constantinescu and Sandu, 2007) and consider adaptive multirate strategies for implicit methods (Savcenko et al., 2007).

At the end, we are convinced that building appropriate time stepping strategies for multi-scale computations will enable us to gain another order of magnitude. For instance, consider a typical mesh of the Great Barrier Reef (Figure 3). The mesh is made up of 884,183 triangles. Element sizes were determined in order to capture the relevant bathymetric and topographic features, and the associated hydrodynamic processes, such as eddies and tidal jets (Legrand et al., 2006; Lambrechts et al., 2008a). Unstructured-mesh generation processes are complex and, even though it is possible to control average element sizes in specific regions of the domain, it is not possible to control individual element sizes. In other

\(^{30}\) Almost Runge-Kutta
words, the smallest element is usually much smaller than the smallest element size that was prescribed \textit{a priori}. In this case, the smallest element of the mesh has a size of 7 metres while the largest one has a size of 3,300 metres. It must be pointed out that 99\% of the elements have a size larger that 60 metres, which means that, if a local CFL restrictions had to be applied, the time step would be ten times smaller than the one that would be acceptable for 99\% of the elements. The development of stable and accurate local time stepping methods is a challenge. Ideal schemes should preserve the linear invariants of the system; in conjunction with conservative spatial discretisations, they should conserve (within round off errors) the total mass of the fluid and that of the tracers. Our focus will be on “practical” time-stepping methods of orders of accuracy 2 to 4.

\textbf{Figure 3.} Mesh of the Great Barrier Reef (GBR), Australia, with a detailed representation of the region of the Withsunday Islands (lower left corner). The size of the smallest and the largest are of the order of 10 m and a few kilometres, respectively. Such a large variation in mesh size — which is necessary to simulate both the large-scale and small-scale features of GBR's hydrodynamics — is made possible by the unique geometrical flexibility offered by unstructured meshes.

\textbf{Route 3: Multi-level methods for the implicit linear and non-linear solvers.} Even though explicit integration may turn out to be adequate for some local or regional applications, implicit time integration will be required for solving large multi-scale problems. Here, a nonlinear system of equations has to be solved at each time step. Typically, linear systems resulting from the linearization of our models are \textbf{stiff, non-symmetric} and \textbf{non-positive-definite}. For symmetric positive-definite systems, the conjugate gradient method is both inexpensive and optimal with respect to the energy norm. Unfortunately, there is no generalisation of the conjugate gradient method to non-definite problems that enjoys both properties.

Effective strategies have been derived by exploiting the connection between algorithms for estimating the eigenvalues of matrices and those for solving systems. The GMRES method (Saad and Schultz, 1986), which is related to the Arnoldi algorithm, computes, at each iteration, the exact minimum of the residual among a growing Krylov subspace. The
main drawback of GMRES is that its computational cost grows linearly with the number of iterations. Preconditioners have to be used in order to make GMRES efficient, i.e. reduce the number of iterations to convergence.

Multigrid methods are a family of algorithms for solving differential equations using a hierarchy of discretisations (Elman et al., 2005). In short, multigrid methods aim at accelerating the convergence of a base iterative method by correcting the solution globally using coarse problems. Multigrid methods can be used both as solvers and as preconditioners. For our multi-scale problems, we will mainly investigate multigrid methods as a preconditioner of a Krylov iterative solver. It can be seen that a fast convergent multigrid scheme leads to an efficient preconditioner for a Krylov subspace method.

There are two main issues in the design of multigrid schemes. First, the smoother has to take into account the underlying physics. Typically, a multi-directional block Gauss-Seidel scheme is adapted to smooth the error on the advection term. Then, transfer operators (projection and prolongation) have to be chosen carefully in order to avoid aliasing errors. Here, we will consider both hierarchical and non-hierarchical grids, even though our preference is clearly on non-hierarchical grids that allow more general algorithmics.

I.4.b. Implementation on massively parallel computers

Over the last years, our research team has gained an invaluable experience in parallel and high performance computing. We are intensively using the computers of UCL's Institut de calcul intensif et de stockage de masse (CISM\(^{31}\)), i.e. the high performance computing and mass storage facilities of our university. The latter is in the process of renewing its cluster and reach the size of 2,000 computer cores. In order to gain access to even larger computer power, we will also apply for participation in the European Union DEISA\(^{32}\) programme. The latter is an FP7 Research Infrastructure Project aimed at advancing computational sciences in the area of supercomputing in Europe. Our team has already benefited from an DEISA grant, called CoBaULD\(^{33}\), for performing a comparative convergence analysis of some methodologies for DNS\(^{34}\) computations, as an intermediate step toward LES\(^{35}\) computations.

The objective is that the maximal resolution of our model will be dictated only by the computational power optimally usable by the model and the available computational resources: a desktop with 4 cores, our CISM cluster with 1,000 cores or one of the supercomputer of the DEISA infrastructure with a million cores. This means that we have to develop methods that can be used efficiently on a wide range of machines, especially massively parallel computers.

Purely explicit computations should scale very well up to an arbitrary number of cores. Yet, the issue of load balancing for a computation that uses local time steps has to be addressed — if we decide to have recourse to a time stepping of this kind. For implicit or semi-implicit computations, the task is more challenging. One of the reasons thereof is as follows: the choice of the DG method as our main space discretisation scheme was dictated,

\(^{31}\) http://www.uclouvain.be/cism

\(^{32}\) DEISA: Distributed European Infrastructure for Supercomputing Applications (http://www.deisa.eu).

\(^{33}\) http://www.deisa.eu/science/deci/projects2009-2010/COBAULD

\(^{34}\) DNS: Direct Numerical Simulation of turbulent flows.

\(^{35}\) LES: Large-Eddy Simulation of turbulent flows.
among other reasons, by the fact that implicit DG matrices can be solved using an ILU(0) preconditioner (incomplete LU factorization with no fill-in) with a simple additive Schwartz procedure in parallel. Yet, the memory footprint of a DG method-based ILU(0) is large, maybe too large for modern architectures that have typically a relatively small amount of RAM on each core. Here, multigrid preconditioners could be advantageous because they typically require one order of magnitude less memory that ILU’s. The multigrid approach we would like to investigate does not use nested grids. Here, the use of non-nested multigrids on massively parallel computers will require the development of some “rendezvous” meshing techniques that will scale up to a large number of processors.

I.4.c. Improvement of the wetting and drying algorithm
Most of the World's coastal areas are influenced by the tide. Depending on the local topography the tidal range may reach considerable magnitudes. Combined by the fact that shallow seas and embayments often feature mildly sloping beaches, tidal flats, wetlands or salt marches, the total area submerged under water typically varies significantly with the tide, which has to be taken into account in the numerical models.

As the movement of the interface between wet and dry areas is essentially a Lagrangian process, adapting the computational domain to match the wetted area is probably the most appropriate procedure. Unfortunately, doing so turned out to be computationally too expensive in practical applications (Zheng et al. 2003). Therefore, working out less elegant, but much more efficient, fixed-mesh methods seems to be the only feasible option. In other words, improving the physical underpinning as well as the numerics of the wetting and drying algorithm is vital for most of SLIM's applications.

Fixed-grid hydrodynamic models have featured wetting-drying (WD) methods ever since the seventies, but the multitude of different approaches proposed in the literature reveal that representing the moving boundary line in a Eulerian model is far from trivial. The shallow water equations break down if water depth goes to zero and the major difficulty in simulating WD processes is that the positivity of the water depth generally cannot be guaranteed. As a very common remedy, a thin layer of water is left on the dry bed (Balzano, 1998; Bunya et al., 2009; Gourgue et al., 2009). However, a layer of water on sloping bed results in an artificial pressure gradient (or surface slope) term that tends to drive the water down the slope. This term must be cancelled or balanced out (Bunya et al., 2009; Gourgue et al., 2009).

In typical approaches, for both finite-difference and finite-element models, the physics is hampered when the water level falls under a certain threshold level in order to prevent nodes from drying out. Unfortunately, applying such a threshold renders the entire numerical procedure highly non-linear and it is difficult to avoid oscillations near the threshold depth. Due to the high non-linearity such formulations can only be solved with explicit time stepping, in which the length of a feasible time-step is greatly restricted. The short time steps significantly increase the computational cost, which becomes a limiting factor in long-term, large-scale simulations (Stelling and Duinmeijer 2003). However, such explicit methods have been reported to yield excellent accuracy.

In order to keep computational cost at a feasible level, we will pursue an alternative approach that demands an implicit algorithm to be implemented, a challenging task for so
non-linear a problem. Such a formulation can be obtained by introducing a smooth transition between wet and dry regimes (Ip et al., 1998). Possible procedures include marsh porosity (Ip et al., 1998; Heniche et al., 2000; Nielsen and Apelt, 2003), connective channels (Jiang and Wai, 2004), subgridscale bathymetry (Bates and Hervouet, 1999; Defina, 2000) and moving bathymetry. The advantage of these approaches is that the WD process can be described on the level of the primitive equations and, therefore, they are applicable in a wide variety of numerical models. Furthermore, the inherent smoothness of the WD interface — as opposed to using a simple threshold — greatly improves the stability of the numerical scheme and allows implicit time marching, which makes these methods highly appealing for large-scale simulations. The drawback is that the flow near the drying front may be inaccurate and water may be leaking through dry areas (Nielsen and Apelt, 2003).

We have initiated the development of a fully implicit, moving bathymetry WD method for two-dimensional, DG, finite-element, shallow-water models. It is worth underscoring that our method is mass-conservative and fully consistent with tracer equations, both of which are of a crucial importance in long-term environmental simulations — in which no gain or loss of tracer caused by deficiencies of the numerical scheme is allowed. Furthermore, compared to explicit WD approaches, preliminary test suggest that, in realistic applications, the proposed method is likely to be two orders of magnitude faster than most existing techniques, including the best option presently available in SLIM, i.e. the scheme of Gourgue et al. (2009).

We trust that the two-dimensional wetting-drying scheme will be operational in the near future and applicable to slowly varying flows. It still remains a challenge to adapt it to rapid flows and to ensure proper conservation of momentum and energy head (Stelling and Duinmeijer 2003, Kramer and Stelling 2008). Moreover, extending the method to the three-dimensional version of SLIM is likely to present us with novel questions also. Taking up this challenge is part of the work to be done herein.

I.4.d. Development of the sediment dynamics module

SLIM's sediment transport module is in its infancy, with only one class of fine sediments being taken into account in the two-dimensional module. This is far from sufficient for the present project.

Sediment is continuously transferred from source (mountains) to sink (deep ocean) through riverine, estuarine and coastal waters. Sediment is being transported in distinct modes, and over a wide range of spatial and temporal scales. Three modes of transport are classically identified (Jansen et al., 1979): washload, suspended load and bedload. Washload remains in suspension indefinitely and in normal conditions does not interact with the bed (Einstein and Chien, 1953); it may therefore be modelled as a passive — or inert — tracer. Suspended load is moving over the whole water column but with continuous interactions with the bed through entrainment and deposition resulting from a balance between settling and turbulence. Finally, bedload consists of coarser sediment grains saltating and rolling over short distances in a region close to the bed. These three modes are driven by distinct physical mechanisms but often coexist simultaneously. In addition, the case of cohesive sediment (Toorman, 2001) and carbonates, usually considered as suspended load, requires
special treatment to account for flocculation of clay particles (Partheniades, 1993) and the varying density of carbonate sediment.

As for spatial and time scales of interest for the interaction between flowing water and sediment, they span over several order of magnitudes. Suspended sediment and bedload are in dynamic continuous interaction with the underlying bed on a timescale characteristic of the turbulent structures of the flow, i.e. a timescale of the order of a few seconds (Lyn, 2008). However, the relation between flowing discharge and sediment transport rates being highly non-linear, yearly sediment budgets at a catchment scale are predominantly determined by floods occurring on a timescale of a few months to years (Leopold et al., 1995). These floods determine erosion and deposition patterns at the kilometre scale. Interactions between sediment transport and the bed almost invariably generate sedimentary bedforms that significantly affect bed resistance and bed shear stresses, and create complex and highly dynamic morphological features (Best, 2005). But, again, if these interactions are considered over much larger time scales (years to decades and centuries), alluvial rivers and coasts interact with antecedent sedimentary deposits; river systems and estuaries react to anthropogenic or climatic forcing and modifications of their dynamic equilibrium result in morphological changes (Leopold et al., 1995): bank erosion and meander migration, formation of bars and terraces, tidal flats, channel aggradation, etc.

Research in sediment transport has initially focused on understanding the fundamental principles of sediment movement at the particle level (Bagnold, 1966). When applying such principles outside the laboratory to model large-scale real-life problems of geomorphology, there must be a trade-off between the various time and spatial scales at play (Xiang and Zhanbin, 2004), prompting Graf (1971) to state that “an application of [sediment transport] equations to field determination remains but an educated guess”. In the meantime, empirical relations for sediment transport at a macro scale have been developed to be included in predictive models (see Garcia, 2008, for a review). These models are however usually devoted to solving problems on limited scales: depth-averaged models for slow bed evolution without considering changes in the river plan form (Correia et al., 1992), depth-averaged and layered models (Spinewine, 2005; Zech et al., 2009) dedicated to fast transients attempting to account for bank erosion processes (Spinewine et al., 2002), or more sophisticated three-dimensional models — but dedicated to a particular application such as the flow past a bridge pier (Kirkil et al., 2009).

One of the objectives of the present proposal is to predict sediment movement in rivers and estuaries, and the resulting morphological changes over timescales relevant to the long-term evolution of the land-sea continuum of rivers and estuaries. Indeed, the development of a sediment transport module and a morphological evolution module in the existing simulation tool SLIM could open new windows of application. These include:

- modelling of sediment transport (bedload/suspended, load/washload) in river channels and on floodplains, including the transfer of sediment between channel and floodplain during floods;
- modelling the transport of any pollutant dispersed into the water by linking the sediment transport module to existing modules for tracer advection/diffusion;
- predicting sediment plumes in estuaries and geographical distribution of sediment on the
coastal shelves;
• estimating the morphological evolution of rivers/estuaries (movement of bars, sedimentation in harbours, efficiency/optimization of river training works or dredging operations);
• determining the impact of sedimentary structures (dunes, sediment waves) on bottom boundary layers and flow resistance;
• modelling the remobilization of coastal sediment during storms;
• assessing sediment transport associated with river or tidal flows around bars / islands.

Figure 4. Compound channel of UCL’s hydraulics laboratory.

It will be necessary to (1) relax the fixed-bed constraint in the existing model in order to account for possible, long-term morphological changes, and (2) couple these equations with an equation describing the morphological evolution of the bed, typically the Exner equation. Well-suited closure equations will then provide the missing information about transport rates and shear stresses along the bed. From the numerical modelling point of view, this coupling will bring new challenges: the timescales for sediment transport phenomena are usually very different from those characterising the hydrodynamics. The resolution algorithm will have to cope with these vastly different timescales, which are likely to yield a “stiff problem”.

Validation of these new modules will be achieved first by means of comparison with existing analytical solutions (e.g. dispersion from a point source, Rousean equilibrium sediment distribution), then by comparison with laboratory measurements. For example, experiments for idealised situations involving sediment transport will be performed at UCL’s Hydraulics Laboratory36. In one of the available facilities, sketched in Figure 4, experiments will focus on equilibrium vertical profiles of suspended sediment and sediment interactions between main channel and floodplains. In another facility, lock-exchange type experiments will be carried out to look at the propagation of sediment-laden intrusions in clear water.

For reasons explained in Section I.5.b, the Mahakam River provides a particularly interesting field study. The river is associated with a large sediment delivery to the coastal zone that has emplaced a delta that has protruded 40 km on the continental shelf (Storms et al., 2005; Dalman et al., 2009). The lower Mahakam is extremely flat and the tidal influence penetrates far upstream and interacts with lakes and peat swamps that alternatively feed or drain the river, creating a rich and highly dynamic morphological environment, with several river junctions that control sediment distribution. Simulations will focus on (i) sediment budgets associated with the propagation of a large flood, including its interaction with the tidal zone and within the lakes area, (ii) sediment dynamics at river junctions and bifurcations, and (iii) simulations on a longer timescale to identify trends of morphological adjustments for different scenarios. The latter will include ENSO\textsuperscript{37} events and climate change projections.

I.4.e. Completing the baroclinic module

The distribution of the meshes along the vertical will be such that the motion of the ocean-atmosphere interface as well as the precipitation or evaporation fluxes will be taken into account “exactly” (Campin et al., 2008), i.e. without having recourse to approximations that could be detrimental to the water budget. In other words, the makeshift solutions of Goosse and Fichefet (1999) or in Tartinville et al. (2001) will no longer be resorted to. In the ocean interior, the mesh will mimic the $z$-coordinate system, while shaved cells will be implemented in the vicinity of the bottom. SLIM's vertical discretisation is sufficiently flexible that other, more sophisticated, vertical mesh arrangements are possible.

Isopycnal and Gent-McWilliams operators will be introduced. Although continuous finite elements guarantee zero isoneutral density flux — with a linear equation of state (Wang, 2007) —, DG discretisations are unlikely to enjoy this favourable property. Attempts to circumvent this difficulty will be made, seeking inspiration in Griffies et al. (1998).

The test cases mentioned in Section I.2.b. will continue to be performed. But, most of the “model tuning” work will be achieved after the coupling of the liquid and solid water components of SLIM. This couple model will be applied to the whole World Ocean. It is this version that will be carefully calibrated and validated.

I.4.f. Coupling SLIM's solid and liquid water components

The coupling of the ocean and sea ice module has to be performed in a manner that strictly guarantees the conservation of exchanged quantities such as heat, freshwater and salt.

The exchange of momentum has also to be carefully treated. The water-drag formulation traditionally used for the sea ice-ocean boundary layer causes a fictitious damping of sea ice motion and deformation at subdaily timescales. By solving the integrated oceanic boundary layer transport with an inertial embedding of the sea ice, Heil and Hibler (2002) reproduced observed high frequency variability of sea ice dynamics. We will take advantage of this finding.

Several major improvements need to be accomplished in the ice model. First, the set of equations emerging from the sea ice dynamics need to be resolved on spherical geometry, following the approach described in Comblen et al. (2009b). Second, the representation of a

\textsuperscript{37} ENSO: El Nino / Southern Oscillation (http://www.esrl.noaa.gov/psd/enso/).
subgrid-scale ice thickness distribution (ITD, see Thorndike et al., 1975) will allow to
describe the relative surface coverage of sea ice of different thicknesses. Changes in the ITD
are due to thermodynamic (growth and melt) and dynamic (opening and deformation)
effects. Models including an interactive ITD improve the representation of ice growth and of
the summer ice-albedo feedback, which in turn significantly improves the simulation of the
large-scale sea ice characteristics (Holland et al., 2006), speaking for the use of such
distribution functions in sea ice models. Furthermore, Vancoppenolle et al. (2009) have
shown that, given the importance of the ice salinity on the simulated sea ice mass balance,
the model clearly gains in accuracy from a better representation of salinity. The essential of
the halo-thermodynamic component included in the LIM3 model has hence to be
incorporated in the finite-element model.

I.4.g. Dealing with unexpected issues
While tackling physical questions, numerical issues will arise that will suggest modifications
or new developments of the model. One of them might be the need for a non-hydrostatic
option, which should not require profound modifications of the algorithms. Indeed, Marshall
et al. (1997) and Marshall et al. (1998) suggest efficient solutions to set up a non-hydrostatic
module at an acceptable CPU cost. This approach is based on a projection method that needs
at each step the resolution of a global Poisson problem.

Another issue that might arise is related to the dependency of the subgrid-scale
parameterisations to the horizontal mesh size. Little research has been done so far on this
topic. It may turn out to be sufficient to rely on the scaling of the viscosity and diffusivity
suggested in Smagorinsky (1963) and Okubo (1971), respectively. If not, we will consider
more advanced methods.

I.5. Physical questions

I.5.a. Ice-ocean interactions in a complex-geometry region
The climate of the Earth is on a track to severe and unprecedented change (Bernstein et al.,
2007) characterized by an increase in global surface temperature, a shift in atmospheric and
oceanic patterns, an accelerated sea level rise and wide ranging socio-demographic-economic consequences. Sea ice is a key component of the high latitudes climate (e.g., Serreze et al., 2007). In particular, the ice-albedo feedback (Ebert and Curry, 1993) is considered to be largely responsible for the high sea ice sensitivity to climate change, as highlighted by the recent Arctic sea ice minima of extent on the one hand (Stroeve et al., 2005; Comiso et al., 2008), and by simulations with climate general circulation models (CGCMs) on the other hand (e.g. Manabe and Stouffer, 1980). Nevertheless, recent comparisons (e.g. Holland and Bitz, 2003; Arzel et al., 2006; Zhang and Walsh, 2006; Lefebvre and Goosse, 2008) between CGCM simulations plead for the need to improve our understanding of sea ice and its representation in climate models. In this part of the project, we would like to address the following question: Can we accurately simulate sea ice physics and its interactions with ocean, including the formation of polynyas and landfast ice, in an area characterised by a complex geometry? In order to evaluate the
benefits from the new developments in the model, a series of numerical simulations will be conducted on a region clearly presenting these features: the Canadian Arctic Archipelago (CAA). Of particular concern are (1) the interannual variability of the sea ice cover and freshwater transports in the CAA, and (2) the impact of recent and future climate changes on the sea ice features in this area, including the possible opening of the Northwest Passage.

![Unstructured mesh in the Northern Hemisphere, high-latitude regions, with details of the Canadian Arctic Archipelago in the lower left corner, displaying numerous island, headlands, and rugged coastlines.](image)

**Figure 5.** Unstructured mesh in the Northern Hemisphere, high-latitude regions, with details of the Canadian Arctic Archipelago in the lower left corner, displaying numerous island, headlands, and rugged coastlines.

The Canadian Arctic Archipelago is a complex area exhibiting numerous islands, headlands and rugged coastlines (Figure 5). The straits constitute an important pathway for the cold waters from the Arctic Ocean to the Atlantic. This area is currently being of strong economical importance and political interest in the context of the possible opening of the Northwest Passage during summer months in the coming decades.

Modelling the CAA is a challenging task: on the one hand, the ice circulation is very complex (presence of numerous islands, the ice is landfast during a long period of the year and forms static arches, etc.) and covers a non-negligible part of the ice mass balance. On the other hand, the physics of this region is the result of the strong coupling between the ocean and the ice. First, the role of the freshwater flux through the CAA is thought to be important for the overall freshwater budget of the region (Stigebrandt, 2000; Dickson et al., 2007), and may significantly impact the convective overturning in the Labrador Sea (Goosse
et al., 1997) and, hence, the global climate. Lesser known is the influence of the ice contribution and the river discharge to this freshwater export. Second, most models simulate with difficulty the decay of the summer sea ice cover in Baffin Bay (Timmermann et al., 2005; Johnson et al., 2007; Vancoppenolle et al., 2009). Of particular interest is the formation of the North Water Polynya occurring almost every year in Northern Baffin Bay, which is thought to be linked to the formation of static arches in Nares Strait. Though spatially sparse, polynyas\textsuperscript{38} play a crucial role at the interface between ocean and atmosphere in polar regions. First, they enable important oceanic heat losses and modify the surface albedo. Next, they are at the origin of new ice formation and, thus, the associated brine rejection, which combined to the cooled ocean surface can lead to vertical mixing, convection and possibly to dense water production. Polynyas also play an active role in the biogeochemical cycles by modulating the atmosphere-ocean exchanges of gases such as carbon dioxide (e.g. Delille, 2006). Finally, modelling of the landfast ice also constitutes an open issue, partly because of the smallness of length scales to be resolved.

As can be expected, data from this harsh and remote region of the world are scarce (e.g. Melling, 2002), especially concerning the ice thickness, ranging between 2 and 6 m in the CAA (Bourke and Garrett, 1987; Melling, 2002; Kwok, 2005), underlining the need for numerical experiments. Very little model research has been performed on the CAA. Two studies are based on structured-grid regional models: Kliem and Greenberg (2003) constructed gridded fields of potential temperature and salinity, used in a second step to simulate the mean circulation in the area, while Sou and Flato (2009) studied the impact of future climate scenarios on the CAA.

It is beyond doubt that modelling sea ice in the CAA constitutes a problem with many scales. The largest ones are comparable to the size of the Arctic Basin, or even the World Ocean, whereas the smallest ones are associated with landfast ice and static arch formation. The first task of the proposed project consists in improving the physics of the sea ice model (ITD, halo-thermodynamic model, etc.) and of the baroclinic component of the ocean model (isopycnal mixing, sufficiently sophisticated turbulence closure scheme, convective adjustment, etc.), and finally couple both models (See Sections I.4.e and I.4.f). This also includes a parameterisation of the salt, momentum and heat fluxes between both models.

This fundamental step will be thoroughly validated through a set of simulations of the World Ocean over the last 50 years. For this purpose, a mesh of the domain under study will be designed to include the World Ocean with a mean resolution of 2 degrees with a progressive refinement in the Arctic Basin, reaching a typical mesh length of a few kilometres in the CAA, which is sufficient to resolve the landfast ice processes, as their typical length scale is of the order of a few tens of kilometres. The forcings used to run the model will be carefully chosen and analyzed. In particular, as shown by Sou (2007), the air temperatures from the NCEP/NCAR reanalysis data are too cold in the CAA during the summer and have to be corrected by means of other data sets. Once the set up is complete, a first run can be achieved and analyzed. The model results will be assessed at the global scale (world oceanic current pattern, Gulf Stream and Antarctic Circumpolar Current transport, etc.) and at the scale of the Arctic and the CAA by means of a series of data sets: Arctic ice

\textsuperscript{38} Polynya: a large area of open-water within the sea ice pack.
concentration (SMMR\textsuperscript{39}-SSM/I\textsuperscript{40}, Comiso, 1999) and ice drift (daily observed ice motion vectors, Fowler, (2003), Fram Strait ice export (Kwok et al., 2004) and CAA ice fluxes (Kwok, 2006), etc. Of particular concern is the interannual variability of the sea ice cover and freshwater transports in the CAA.

Finally, we suggest that a model run in predictive mode, for 2091-2100 say, be carried out to study the impact of future climate change on this particular region (including the possible opening of the Northwest Passage). For this purpose, a forcing data set can be produced by adding the anomalies in air temperature, wind and freshwater fluxes coming from available ocean general circulation model outputs (e.g., from runs performed for the forthcoming IPCC report) for the considered period to the interannual forcing data set used to run the model during the past decades.

\textbf{I.5.b. Water and sediments fluxes in a tropical land-sea continuum}

An application that seems tailored to test, and hopefully demonstrate, the multi-scale capacities of SLIM is the study of “land-sea continua”. This type of applications refers to studies comprising the whole range of systems from the river catchment to the downstream sea or coastal waters (e.g. Vanderborght et al., 2007). Such an integrated approach is essential, for instance, for assessing the ecological status of coastal waters, generally being a reflection of activities and reactions along the path of the incoming waters in addition to coastal processes (Borja et al., 2008; Hofmann et al., 2005). Another example is the study of geomorphological changes in a river basin, where the sediments deposited close to the sea may originate from a location far more upstream, whose specific dynamics should be modelled explicitly for an accurate representation of the downstream processes. Such an integrated approach allows to run scenarios and identify sensitive forcings, and is therefore often used to determine management actions (Marinov et al., 2007; Nobre, 2009). To correctly evaluate the impact of these combined effects, they should be modelled all simultaneously, highlighting the need for multi-scale models. SLIM will be applied to the East-Kalimantan region and the Great Barrier reef, two distinct regions for which the influence of the continental system on the coastal (or reef) system is of interest. It is clear that only a part of the complete land-sea continuum will be considered first, focusing mainly on those components in which the tide is significant.

We will first model in an integrated manner the region of tidal influence of the Mahakam River (East Kalimantan province, Borneo Island, Indonesia) and its tributaries, as well as the associated lakes, peat swamps and coastal sea, is a challenging first step in the development of full-fledged model of the land-sea continuum (Figure 6). In this region, large fluxes of waterborne sediments, extreme meteorological variability causing droughts and floods and the interactions of rivers, lakes and peat swamps (i.e. components functioning with vastly different time and space scales) present the modeller with a number of difficult numerical and modelling issues. We will investigate river flow, sediment transport and morphodynamics under the influence of climate change, anthropogenic pressure and ENSO variability.

\textsuperscript{39} SMMR: Scanning Multichannel Microwave Radiometer.
\textsuperscript{40} SSM/I: Special Sensor Microwave Imager (SSM/I).
Figure 6. Location of the Mahakam River delta and the land-sea interface of the Borneo Island, East Kalimantan Province, Indonesia (upper panel). The lower panel displays the lakes, rivers, delta and part of marine region (with a tentative unstructured mesh) that will be modelled by means of SLIM tools.

At the global scale, tropical rivers are the principal source of sediments to the coastal ocean (Milliman and Meade, 1983). This relates to the intensity of rainfall events at low-latitudes and the high erodibility of tropical soils (Allen, 1997). Rivers in Southeast Asia in general, and in Indonesia in particular, have received relatively little attention in the literature. There are many diverging reasons to study terrestrial sediment delivery to the coast, which include ecological consideration focusing on coral reefs (Wolanski, 2001; Hoitink and Hoekstra, 2003), mangroves (Wolanski, 1995), sea grasses (Hovel et al., 2002) and fisheries (Bilotta and Brazier, 2008), and geological considerations related to the formation of deltas, coasts and continental shelves (Bridge and Demicco, 2008). The
Mahakam is the largest river in the East Kalimantan, which has produced a delta that protrudes some 40 km into the continental shelf (Storms et al., 2005). Studying the development of sediment discharge waves in a system like the Mahakam will reveal the controls of fluid dynamics over the transfer of terrestrial sediment from sources to sinks in a medium-sized tropical river.

The island of Borneo suffers strongly from variations in climatic forcing related to the El Nino - Southern Oscillation (ENSO) cycles (Curran et al., 1999; Harrison, 2001; Aiba and Kitayama, 2002; Fredriksson et al., 2007; Kishimoto-Yamada and Itioka, 2008). Pristine tropical rainforests catch fire during periods of drought, when rainfall is much lower than under regular conditions. At the oceanic boundary of East Kalimantan, the Makassar Strait is a principal corridor of the Indonesian Throughflow between the Pacific and Indian Oceans (Gordon et al., 1999; Susanto and Gordon, 2005; Vranes and Gordon, 2005; Gordon et al., 2008). Modelling the hydrodynamics of the Mahakam River and the distributaries in the delta would allow studying both hydrologic and coastal oceanographic consequences of ENSO variation to floods and droughts in a developing region in the tropics. Droughts result in salinity intrusion with problems for agriculture and the production of drinking water. Floods cause urban and rural inundations.

Tides and river discharge interact in lowland areas (Dronkers, 1964; LeBlond, 1978; Buschman et al., 2009). Predictions of water levels in tidal rivers often rely on harmonic analyses, despite that this is known to be inappropriate (Jay and Flinchem, 1997). Existing neural network approaches to predict water levels can be successful (Lee and Jeng, 2002; Chang and Lin, 2006; Chen et al., 2007), but do not provide insight into the physical mechanisms of the system. Both stochastic and neural network approaches typically fail to provide knowledge about the consequences of engineering works to flood levels. This vouches for the development of physics-based methods to predict water levels in tidal rivers. The Mahakam encompasses a 200 km long tidal river section, where the points of extinction of diurnal and semidiurnal tides travel back and forth in the river, in response to fluvial discharge. A SLIM-type model of the Mahakam, including the channels in the lake area, the tidal river part and the estuarine channels, would allow to study the behaviour of fluvial discharge waves in tidal rivers, and to develop physics-based prediction methods of water levels in tidal rivers. In a larger framework, the ultimate challenge is to forecast water levels in tidal rivers from rainfall data and predictions of the astronomical tides at the oceanic boundary. Virtually no attention has been paid in the literature to the fact that fortnightly tides penetrate much further inland than diurnal and semidiurnal tides. Long-term time-series of discharge in the Mahakam show that fortnightly tides can be substantial (amplitudes over 30 cm), rendering it an important research topic.

Tropical peat swamp forests are important reservoirs of biodiversity (Page et al., 1999; Wosten et al., 2008), and carbon dioxide (Page et al., 2002). They contain a large number of endemic tree species and rare, endangered animals (Ismail, 1999). Over the past decade, the government of Indonesia has drained over 1 million hectares of the Kalimantan peat swamp forests for conversion to agricultural land (Wosten et al., 2008). Whereas current studies are primarily focused on carbon dioxide impacts of peat swamp degradation (Hirano et al., 2007; Jauhiainen et al., 2008), little attention is paid to consequences for hydrology. Peat
swamp forests act as a retention area of rainfall (Hoekman, 2007). A numerical model of the Mahakam would allow to investigate the effect of enhanced dewatering of converted peat swamp areas to discharge regimes.

Figure 7. Points where measurements have been or are being made in the Mahakam River region. The nature of the data collected is indicated in lower left corned of the figure.

The depth-integrated, two-dimensional version SLIM will be used in the entire domain, except in the riverine part and the peat swamps — which, roughly speaking, are located around the Lakes Jempan, Melintang and Semayang (Figure 6). The former will be represented by means of the one-dimensional river network module that is now part of the SLIM system, while the peat swamps will be parameterised as long-residence time reservoirs, unless it appears that they can be modelled as porous media — for which a module of SLIM is being developed in a project41 unrelated to the present proposal. The sediment module will be activated as soon as possible, and attempts will be made to represent the morphological changes caused by sediment transport.

The boundaries of the lakes vary considerably over the year; they can sometimes be dry. In the riverine part of the domain there are also large water level variations. Therefore, an accurate and computationally-efficient wetting-drying algorithm is crucial for simulating successfully the Mahakam River region hydrodynamics.

Figure 7 shows the main locations where in situ measurements have been or are being made. Other types of data are available, as indicated in Appendix A.

41 This exploratory project is entitled Développement d’un modèle multi-échelle d’écosystème terrestre, is led by Emmanuel Hanert, and is funded by the Fonds Spéciaux de Recherche de l’Université catholique de Louvain, from 1 October 2009 until 30 December 2010 [47,000 EURO]
I.5.c. Coral reefs: impacts of land-to-sea fluxes and physical aspects of connectivity

Coral reefs cover about $2 \times 10^6$ km$^2$ of equatorial and tropical oceans (e.g. Achituv and Dubinsky, 1990). A vast number of them are threatened by overfishing, increasing water temperature, water acidification, or various forms of pollution originating from the land, etc. Some aspects of the latter problem will be investigated by means of SLIM, with the longest and most complex reef of the world as study site, i.e. the Great Barrier Reef (GBR), Australia. The latter extends over 2,000 km and covers an area of about 348,000 km$^2$ along Australia’s northeastern coast. It comprises two to three thousands reefs and islands, a few metres to a few tens of kilometres in size, rendering it the most complex topographic and, hence, multi-scale, domain that can be found in the seas of the Earth.

The hydrodynamics of this domain is rather complex, exhibiting a wide range of time and space scales, with the smallest-scale features impacting significantly the larger-scale ones (Figure 8). Clearly, a model relying on a nested-grid system cannot deal with all of the topographic features of this domain, just because there are too many of them. Another option is the brute-force approach, consisting in setting up a very high-resolution grid covering the whole GBR. Though this can be done in a classical structured-grid model, the CPU cost is unlikely to be acceptable. Therefore, to model the hydrodynamics of the whole GBR, including small-scale features such as eddies and tidal jets (at least the larges ones, i.e. those whose dynamics is approximately hydrostatic), an unstructured-mesh model seems to be the best approach, provided the mesh size ranges from a few tens of metres in the vicinity of headlands, small reefs and islands, to a few tens of kilometres in the “open” sea (Legrand et al., 2006; Lambrechts et al., 2008a; Lambrechts et al., 2008b). The width of the spectrum of the space scales to be represented is not the only difficulty to be taken into account. Indeed similar problems arise for the timescales. Thus, there is no doubt that modelling the whole GBR hydrodynamics is a tough test, if not the toughest, in multi-scale modelling.

In 1982, the GBR was inscribed on the World Heritage List in recognition of its outstanding and universal natural values. Evidence of coastal ecosystem degradation in the Great Barrier Reef has been linked with land-based runoff of suspended sediment, nutrients and pesticides from agricultural sources (Bellwood et al., 2004; Fabricius, 2005; Fabricius et al., 2005; Cooper et al., 2009) and climate change, principally the increased incidence of coral bleaching from global warming as well as decreased coral growth from ocean acidification (Bellwood et al., 2004; Wolanski and De’ath 2005, De’ath et al. 2009).

The scientific evidence that terrestrial run-off from the GBR catchment continues to be of poor quality in many locations is strong (Brodie et al., 2009, Reef Water Quality Protection Plan Secretariat, 2008). The cause-and-consequence link between deteriorating riverine water quality and reef health is a matter of considerable scientific discussion and interest, and this link remains difficult to quantify. This is because there exists a lack of quantitative modelling frameworks linking land use and practices in catchments to end-of-river pollutant loads, then to water quality in coastal waters, and ultimately to reef ecosystem health. Making steps towards quantifying this link is part of the work suggested herein.

The resilience of the GBR ecosystem now threatened by land-use in the watershed and to climate change is largely determined by the location of the Marine Protected Areas (MPAs;
Pandolfi et al., 2003; De’ath and Fabricius, 2008). A key factor determining this resilience is the connectivity between these MPAs. **Connectivity describes the extent to which water parcels, dissolved constituents, particulate matter or living organisms can travel from one reef to another.** From a biological point of view, two reefs are said to be well connected if organisms originating from one can easily migrate to the other either during the larval phase or when mature. As such, a decline in the population of one species on one reef can be more easily replaced if it is well connected to other reefs that have a healthy population of the same species; the opposite would lead to regional extinction and have augmented effects on the biodiversity and structure of the ecosystem.

The development of quantitative modelling frameworks which link land use, water quality from land run-off and coastal ecosystem responses is rather complex (Rabalais et al. 2009, Smith and Schindler 2009; Thomas et al. 2009). This project will use existing and available estimates of catchments’ runoff of water, sediment, and nutrients in a biophysical model of coastal waters and an ecosystem model of coral reef health to develop a catchment-to-reef ecosystem model. SLIM forms the foundation on this ecosystem model by providing the oceanography that controls the connectivity between reefs and the watersheds (Lambrechts et al., 2008b). Several years of data of water quality and ecosystem health data now exist and are available from the AIMS\(^{42}\) Long-Term Reef Monitoring Programme. Oceanographic data spanning 20 years are available near Myrmidon Reef, offshore Townsville and at the shelf break, while the extensive data set of Wolanski (1994) is available for currents, tides, and wind, over most of the central and northern regions of the Great Barrier Reef.


**Figure 8.** Illustration of the multi-scale nature of the Great Barrier Reef topography and hydrodynamics. The left-hand side panel is reproduced from Wolanski et al. (2003).
Great Barrier Reef. Open ocean currents, in terms of the strength of South Equatorial Current generating a net current (the East Australian Current) on the continental shelf of the Great Barrier Reef, are available from NOAA altimetry data. Other data and model results will be used to force SLIM, as is outlined in Appendix A.

First, the two-dimensional, depth-integrated version of SLIM will be used, since the water column generally is rather well mixed — mainly because of the relative shallowness of the domain, with a water depth ranging from 0 to about 100 m. Due to the tides, there are large reefal areas that are alternatively wet and dry, pointing to the crucial importance of the wetting-drying algorithm in this domain of interest. Then, we will consider using the three-dimensional version of SLIM. Whether or not SLIM's three-dimensional version will offer benefits compensating for the extra computer cost will be assessed by comparing 2D and 3D model results with available data. It is conceivable that the three-dimensional barotropic version would be sufficient, whereas the baroclinic one would turn out be unnecessarily expensive.

The fine sediment module of SLIM will be adapted from Wolanski and Spagnol (2003) and will be calibrated against 3 years of continuous data of suspended sediment concentration, waves and wind at two sites off Townsville in the dry tropics, and 1 year of similar data at two sites near the mouth of the Tully River and Dunk Island in the wet tropics between Townsville and Cairns (Wolanski et al., 2008).

The marine ecosystem models will be improved based on new empirical data and conceptual models of the responses of marine ecosystems to increasing loads of sediments, nutrient and pesticides, such as the HOME model of Wolanski and De’ath (2005) and the mud-reef model of Humphrey et al. (2008).

About 30% of the Great Barrier Reef is protected as a marine protected area (MPA) where extractive activities (e.g. fishing) are not allowed. However much of this area is made of inter-reefal areas and probably about only 10% of the coral reefs are actually protected by MPAs. The original design of MPAs was largely based on complex socio-economic issues overlaid over a basic scientific knowledge that included little information on the connectivity between the MPAs. The resulting distribution of MPAs appears somewhat haphazard. Nevertheless the MPAs now constitute the backbone of the reef robustness and resilience against climate change and human impacts on the adjoining watersheds (Wolanski, 2007). The key to this robustness and resilience is the connectivity between the MPAs.

The connectivity between MPAS is at present totally unknown. Many methods for estimating connectivity, including genetic ones, have been suggested (e.g. Werner et al., 2007; Munday et al., 2009; and references therein), depending on the specific issue being addressed. Herein, we will focus mainly on the physical aspects of connectivity. In other words, we propose to calculate the connectivity between the MPAs by going back to the fundamentals of how connectivity is achieved. Connectivity is controlled by the oceanography (i.e. physical transport processes) as well as the behaviour of individual species (e.g. coral juveniles settle preferentially in areas where coralline algae exist and emit a chemical sensor; and juvenile coral fish swim directionally towards a live coral reef using biological reef sound to swim towards). The biological sensors and clues have been
extensively studied in the field and mainly in the laboratory. The oceanography will be resolved using SLIM because its unstructured mesh allows a very fine-scale resolution near reefs — where such details of the advection and diffusion processes at small scales are important for the biology — and a coarser resolution far from reefs where open-waters oceanographic diffusion processes prevail that can be quantified using classical oceanographic diffusion models. The connectivity between reefs will be calculated both for corals and for fish by adding to the physical model the behaviour of the juveniles drifting in open waters and activating this behaviour when they perceive chemical or audio signals from potential settlement sites.

A method for assessing quantitatively the connectivity will be designed, by seeking inspiration in the works of Braunschweig et al. (2003) and Condie and Andrewartha (2008), and by having recourse to the conceptual tools of CART\textsuperscript{43}. A connectivity matrix will be established by evaluating the time spent in a given sub-domain by particles or organisms originating from another sub-domain. If the number of sub-domains whose connectivity is to be assessed is rather small, say less than a dozen, this approach is likely to be rather trivial. Unfortunately, for 2,000 to 3,000 sub-domains, the connectivity matrix would have $10^6$ -- $10^7$ elements, rendering it impossible deal with. A relevant aggregation technique has yet to be worked out, which might turn out to be a daunting task. In this respect, graph theory might offer useful clues\textsuperscript{44}.

The coupled models developed in this project will for the first time provide the capability of quantitatively linking land use and reef ecosystem health. This powerful modelling capability will have multiple applications for the management of the GBR and will also enable an interaction between physical and biological oceanographers and reef ecologists so as to understand how a watershed-reef ecosystem work, how it is impacted by land-use and at what spatial and temporal scales these phenomena take place. In addition, it will help quantify how climate change and ocean acidification may compound these issues. It is believed that such a scientific modelling tool will find outcomes and users in other watershed-reef ecosystems worldwide, such as in East Africa and South East Asia.

I.6. Synergy between the promoters and budget

Roughly speaking, the chief area of expertise of each promoter is as follows:

- Eric Deleersnijder: geophysical fluid flow modelling
- Thierry Fichefet: sea ice and ocean modelling
- Emmanuel Hanert: environmental fluid flow modelling
- Vincent Legat: computational fluid dynamics
- Jean-François Remacle: numerical methods and high-performance computing
- Sandra Soares Frazao: sediment dynamics

However, every promoter is competent in more than one field of research. In fact, the areas of expertise of the six promoters of the present project are complementary and exhibit

\textsuperscript{43} CART: Constituent-oriented Age and Residence time Theory (http://www.climate.be/cart).

\textsuperscript{44} Personal communication in 2009 from Professor Vincent Blondel (UCL) to Eric Deleersnijder.
significant overlaps. These considerations also hold true for the external partners, Professors Ton Hoitink and Eric Wolanski, whose primary areas of expertise are tropical hydrology and coral reef eco-hydrodynamics.

**Figure 9.** Project time line.

Four PhD students will need to be hired. Their involvement in the project, as well as that of the promoters, is illustrated in Figure 9. The latter presents the minimal configuration of
the team. In fact, based on the experience gained in previous research programmes, it is safe to assume that a project of the size considered herein will attract applications from a number of excellent students, i.e. students that are likely to be offered a teaching/research assistant position by UCL or win a PhD fellowship from external funding agencies (FNRS\textsuperscript{45} or FRIA). The salary of such PhD students would be supported by the UCL, FNRS or FRIA. In addition, the FNRS and FRIA PhD students receive a lump sum for covering their operational costs, implying that they would work for the project without being chargeable to it. In the light of these considerations, it is not unreasonable to assume that a number of PhD students of the order of 8 would be working — part- or full-time — for the project.

The present project being intrinsically multi-disciplinary, with strong physical and numerical components, we will seek to attract PhD students with a similar multi-disciplinary profile and make sure they have the opportunity to work with most of the promoters. Our ambition is to educate open-minded researchers, able to grasp the complexity of today's environmental issues and propose innovative solutions. In that respect, our group holds an encouraging track record with past PhD students being offered a lectureship at the University of Reading one year after obtaining his PhD from UCL (E. Hanert, 2005), a postdoctoral fellowship at Princeton University (L. White, 2007) and an Advanced Study Programme fellowship at NCAR\textsuperscript{46} (S. Blaise, 2009).

\textsuperscript{45} http://www2.frs-fnrs.be/
\textsuperscript{46} http://www.ncar.ucar.edu/
Appendix A: Data presently available for the domains of interest

Acronyms used in some of the tables:
CIS : Canadian Ice Service (http://ice-glaces.ec.gc.ca/)
GBR: Great Barrier Reef, Australia
ICESat : Ice, Cloud and land Elevation Satellite (http://icesat.gsfc.nasa.gov/)
NCAR : National Center for Atmospheric Research (http://www.ncar.ucar.edu/)
NCEP : National Centers for Environmental Prediction (http://www.ncep.noaa.gov/)
NOAA: National Oceanic and Atmospheric Administration (http://www.noaa.gov)
NSIDC : National Snow and Ice Data Center (University at Colorado at Boulder, http://nsidc.org/)
PHC : Polar Science Center (University of Washington, http://psc.apl.washington.edu/)
### Data presently available for the Canadian Arctic Archipelago

<table>
<thead>
<tr>
<th>Atmospheric forcing</th>
<th>Time/Resolution</th>
<th>Spatial Coverage</th>
</tr>
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<tbody>
<tr>
<td>Air temperature and wind velocity</td>
<td>6 hours 1948-now</td>
<td>2.5 x 2.5 degrees global</td>
</tr>
<tr>
<td>NCEP/NCAR reanalysis</td>
<td></td>
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<tr>
<td>Relative humidity (Trenberth et al., 1989)</td>
<td>Monthly</td>
<td>global</td>
</tr>
<tr>
<td>Cloudiness (Berliand and Strokina, 1980)</td>
<td>Monthly</td>
<td>global</td>
</tr>
<tr>
<td>Solar radiation (Zillmann, 1972)</td>
<td>Parameterisation</td>
<td></td>
</tr>
<tr>
<td>Net longwave radiation (Berliand and Berliand, 1952)</td>
<td>Parameterisation</td>
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<tr>
<td>Turbulent fluxes of sensible and latent heat (Goosse, 1997)</td>
<td>Parameterisation</td>
<td></td>
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<tr>
<td>Precipitation, NCAR (CORE)</td>
<td>Monthly</td>
<td>global</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature and salinity of the ocean</th>
<th>Time/Resolution</th>
<th>Spatial Coverage</th>
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</thead>
<tbody>
<tr>
<td>Climatology</td>
<td>Monthly</td>
<td>1 x 1 degree global</td>
</tr>
<tr>
<td>PHC</td>
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<table>
<thead>
<tr>
<th>Sea ice concentration</th>
<th>Time/Resolution</th>
<th>Spatial Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSIDC</td>
<td>Daily 1987-now</td>
<td>25 x 25 km polar stereographic</td>
</tr>
<tr>
<td>Climatology and annual since 1990</td>
<td>Monthly</td>
<td>Atlas of the Canadian Arctic archipelago</td>
</tr>
<tr>
<td>CIS</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Sea ice thickness</th>
<th>Time/Resolution</th>
<th>Spatial Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea ice draft from submarines</td>
<td>Seasonal 1975-2000</td>
<td>50 x 50 km Half the Arctic</td>
</tr>
<tr>
<td>(Rothrock et al., 2008)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIS</td>
<td>Weekly 1947-now</td>
<td>195 sites in the Canadian Arctic archipelago</td>
</tr>
<tr>
<td>ICESat campaigns (Kwok et al., 2009)</td>
<td>2003-2008</td>
<td>25 x 25 km on the Artic</td>
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</table>

<table>
<thead>
<tr>
<th>Ice motion</th>
<th>Time/Resolution</th>
<th>Spatial Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSIDC</td>
<td>Daily 1978–2006</td>
<td>25 x 25km North polar stereographic</td>
</tr>
<tr>
<td>Ice area fluxes (Kwok, 2006)</td>
<td>Monthly 1997– 2002</td>
<td>Straits in the Canadian Arctic Archipelago</td>
</tr>
<tr>
<td>Ice area fluxes and ice volume fluxes (since 1991) (Kwok et al., 2004)</td>
<td>Monthly 1979– 2002</td>
<td>Fram strait</td>
</tr>
</tbody>
</table>
## Data presently available for the Mahakam River region

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Resolution</th>
<th>Location Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>Google Earth for higher resolution for local studies</td>
<td>~10m</td>
<td>whole Makassar Strait and Mahakam river</td>
</tr>
<tr>
<td></td>
<td>Topographic maps (1980, 1992)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Historical aerial photographs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathymetry</td>
<td>data collected from ship missions</td>
<td>From 50 m to 250 m</td>
<td>whole Mahakam river</td>
</tr>
<tr>
<td></td>
<td>Global Digital elevation models are available (ETOPO) and can be used</td>
<td>1 minute</td>
<td>whole Makassar Strait</td>
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<tr>
<td></td>
<td>for estimating the bathymetry in areas were no echosounding data is</td>
<td></td>
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</tr>
<tr>
<td>Wind and Surface Pressure</td>
<td>NOAA NCEP/NCAR reanalyses data</td>
<td></td>
<td>whole Makassar Strait and Mahakam river</td>
</tr>
<tr>
<td>Water level data</td>
<td>TPXO 7 model : eight primary and two long period harmonic tidal</td>
<td>1/4&quot;, tidal components</td>
<td>Tides on the open boundary condition</td>
</tr>
<tr>
<td></td>
<td>constituents obtained from a model based on TOPEX/Poseidon and Jason</td>
<td></td>
<td>along the shelf break, too coarse to be</td>
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<tr>
<td></td>
<td>satellite data.</td>
<td></td>
<td>used on the shelf.</td>
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<tr>
<td></td>
<td><a href="http://www.oce.orst.edu/research/po/research/tide/global.html">http://www.oce.orst.edu/research/po/research/tide/global.html</a></td>
<td></td>
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<tr>
<td></td>
<td>Measurements in various places along the Mahakam river</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge data</td>
<td>with a horizontal acoustic Doppler current profiler (HADCP)</td>
<td>Every 30 minutes</td>
<td>in Melak and Samarinda (2008-2009)</td>
</tr>
<tr>
<td>Rainfall data</td>
<td>With tipping bucket raingauges</td>
<td>Hourly</td>
<td>in Melak, Penyinggahan, Teluk Tuk, Muara Kaman (2008-2009)</td>
</tr>
<tr>
<td></td>
<td>Historical data from local institutes</td>
<td>Daily</td>
<td>in Melak, Penyinggahan, Kotabangun, Muara Kaman, Sebulu, Tenggarong, Samarinda, Telukdalam (1993-2004).</td>
</tr>
<tr>
<td></td>
<td>Estimations with TRMM (Tropical Rainfall measuring mission)</td>
<td>Three-hourly, daily and monthly</td>
<td>Resolution of 0.25 degrees (1998-present)</td>
</tr>
<tr>
<td>Water and sediment dynamics</td>
<td>Many vessel mounted ADCP surveys</td>
<td>2-3 times for every location. In tidal areas data were collected during spring and neap, and for at least 12.5 hours.</td>
<td>In Melak, Muara Pahu, Muara Muntai, Pela, Muara Kaman, Samarinda, and in the delta (2008-2009)</td>
</tr>
</tbody>
</table>
### Data presently available for the Great Barrier Reef

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Resolution</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coastlines</strong></td>
<td>Global Self-consistent, Hierarchical, High-resolution Shoreline Database</td>
<td>up to 50m</td>
<td>whole GBR</td>
</tr>
<tr>
<td></td>
<td><a href="http://www.soest.hawaii.edu/wessel/gshhs/gshhs.html">http://www.soest.hawaii.edu/wessel/gshhs/gshhs.html</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Google Earth for higher resolution for local studies</td>
<td>~10m</td>
<td>whole GBR</td>
</tr>
<tr>
<td><strong>Bathymetry</strong></td>
<td>Australian bathymetry and topography grid : compiled data from over 1400 surveys</td>
<td>250 m</td>
<td>whole GBR</td>
</tr>
<tr>
<td></td>
<td>Data from the Australian Institute of Marine Sciences</td>
<td>500 m</td>
<td>whole GBR</td>
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<tr>
<td></td>
<td>Local data from ship missions</td>
<td>ponctual data</td>
<td>Rattray Island</td>
</tr>
<tr>
<td><strong>Wind and Surface Pressure</strong></td>
<td>NOAA NCEP/NCAR reanalysis data</td>
<td>whole GBR</td>
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<tr>
<td></td>
<td>Data set from various studies of Pr. Eric. Wolanski</td>
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<td></td>
<td></td>
<td></td>
<td>Northern and central GBR (see figure)</td>
</tr>
<tr>
<td><strong>Currents and Sea Surface Elevation</strong></td>
<td>TPXO 7 model : eight primary and two long period harmonic tidal constituents obtained from a model based on TOPEX/Poseidon and Jason satellite data.</td>
<td>1/4°; tidal components</td>
<td>Tides on the open boundary condition along the shelf break, too coarse to be used on the shelf.</td>
</tr>
<tr>
<td></td>
<td><a href="http://www.oce.orst.edu/research/po/research/tide/global.html">http://www.oce.orst.edu/research/po/research/tide/global.html</a></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Bluelink/BRAN model : regional model around the Australia with data assimilation</td>
<td>1/10°</td>
<td>Used to force the low frequency current on the open boundary condition along the shelf break. Can be used for model comparison on the shelf.</td>
</tr>
<tr>
<td></td>
<td>NOAA altimetry data and reconstructed currents</td>
<td></td>
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<tr>
<td></td>
<td>Data set from various studies of Pr. Eric. Wolanski</td>
<td></td>
<td>Northern and central GBR (see figure)</td>
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<tr>
<td><strong>Reef Connectivity</strong></td>
<td>A wealth of biological data (e.g. Munday et al., 2009)</td>
<td></td>
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<tr>
<td><strong>Sediments</strong></td>
<td>3 years of continuous data of suspended sediment concentration, waves and wind at two sites off Townsville (dry tropics)</td>
<td></td>
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<tr>
<td></td>
<td>1 year of similar data at two sites near the mouth of the Tully River and Dunk Island (wet tropics)</td>
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<tr>
<td></td>
<td>Several years of data of water quality and ecosystem health data from the AIMS Long-Term Reef Monitoring Programme</td>
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</tr>
</tbody>
</table>

A-4
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Appendix C: Letters of intent from the external partners
Dear Eric,

Regarding the Concerted Research Actions programme, entitled ‘Taking up the challenges of multi-scale marine modelling’, I would like to express my wish and intent to become a partner in that programme. Over the past decade I have gradually become convinced of the necessity of the development of hydrodynamic models with unstructured grids. Too often I have seen detailed hydrodynamic models adopting a traditional finite-difference approach expand, nesting detailed models in meso- and macro-scale models until the model environment becomes unmanageable. The feedbacks between flow phenomena at smaller and larger scales call for a rigorously different numerical solution method. Now that problems regarding conservation of mass in finite element models have been resolved, the list of pros and cons of different numerical methods has become unbalanced, in favor of the finite element approach as thoroughly implemented in SLIM. I am convinced the developers of SLIM employ an excellent approach to deal with the interdependence of flow phenomena at different scales, which explains why they are internationally leading in computational fluid mechanics of the environment.

As an assistant professor of environmental fluid mechanics, I am the principal investigator of a project that aims at understanding discharge dynamics in the Mahakam catchment in East Kalimantan under the influence of climate change. In this context, I supervise three PhD researchers, two of whom intend to setup a hydrodynamic model of the River Mahakam in the SLIM environment. The model will span from the shelf break up to the five main tributaries of the Mahakam, covering an area of about 250 km. The complexity of the network of channels, lakes, floodplains and continental shelf waters, renders SLIM one of the few feasible options to setup an all-encompassing model. When funding becomes available this model will be setup, using the calibration and validation data we gathered during an elaborate field campaign over the past 16 months, in a joint effort of Dutch and Indonesian researchers. Kalimantan is scientifically renowned for its susceptibility to ENSO events, causing droughts and resulting forest fires, and flooding.

Within Wageningen UR, Wageningen University’s department of Environmental Sciences co-operates closely with Alterra on research and education with regard to our green living environment.
of densely populated cities. The model will allow to investigate discharge dynamics in response to varying meteorological and marine conditions, exploring the interactions between hydrological and oceanographic processes.

Yours sincerely,

[Signature]

Dr. A.J.F. Hoitink
Hydrology and Quantitative Water Management Group
Department of Environmental Sciences
Wageningen University
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Atlasgebouw (building 104)
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The Netherlands
ton.hoitink@wur.nl
tel. +31 (0) 3174 82775
September 1, 2009

Professor Eric Deleersnijder
CIESAME
Université catholique de Louvain
Louvain-la-Neuve
Belgium

Dear Eric,

LETTTER OF INTENT

With regard to the Expression of interest for your Concerted Research Actions (ARC) programme “Taking up the challenges of multi-scale marine modeling”, I wish to express my interest and intent to become a partner outside UCL. I have already used the SLIM model for several applications in the Great Barrier Reef (GBR) concerning 2D and 3D oceanography processes, flushing and residence times, and fine sediment dynamics. I have modeled various aspects of oceanography and ecology in the GBR for thirty years and the SLIM model is by far the best model that I have used for the GBR because of its ability to merge scales from large-scale to small-scales and with a feedback unto small scales mainly via the sticky water phenomenon. SLIM truly is a most versatile tool and the only one in existence at this stage that can handle the multitude of relevant scales in the GBR. I have collaborated many times in GBR oceanographic studies over the last twenty years with yourself and members of your team and we were always very productive as judged for instance by the many (14) papers between us.

I would use SLIM as the primary oceanography model to estimate connectivity in the GBR, and drive an ecohydrology model to assess the human impact from agriculture in adjoining river catchments as well as from climate change.

As soon as funding becomes available I will help a PhD student who I co-supervise at JCU with the use of the SLIM model for estimating the residence time, and an undergraduate student estimate through altimetry data and 20 years of my current meter data the interannual variability of the East Australian Current on the outer shelf of the GBR – this being a key driver of the water circulation in the GBR. I also plan to collaborate with the marine biologists at JCU to use the SLIM model to estimate the fate of juvenile turtles and coral fish near their natal beaches/reefs.

Yours Sincerely,

[Signature]

Professor Eric Wolanski, FTSE, FIE Aust
The authors of the present proposal are deeply indebted to all those who have contributed time and efforts to its writing, be they members of the SLIM team or not. Without them, this document could not have been prepared.