Multisensor Impact assessment in Coastal and Shelf Seas

(MICSS)

A proposal submitted to the NASA/CNES/EUMETSAT
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Principal Investigators:

Name: Pierre De Mey

Department: ____

Institution: __LEGOS – UMR5566 (CNRS/CNES/UPS/IRD)___________________

Street/PO Box: _18, av. Edouard Belin__________________________________

City: __Toulouse__________ State: ___________ Zip: _31401 Cedex 9 __

Country: _FRANCE__________ E-mail: Pierre.De-Mey@legos.obs-mip.fr,

Telephone: +33 (0) 561332928 ___________ Fax: __+33 (0) 561253205________

Co-Investigators:

Name	Institution	Telephone
N. Ayoub	LEGOS	+33 (0) 561332902
F. Birol	LEGOS	+33 (0) 561332924
J. Lamouroux	NOVELTIS	+33 (0) 562881135
F. Lyard	LEGOS	+33 (0) 561332988

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3.Identifying information

3.1 Title of the investigation

"Multisensor Impact assessment in Coastal and Shelf Seas (MICSS)"

3.2 Investigators and external collaborators

Name	Position	Organization	Project status
Nadia Ayoub	Chargée de Recherches CNRS	LEGOS-POC	Co-I
Florence Birol	Physicien adjoint CNAP	LEGOS-POC	Co-I
Pierre De Mey	Directeur de Recherches CNRS	LEGOS-POC	PI
Julien Lamouroux	Ingénieur-Docteur	NOVELTIS S.A.S.	Co-I
Florent Lyard	Chargé de Recherches CNRS	LEGOS-POC	Co-I
Joël Hoffmann	Ingénieur	Météo-France	External collaborator
Alexander Kurapov	Assistant Professor	Oregon State U.	External collaborator
Dominique Obaton		MERCATOR	External collaborator
Vincent Taillandier		IPSL	External collaborator

3.3 Principal Investigator

Pierre De Mey
Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS UMR5566 CNRS-CNES-IRD-UPS)
18 avenue Edouard Belin
F-31401 Toulouse Cedex 9
France
Phone: +33 (0) 5 61 33 29 28
Fax: +33 (0) 5 61 25 32 05
E-Mail: Pierre.De-Mey@legos.obs-mip.fr

Pierre De Mey is a physical oceanographer, CNRS Research Director at LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales), Toulouse, France. He is Habilité à Diriger des Recherches at Paul Sabatier University, Toulouse, and leads the Ocean Dynamics team at LEGOS. With his team, he is conducting research in deep-ocean and coastal data assimilation, on theoretical aspects (Ensemble filters, Array design methods), physical aspects (Reduced-Order schemes, Isopycnal schemes, Downscaling) and applications. He is a member of the International GODAE Steering Team and of the MERCATOR and LEFE/IDAO Science Committees. He has been Project Scientist for assimilation in MERCATOR in 1996-2003, where he has developed the multivariate assimilation system currently used by MERCATOR for real-time forecasting and reanalyses, former member of the EuroGOOS Mediterranean and Atlantic Task Teams, and Principal Investigator for TOPEX/POSEIDON, JASON-1, ENVISAT and OST. Along with colleagues of the Laboratoire d'Aérologie and LEGOS, he is a founding member of the Pôle d'Océanographie Côtière (Coastal Oceanography Group) in Toulouse.

3.4 Participating institutions

3.4.1 Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS)

The Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) is Unité Mixte 5566 of CNRS, IRD, Université Paul Sabatier (UPS), and CNES. Its main domains of research are geodesy, geophysics, oceanography (physical, geochemical and biogeochemical, open-ocean and coastal) and dynamics of polar ice shelves. Our main data sources include satellite remote sensing and in particular altimetry, tide gauges, drifting float programs as well as dedicated cruise data. The laboratory has also a unique expertise in numerical modelling (prognostic, inverse; finite-difference and finite-element; circulation and free-surface processes such as tides) as well as in data assimilation and estimation methods. LEGOS is involved in the French MERCATOR project aiming to the development of operational oceanography as well as in several EU-funded projects.

The LEGOS participants in this proposal are part of the ECOLA team ("Echanges Côte-Large", i.e. Coastal – Open Ocean Exchanges) and are also part of the Pôle d'Océanographie Côtière (POC) described below.

3.4.2 Pôle d'Océanographie Côtière (POC)

The Pôle d'Océanographie Côtière de Toulouse is part of the Observatoire Midi-Pyrénées (OMP), itself a component of the Université Paul Sabatier (UPS, Toulouse-III) and an Observatoire des Sciences de l'Univers of CNRS/INSU. OMP hosts six laboratories having in common of carrying out research in Sciences of the Universe. Researchers belonging to two of the laboratories, namely Laboratoire d'Aérologie (LA) and Laboratoire d'Etudes en Géophysique et Océanographie

Spatiales (LEGOS), make up the Pôle d'Océanographie Côtière de Toulouse. The Pôle is structured under a Plan Pluri-Formation, recognized by both sponsoring agencies, CNRS and UPS. Besides, CNES is one of the sponsors ("tutelles") of LEGOS.

The POC is active and has experience in the areas of coastal numerical modelling, shelf modelling, river plume modelling, coastal/shelf data assimilation, coastal remote sensing, coastal/shelf physics. It is equipped with a Linux PC cluster that would need to be expanded to meet the project's objectives.

The POC has been recently recognized ("labellisé" in French) by the CSOA as providing service to the community. It is in the process of hiring an engineer to take care of these aspects.

3.4.3 NOVELTIS

NOVELTIS is a French SME ("Société par Actions Simplifiée" – S.A.S.) specialized in remote sensing. The company is composed of 45 science PhD graduates and engineers with skills in atmospheric physics and chemisrty, oceanography, geodesy, Geo- and biophysics of continental surfaces and astrophysics. In particular, the oceanography / geodesy team developed skills in remote sensing, particularly in altimetry, ocean modelling (coast and shelf zones) and data assimilation (remote and in situ observations). NOVELTIS has a strong partnership with research laboratories, in particular with LEGOS, with which it has several collaborations on projects for CNES, ESA, the UE.

3.5 Recent relevant references of the proposing team

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4.Investigation and technical plan

4.1 Summary

This cross-cutting proposal concentrates on the Coastal Ocean, and proposes to examine (1) the signature of dynamical processes and errors in the observed variables (including sea level), in particular extreme meteorological events, and (2) the objective impact of observations onto estimates and forecasts of those processes. Objective (1) will be largely modelling-based, and will provide an opportunity to confront multisensor observations and realistic, state-of-the-art numerical models. Objective (2) will use numerical models along with advanced, ensemble-based data assimilation methods.

4.2 Background

As stated above, one of the main objectives of this proposal is to confront realistic, state-of-the-art numerical models with JASON/OST altimetry and other data types. In this section, we review some issues and requirements related to realistic modelling and data assimilation in Coastal Ocean models.

4.2.1 Specific physics of coastal ocean models

There are major differences between open-ocean and coastal ocean numerical models. First of all, the physics and scales are different. An important issue arises with the rapid change in dominant physical processes moving between the coastal areas and the open ocean, and the corresponding requirements concerning the required model forcing functions. Continental shelf and slope seas differ from the open ocean in the presence of the coast, strong bathymetry gradients, inputs from rivers, and shallower water. Coastal-trapped waves propagate cyclonically around the ocean basin, on the gradient of potential vorticity caused by this depth change (Huthnance, Mysak and Wang, 1986). Shelf-scale responses to forcing are transmitted along the shelf in this sense. Flows in these shallower seas are forced by (*inter alia*) pressure and current fields from ocean-scale mass balances, circulation, tides and eddies, winds and air pressure variations, non-uniform density (due to solar heating, river inputs, precipitation-evaporation, latent and sensible heat fluxes). For all these, responses differ between the deep ocean and shallower shelf as follows.

Along-slope currents can be forced by an along-shelf pressure gradient from the oceanic density field. The barotropic pressure gradient can be larger in shallower shelf and slope waters, with only part of the steric gradient, than in the deep ocean where steric and surface-elevation contributions nearly cancel. Other agents of along-slope flow are: steady wind stress; a response to fluctuating winds that is biased because coastal-trapped waves only cause form drag on flow that is anti-cyclonic around the ocean basin; rectified tides and other waves; geostrophic balance in a front along the shelf-break (Gawarkiewicz and Chapman, 1992), e.g. significant fresh-water input on a narrow shelf.

Tides in the open ocean often have amplitudes O(0.2 m) that scale with the equilibrium tide. (The near-resonant Atlantic has larger tides). However, wave dynamics and energy convergence often amplify the response in shelf seas, by a factor as large as 10 or more. Shelf-sea currents filling the volume between high and low tide are shallow and correspondingly strong. Tides carry momentum-flux and sharp spatial gradients (e.g. headlands and the shelf edge) give rise to tidal *residual currents*, along depth contours if friction is weak (e.g. Huthnance, 1981). *Tsunamis* also amplify on the shelf for similar reasons; their shorter period favors a progressive form and continued run-up at the coast.

Internal waves are ubiquitous in the ocean. The continental shelf edge in particular generates internal tides where vertical (possibly non-hydrostatic) displacements are induced by tidal flow across the steep slope. Then non-linear interactions distribute the energy over a spectrum between the Coriolis and buoyancy frequencies. Internal tides often propagate onto (and off) the shelf, and may be generated at banks on the shelf.

Storm surges are driven by winds and air pressure of large spatial scale 100 – 1000 km to which shallow shelf seas respond quickly (hours) with the coast acting as a barrier and setting up pressure gradients. A layer below stratification may be 180° out of phase with the surface layer (Rippeth et al., 2002).

Upwelling and downwelling are induced by (respectively) offshore or onshore transport of surface water, forced by the wind and diverging or converging towards the coast. Spatial gradients of wind stress in the land-sea transition (effects of vegetation versus waves, topography, sea breezes) also cause surface transport gradients and sheltering in various configurations (e.g. Huthnance, 2002). Divergent transport requires surface-water replacement by upwelling; downwelling is the reverse. Capes tend to favor upwelling, through topographic effects and because a wider range of wind directions causes offshore transport somewhere. Upwelling may raise a seasonal thermocline to the surface as a front, which may further develop instabilities and filaments.

Surface-wave currents reach the bottom in shallow shelf seas, causing sediment suspension, mixing and increased wave breaking, a source of near-surface turbulence.

(Seasonal) heating and cooling are affected by mixing: by bottom turbulence from tidal currents and from the surface by winds and waves. Dense water, formed by heat removal from shallow shelf seas in winter, may *cascade* down the continental slope (Shapiro et al., 2003). Seasonal *fronts* occur between summer-stratified areas and (usually shallow) areas where the water column is well-mixed (Simpson and Hunter, 1974). Fronts may also occur between oceanic waters and coastal waters freshened by river inputs. Frontal density fields imply pressure gradients, typically in near-geostrophic balance with along-front or coastal currents (which may be baroclinically unstable).

A close relationship with the topography is common to all these features. Hence good predictions require bathymetry on the predominant scales of a few kilometers at the shelf break and coast. Near-coast predictions also require winds, air pressure and waves resolved on similar scales, and well-resolved in time; Warrach (1998) found that monthly-, daily-averaged and hourly winds gave successive improvements in shelf-sea seasonal thermocline prediction, and that local winds were needed. Other meteorological variables needed are temperature and relative humidity, precipitation, cloud cover and radiation (long-wave and short-wave, downwards and upwards). Temperature in shallow seas is sensitive to the heating; cloud-cover especially can be a problematic input. Obtaining local meteorology which resolves the effects of coastal features, such as exposed sandbanks/mudflats or cliffs/steep coastal topography is usually not possible. An example of its impact was demonstrated in the German Kustos experiment, where a local high resolution atmospheric model was coupled to coastal ocean model of the German Bight thereby better resolving the processes at the sea/land interface (see Ocean Dynamics, 51 (2/3), 1999 for a selection of papers on Kustos); also see results from the MEAD experiment in the Kattegat (Spokes et al, 2005). River inputs are important to near-coast salinity and dynamics, but are often not readily available as time series; un-gauged inputs are often significant.

4.2.2 Tides and barotropic modelling

The tides are the dynamical process with the largest amplitude in shelf/coastal seas. During severe meteorological events, storm surges can match the tidal elevation and currents, especially close to shore. In contrast to the open ocean, high frequency dynamics (HFD) can impact the lower frequency coastal processes (LFD) for several reasons e.g. vertical mixing (bottom layer, internal waves along the shelf break), horizontal exchange across the shelf break, residual transport along shelf edges and shorelines. Two choices can be made when modeling the effect of tides in coastal circulation models:

1. The tides and storm surges are not taken into account in the external forcing (open boundary conditions), body forcing (astronomical and loading/self-attraction potential) and surface forcing (HF wind and pressure). In addition any assimilated data must be carefully detided and lowpass-filtered. When such a choice is made, all the possible interactions between HFD and LFD must be parameterized. The parameterizations would preferably be fed with dedicated HF models (such as the 2D barotropic models developed at POC, Toulouse and in other groups). The advantage of this choice is to keep the time step and archive dump at reasonable levels. However, nothing can guarantee today that such parameterizations will be accurate enough to meet the requirements of realism of the applications.
2. The full HFD is taken into account. Providing that proper numerical schemes are used for the external mode, the advantages of this choice are obvious: improved state vector representativity (when assimilating or comparing to data), less parameterization hassles. In the other hand, such an approach will require time splitting capabilities in the numerical schemes to limit the computational cost of the fast barotropic modes. More annoyingly, the vertical current generated by the tides at the shelf edges might limit the internal time step (Courant-Friedrichs-Levy condition on the vertical, although there are numerical treatments to overcome this, e.g. James 2000[1]). Also the periodic variation of the

[1] James, D., 2000. A high-performance explicit vertical advection scheme for ocean models: how PPM can beat the CFL condition. Applied Mathematical Modelling, 24(1): 1-9.

ocean surface layers due to the internal waves can interact with some turbulence closure schemes. Last but not least, the model archive will need a built-in post processing module to filter out the HF signal, especially tides. This can be performed by the means of harmonic analysis.

In our opinion, the parameterization approach should remain a last option choice as it adds some conceptual noise in the model. The full dynamics option is more natural, but will require a significant initial effort.

Plans have been made at LEGOS to build a state-of-the-art Tidal Library that will include all functional aspects needed to force and remove tides in a numerical model. A preliminary version is being successfully implemented in the TUGO finite element model at LEGOS, see below). Such a library would benefit a large number of hydrodynamical models used in coastal areas in the international community since most of them have none or very limited tidal capabilities (such as NEMO, ROMS, HYCOM etc..).

4.2.3 Unstructured grid modelling

The recent progress in ocean modelling has highlighted the need to solve for the short scales of the ocean dynamics. Among others, the most demanding processes in terms of space resolution are the ocean fronts, deep convection and internal waves. The unstructured grid modelling is a powerful approach to extend the model resolution range at a reasonable computational cost, while eliminating the need for nesting. The inherent geometric flexibility of unstructured mesh numerical models offers distinct advantages for oceanic simulations at various spatial and temporal scales. Chief among these are a faithful and efficient representation of the complex coastlines and topography, and a variable resolution grid that can be adapted to capture critical evolving dynamical features. Vertical coordinate specifications are also much more flexible when using the unstructured discretization.

The unstructured mesh approach can easily accommodate a vast variety of numerical schemes, such as the finite elements with Continuous Galerkin or Discontinuous Galerkin schemes, finite volumes schemes, as well as an unlimited range of higher order schemes. Moreover, it allows the flexibility of mixing different numerical schemes and their orders in the same model, hence offering to the modellers an unprecedented flexibility in picking the optimal scheme for a given dynamical problem to solve. The geometric and numerical flexibility of the unstructured mesh approach is illustrated by the present developments, such as the mesh adaptivity and the temporal sub-cycling. A wide range of new techniques are being assessed and used, both with respect to hydrodynamic modelling as well as for data assimilation. At the price of a higher preliminary complexity, the unstructured mesh approach offers the modellers a nearly unlimited flexibility and the ability to select numerical solutions appropriate for different classes of problems, and reduces the need for multi-level nesting in mixed open ocean and shelf applications.

Building on the recent progress in finite-element and finite-volume flow solvers, a number of research groups have embarked on a journey to develop unstructured mesh ocean models aimed at simulating basin, coastal and estuarine flows. The UGO initiative (Unstructured Grid Ocean) has been initiated in 2002. It aims to federate the international efforts toward a new generation of hydrodynamic ocean models based on the unstructured grid discretization. A series of annual workshops serves as a forum for developers and users to discuss common issues, share ideas and collaborate on model development and applications. The fifth workshop on unstructured grid numerical modelling has been held on November 13-15 2006 in Miami (http://www.rsmas.miami.edu/personal/ugom06).

The TUGO model (for "Toulouse UGO"; Lyard, 2007, pers.comm.) is one of the state-of-the-art models used in this proposal in the purpose of better explaining the sea-level signal contained in altimetry products.

4.2.4 Data assimilation in coastal ocean models

The most important practical use of coastal data assimilation is in the estimation of past, present and future conditions on continental shelves and also providing associated measures of uncertainty. It is typically used to sequentially update initial conditions and sometimes the open boundary conditions. Estimation of past changes (sometimes called historical reconstructions or hindcasts) gives climatologies of the seasonal mean state of the coastal ocean and its variability. The reconstructions can also be used to generate maps of the return period of extreme events (e.g. Bernier and Thompson, 2006). Such statistics are essential when designing coastal infrastructure or assessing, for example, the risk of coastal flooding. Maps of the present state (i.e. nowcasts) are used in adaptive sampling of the coastal ocean (e.g. Robinson and Lermusiaux, 2006). Forecasts of future states are needed for a wide range of applications including marine search and rescue, pollution control, and mitigating the effect of coastal flooding and harmful algal blooms.

Data assimilation methods are also used to downscale predictions from open ocean models to the coastal zone. More specifically data assimilation can be used to (i) suppress the unrealistic transients that can be generated by the change in model physics, forcing and resolution at the coastal model's open boundary (POC: Auclair et al., 2001), (ii) blend information from the larger-scale ocean model field with local observations.

The design of sustained coastal ocean observing systems, and adaptive/targeted field programs, are topics of considerable interest. The design of future satellite missions is of critical importance to oceanography at the present time (e.g. the OST/JASON series and the SWOT project). Data assimilation can help with Observing System Simulation Experiments (OSSEs; e.g. Lamouroux et al., 2006), and can provide useful design tools and concepts such as adjoint models, representers, ensemble spread in EnKF (Mourre et al., 2004, 2006), and singular value decomposition of representer matrices approximated using ensembles. After an observing system is operational, data assimilation can help with near real-time quality control of observations and the ongoing assessment of the observing system's performance.

Data assimilation is also used to test dynamical hypotheses and make inferences about ocean processes. This is particularly important when developing biogeochemical models because the parameterizations of many biogeochemical processes is highly uncertain (e.g. Robinson and Lermusiaux, 2002 and references therein).

A wide range of methods are presently used to assimilate data into coastal models. The sequential methods include simple nudging, optimal interpolation, reduced order optimal interpolation (as in ADRICOSM in the Adriatic sea), ensemble-based optimal interpolation (e.g. Lamouroux et al., 2006) and various forms of Kalman filter including the extended Kalman filter, singular evolutive Kalman Filter (SEEK), and Local Ensemble Kalman filters (e.g. Mourre et al., 2004, 2006; De Mey, 2007, pers. comm.). Adjoint-based methods continue to be used extensively to identify parameters, initial or boundary conditions (Taillandier et al., 2006) based on the minimization of cost functions. Variational balanced analyses are used to suppress transients, and to adjust solutions when projecting a coarser solution onto a finer model grid. Ensemble-based methods are also being used to explore the model error subspace and help specify assimilation statistics e.g. forecast error covariances (e.g.. Echevin et al., 2000; Auclair et al., 2003; Lamouroux et al., 2006; Le Hénaff et al., 2007).

Several important issues are related to coastal data assimilation:

Large number of variables to be predicted and the models to predict them: The variables of interest for coastal applications include physical properties throughout the water column (e.g. near surface currents for marine search and rescue, near bottom currents for sediment transport) with time scales that range from minutes and hours (e.g. tsunamis, tides) to decades (effect of sea level rise). Recently there has been increased interest in predicting biogeochemical properties (e.g. harmful algal blooms) and this greatly increases the number of variables and the complexity of the assimilation schemes (Lermusiaux and Robinson, 2002). Given the large number of variables to be predicted, and the scales of interest, it is not surprising that many types of shelf models have been developed over the years e.g. nested finite difference and unstructured grid, sigma coordinate and spectral in the vertical, barotropic and baroclinic, hydrostatic and non-hydrostatic, advection-diffusion and individual based (Lagrangian) models for biological variables.

Many data types available for assimilation: Data assimilation in coastal models offers the possibility to incorporate information not or improperly incorporated in the large-scale estimates such as GODAE simulations (MERCATOR, FOAM, MFS, TOPAZ in Europe). A wide range of data is available for assimilation into coastal models, e.g. sea level from altimetry, coastal tide gauges and bottom pressure gauges, currents from land-based radars and acoustic Doppler current profilers mounted on moorings and moving vessels, water properties from fixed moorings and ferries, multi-frequency acoustics and multi-spectral optics for biological state estimation, satellite observations of sea surface roughness, height, temperature and color, measurements from Lagrangian profilers (ARGO), gliders and AUVs. The assimilation of sea-level and satellite data from coastal regions hold particular promise but both present major challenges. The assimilation of thermal satellite imagery is complicated by the fact that a composite of several hours of satellite data can introduce distortions because of tidal (and other forms of) advection. This can complicate the specification of the model error. The assimilation of tide gauge data must take into account the fact that sea-level is a spatial integrator of ocean dynamics and is thus influenced by shelf and deep ocean conditions. The assimilation of altimetry must also correct for the aliasing of the strong tidal signals evident in many coastal regions as well as for inertial oscillations. In addition the sampling configuration of nadir altimetry is not well adapted to constraining the high spatial and temporal frequencies characterizing the coastal processes. Projects using wide-swath altimeters such as SWOT, or constellations of nadir altimeters, are of great interest to coastal forecasters. The economic implications of coastal forecasting could provide a strong argument for pushing global coastal observing systems such as these.

Complex physics and range of scales of variability: In the coastal zone one has to deal with many factors that can complicate the assimilation of data compared to the open-ocean, e.g. free-surface variations (tides, storm surges), anisotropy (offshore scales are generally shorter than alongshore scales), non-homogeneity, non-separable covariance functions in space, non-hydrostatic motion, friction and mixing effects throughout the water column (driven in part by tides), shallow water and strong variations of bathymetry, baroclinicity and significant freshwater input from terrestrial sources. To further complicate the situation, the time scales of these factors range from hours (tides) to decades (e.g. river runoff) and complex nonlinear processes can couple the variability at different frequencies. This means that it is often not possible to model the error subspace in one frequency band in isolation (e.g. a realistic estimate of the seasonal mean state must include the effect of the tides and rapidly evolving storms).

Characterization and specification of model error: This is critical in any assimilation scheme but extremely challenging in the coastal zone. The model errors are strongly dependent on time scale (and thus application) but any attempt at separation is confounded by strong nonlinearity in the dynamics that can couple variability at different frequencies. (For example, model error at tidal frequencies can influence the predicted tides and this, in turn, can influence the lower-frequency baroclinic motion through the effect of tidal mixing on the vertical structure of temperature and salinity.) This argues in favor of "advanced" assimilation methods (including dynamically-consistent error prediction schemes, as in Mourre et al., 2004, 2006). As a first step, one must characterize the forecast errors under various error regimes by methods which include realistic error dynamics such as stochastic modelling (e.g., Echevin et al., 2000; Auclair et al., 2003; Lamouroux et al., 2006; Le Hénaff et al., 2007).

Non-Gaussian errors and biases: Most existing assimilation schemes are based on the Kalman Filter which is optimal for linear systems and unbiased Gaussian observation and model errors. For many physical processes the Gaussian assumption is open to question (e.g. penetration of slope currents onto the shelf) and the situation is even less clear for biogeochemical processes (e.g. eutrophication). Similarly, biases can be a major problem in limited-area coastal models that are strongly influenced by imperfectly known fluxes across the air-sea interface and lateral boundaries. Eventually it will be necessary to allow for non-Gaussian observation and model errors and use bias-aware approaches as in Drécourt and Haines (2006).

Assimilation into coupled coastal-deep ocean models and unstructured-grid models: Downscaling allows the changes on the coarser deep-ocean model grid to influence the higher resolution shelf model through its open boundary condition. Ideally one would like the shelf model, into which has been assimilated all available coastal data on the finer shelf model grid, including inputs from terrestrial sources, to similarly influence the deep-ocean model (upscaling). The most effective way to achieve this is by assimilating in a coupled shelf-deep ocean model or in an unstructured-grid model representing both types of scales. This will allow shelf data to correct the deep ocean state and the deep ocean data to simultaneously correct the shelf state. A good example of a measurement that would benefit from such an approach is coastal sea level which, as mentioned above, is influenced by both shelf and open-ocean processes.

Limits to predictability and skill assessment of assimilation models: A secondary topic of this proposal is the study of the predictability limit of coastal models, and how it is influenced (hopefully, improved) by data assimilation (e.g. Andreu-Burillo et al, 2006) and by the downscaling from GCMs. A related issue is skill assessment i.e. how we assess the effectiveness of data assimilation schemes in the coastal zone. Two categories of indicators can be considered to that end: skill assessment metrics and internal consistency (cross-validation, minimum value of the cost function). Finally let us mention the perspective of probabilistic prediction, i.e. methods which do not provide a single estimate but a posterior distribution of the ocean state given the prior distribution the state and the observations. On the "elementary" end of the spectrum, multi-model ensembles could be very useful for practical applications; we intend to follow that approach in this proposal concerning atmospheric models. On the "advanced" (and expensive) end, one could consider Particle Filters and Markov Chain/Monte-Carlo (MCMC). Such methods have the potential to significantly advance data assimilation in coupled physical-biogeochemical models. We anticipate that results obtained in this Proposal will constrain the future directions of research concerning advanced data assimilation schemes for coastal ocean models.

4.2.5 References

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4.3 Experimental objectives and approach

4.3.1 Objective (1): Signature of coastal and shelf seas dynamical processes and errors in the observed variables (observation state space)

This first objective deals with how processes and errors typical of the coastal ocean are seen in observed variables (including sea level), and also in non-observed ones. We also have as a secondary objective to make comments on adequate observing systems for coastal and shelf seas.

Challenges taken on by the proposal include:

- Combined analysis of existing multisensor data in focus regions to illustrate the signature of dominant processes such as: slope current and variability, upwellings, tides and barotropic response to wind and pressure, abyssal plain mesoscale features and deep water formation, tidal-induced mixing and fronts, thermohaline processes.
- Advanced three-dimensional, realistic, multiscale numerical modelling, with (a) verification against existing multisensor data, and (b) study of the signature of dominant processes onto observations.
- A study of the signature of storms and extreme meteorological events in observed variables (including sea level), as well as in poorly-observed or non-observed ones (surface layer, thermohaline structure, HF transients).
- Stochastic modelling and Ensemble-based data assimilation will be performed in support of other activities in this proposal, in an attempt to represent the uncertainties associated with known error sources in numerical models. The signature of those errors in the observed variables will be studied by means of representers calculated from ensembles, and in particular from the so-called Representer Matrix Spectrum (RMS) approach recently introduced. The investigators could be led to recommend particular observing strategies and complementarities e.g. between space-borne and in situ measurements.

4.3.2 Objective (2): Potential and effective impact of observations onto estimates and forecasts of those processes (model state space)

This second objective, in the light of the first one, is about how potential or real observations (including sea level) will impact estimates and forecasts of processes listed above.

Specific challenges include:

- Advanced data assimilation in Coastal and Shelf Seas. The DARSS OST project has shown that this is a difficult endeavor because of the non-homogeneous, non-isotropic, non-stationary, non-Gaussian character of model errors in CSS models, and because of the inherent limitations to predictability linked to the “open” character of CSS systems forced by lateral and surface boundary conditions. This will be done here by means of advanced schemes such as the Ensemble Kalman Filter and possibly derived schemes (such as Importance Resampling schemes) with ad hoc definitions of the state vector – i.e. including surface atmospheric variables and possibly open parameters e.g. those related to vertical turbulence.
- Impact assessment of various existing or planned observational strategies, modelling strategies, model parameters, onto model fields. This will imply the definition of ad hoc metrics measuring quality of estimates (derived from the GODAE/MERSEA metrics; Le Provost *et al.,* 2002) and internal assimilation consistency.
- Ensemble filters and stochastic modelling again provide interesting insight here, but this time in model state space via the study of representer functions. In particular, we will attempt to relate the dominant observation-space modes from the above RMS analysis with model space by means of Modal Representers (De Mey and Le Hénaff, pers. comm., 2007). Another option will be to calculate a posteriori forecast skill diagnostics from ensemble forecasts (Continuous Ranked Probability Score – CRPS).

4.3.3 Approach

The tasks are summarized in **Table 1**, as well as the permanent personnel attached, main collaborations outside of the project, related objectives (**Section 4.3**), approximate calendar (see also **Section 5.1**) and main task dependencies.

Table 1: MICSS tasks

Task / Subtask	**Title**	**Permanent personnel & collaborations**	**Objectives**	**Calendar & dependencies**
T1	Signature of coastal and shelf seas dynamical processes in satellite altimetry and other data	Birol, Lyard, coll. DYCOMED	1	years 1-4 (background)
T2	Objective impact of multisensor data in Coastal and Shelf Seas and application to Array Design	Lead: De Mey	1,2	
S2.1	Representer analysis and array design via stochastic modelling	De Mey coll. Taillandier, IPSL	1,2	year 1
S2.2	Representer analysis and array design by Local Ensemble Kalman filtering	De Mey, Ayoub, coll. A. Kurapov, OSU	1,2	years 1-4 (background)
S2.3	Maintenance of the Bay of Biscay LEnKF and array design methodology	De Mey, Ayoub, Lamouroux	2	years 1-4 (background)
S2.4	Library of Ensembles for community use	Ayoub, De Mey	1,2	years 1-4 (background)
T3	Signature onto Sea Level and SST of storms and other extreme meteorological events in the Bay of Biscay	Lead: Ayoub	1,2	
S3.1	Gaussian atmospheric variability	Ayoub, De Mey, Lyard, Birol	1,2	years 1-2 (partly dependent on S2.2)
S3.2	Extreme events	Ayoub, De Mey, Lyard, Birol	1,2	years 3-4 (dependent on S3.1) (prospective)
T4	Performance of simplified altimetry assimilation schemes in in the North-Western Mediterranean	Lamouroux, De Mey	2	year 1
T5	Improving regional tidal models by Ensemble spectral OI	Lyard, Lamouroux, De Mey	2	years 1-2
T6	Improving regional, high-frequency barotropic models by advanced Ensemble data assimilation	Lyard, De Mey	2	years 2-4
T7	Applications of Ensemble data assimilation of altimetry and other data in the Bay of Biscay regional, high-frequency 3D model	Lead: Lyard	2	
S7.1	Operational application	Lyard, coll. SUDOE	2	years 2-4 (dependent on S2.3) (prospective)
S7.2	Finite-element configuration	De Mey, Lyard	2	years 3-4 (prospective)
T8	Gravity data impact study in the Bay of Biscay	Lamouroux, De Mey	2	year 1
T9	Impact assessment metrics	De Mey, coll. D. Obaton, MERCATOR	2	years 2-4 (background)

One of the original standpoints of this proposal will be the use of combined multisensor data, both from in situ and space observations. We will consider observations of several types, simulated or real depending on availability and type of use:

- Sea level from nadir and wide-swath altimeters, at time scales ranging from O(1 hour) to O(1 year), and in the case of altimeters at a horizontal resolution improved for coastal studies (this proposal will therefore complement N. Mognard's OST proposal in support of SWOT both for oceanography and hydrology)
- Sea level from coastal tide gauges (hourly data – long time series)
- Sea surface temperature, in particular from the high-resolution products (GHRSST, etc.)
- Mean Dynamic Topography data (GRACE, GOCE)
- Surface atmospheric variables from models
- Cruise data (Bay of Biscay arrays, gliders)
- Lagrangian data (ARGO)

We wish to concentrate on four focus regions already studied or envisaged by the investigators:

- Principally the Bay of Biscay, with a zoom onto the Plateau des Landes area, and a possible inclusion in a larger IBI (Irish-Biscay-Iberian shelves) area such as defined in the MERSEA, ECOOP and MyOcean FP6-7 proposals
- North-Western Mediterranean
- English channel, Dover channel and North Sea
- Amazonian shelf

Case studies will be performed both in "Gaussian" periods and during selected storms and extreme events such as the storms of the end of the second millenium.

4.4 Experimental and work plan

4.4.1 T1: Signature of coastal and shelf seas dynamical processes in satellite altimetry and other data

Involved personnel: Birol (task leader), Lyard

Collaborations: DYCOMED proposal (TOSCA), CTOH OST proposal

Rationale:

A main axis of progress for the development of information systems in coastal area are *ad hoc* studies towards a complete assessment of existing observation systems. Altimetry forms the backbone of a wide range of scientific and operational ocean applications. However, if satellite altimetry has received much attention in the open oceans, its coastal applications, potentially manifold, are still largely unexplored. The transition to routine use of satellite altimetry in coastal areas, as part of operational monitoring systems, requires dedicated studies of both the measurement quality and the observability problem. This work will hopefully provide much greater availability of altimetry data and derived products in the coastal seas to the oceanographic community, and thus open the way to new applications for satellite altimetry in marginal seas.

Approach:

For some years, a dedicated data processing system has being developed by the MAP (Margins Altimetry Project) group: the X-Track software. Among other improvements, since the global ocean models cannot account for the extreme, rapid and high resolution processes occurring in coastal zones, it uses the much higher resolution regional MOG2D model for the HF de-aliasing of the altimeter data (Pairaud et al., 2007). The editing strategy has also been re-defined in coastal ocean conditions (Roblou and Lyard, 2004). Moreover, it uses higher sampling rates processing (up to 4Hz) which increases the spatial resolution to 2 km along-track. Inversion algorithms have then been added for estimating a local mean sea surface directly from the improved altimeter data processed.

The processing is now at a validation stage, where the products obtained are compared against in situ observations and standard altimetric products in different experimental regions. The first analyses performed in the NW Mediterranean Sea and in the western Bay of Bengal have shown a substantial increase in both the number of valid data in the coastal domain and their consistence to tide gauge sea level anomalies (Bouffard et al., 2007a; Bouffard et al., 2007b; Durand et al., 2007a). A range of shelf and coastal ocean dynamics, not observed with standard 1Hz along-track products, has already been identified when using the X-Track processing (eg coastal trapped waves and the meso-scale variability of the coastal circulation; Bouffard et al., 2007a; Durand et al., 2007b). This opens the way to new applications for satellite altimetry in marginal seas

In standard altimetry, the main problems are not only the accuracy of data in marginal seas, but also the gap in data next to the coast (10-40km). The first analyses show that this problem is reduced with the use of the X-Track processing. In particular, the use of high frequency (4 Hz) altimeter data allows getting observations closer to the coast (Bouffard et al., 2007b). The gap in data is then generally reduced to 10-15km. Where available, coastal tide gauge data will be used to bridge the coastal gap in data. However, large differences between tide gauge observations and nearby altimetric measurements can be observed in some areas. In the Bay of Biscay, these differences have been found to be mostly originated by differences in tidal components (Bosch et al., 2006). The use of the new regional T-UGO2D tidal model should enable to optimize the consistency between both types of data. However, other sources of discrepancies exist: the error budget associated to each data type is not the same and tide gauges are located on coastal sites when altimeter data are located further offshore.

A multi-mission and multisensor approach, combined with appropriate data analysis techniques is expected to enable to optimize the spatial and temporal sampling. This work aims to focus on different aspects that are to be solved for an optimal use of altimetry and other data types in coastal areas. In particular, a combination procedure must be defined on a regional basis, after an analysis of the errors, complementarity and inconsistencies of the different data sets. Moreover, classical optimal interpolation (OI) methods used to compute multi-satellite altimeter data are not necessarily well adapted for the coastal area. They use an *a priori* knowledge of the covariance functions of the signal and data error estimated for the open ocean (Le Traon et al., 1998). Regional applications will benefit from the definition of a covariance model which better takes into account the statistical characteristics of the coastal dynamics and measurement noise. Because coastal dynamics is highly nonlinear, OI methods could also not be adapted near the shore. The pertinence of using ensemble statistics provided in other tasks of this proposal will be analyzed.

This study will be done in the NW Mediterranean Sea, and in the Bay of Biscay. It will be based on our knowledge of the regional circulation in the areas of interest and on the analysis of existing 3D regional ocean model simulations with the 3D SYMPHONIE model in the same configurations used by the proposing team.

Our main objective will be to analyze the potential of satellite altimetry, combined with other information systems, in observing and monitoring different major coastal processes. We will focus on the signatures, in the NW Mediterranean Sea, of the North Current coastal current system and variability, eddy formation, water mass transports (into the Corsica Channel and along the North Current), and deep convection; in the Bay of Biscay, of the coastal current system and variability, eddy formation, water mass transports and internal waves.

Calendar:

Years 1-2: define a processing and post-processing strategy for altimetric data on marginal seas; compute improved multi-mission altimetric SLA data sets adapted to coastal applications on selected coastal regions; document the regional processes observed with altimetry; analyze the consistency between in-situ observations, altimetric data and other satellite sensor measurements in the different area of interest.

Years 3-4: test future missions (Jason-II, Cryosat and Saral) performances; define a strategy to combine multisensor and in-situ data on a regional basis; document the regional processes observed in the different area of interest, with altimetry used in concert with tide gauge and other satellite observations; document the corresponding space and time scales (seasonal, interannual and intraseasonal); analyse the lack of resolution for coastal applications.

4.4.2 T2: Objective impact of multisensor data in Coastal and Shelf Seas and application to Array Design

Task leader: De Mey

Rationale:

Let us note *H( )* the nonlinear observation operator associated with an observational array, and its observational error covariance matrix **R**. Our purposes are to examine whether and under which circumstances one particular observational array (*H*, **R**) can be said to be objectively satisfactory, and whether, given two arrays (H_1, $\mathbf{R}_1$) and (H_2, $\mathbf{R}_2$), one of them can be said to be more satisfactory than the other. It seems natural in particular to plan the new observations in areas and on variables for which model errors are expected to be largest (if they are made permanent, such networks can subsequently be used to feed data assimilation). We can formalize the problem by using the notion of *array modes* first introduced in Bennett et al. (1997). These are the rotation vectors obtained by diagonalizing the representer matrix. The spectrum of the associated representer matrix can be compared to observational noise statistics to count the number of degrees of freedom of model error observed by that array, providing a simple criterion of array performance. In the framework of M. Le Hénaff's Ph.D. thesis with P. De Mey, this has been formalized into the so-called Representer Matrix Spectrum method (RMS), which can be tackled with stochastic modelling or Ensemble filters.

Our objectives in this task are three: (1) review statistical criteria, using model error estimates, to assess the relative value of observational network options; (2) illustrate the power of ensemble methods (stochastic modelling, Ensemble Kalman filter) for providing suitable model (forecast) error estimates and simple, objective criteria; (3) perform objective multisensor impact experiments in the Bay of Biscay 3D model configuration.

4.4.2.1 S2.1 Representer analysis and array design via stochastic modelling

Involved personnel: De Mey, with M. le Hénaff (Ph.D. student)

Approach:

The Bay of Biscay and neighbouring English Channel are largely open to the North Atlantic ocean, which is a tidal sea. It features a strong topographically-steered slope current, up to 100km wide depending to definitions, flowing in an anticlockwise manner, and characterised by an associated mesoscale activity inducing strong exchanges between the shelf and the abyssal plain. Because of its geographic extension, and because of the presence of tides and rich shelf dynamics, the Bay of Biscay provides a valuable and unique case study used by several members of the proposing team.

This Subtask gathers the work performed during M. Le Hénaff's Ph.D. thesis. The RMS method is used in the Bay of Biscay on samples provided by stochastic modelling with perturbations of the atmospheric forcings and mesoscale turbulence fields. At the scale of the Bay, we concentrate on the impact nadir and wide-swath altimetry, as well as on the occasional ARGO floats. We also include a zoomed application on the AQUILAND cruise project domain on the Landes plateau, with tips on how to optimize the glider/ADCP/moorings array given our 3D model errors.

The Bay of Biscay SYMPHONIE model has been initially developed at POC during a Ph.D. thesis defended in November 2005 and is in press (Pairaud and Auclair, 2005). It has been set up in its stable form as part of M. Le Hénaff's thesis.

Calendar: Year 1

4.4.2.2 S2.2 Representer analysis and array design by Local Ensemble Kalman filtering

Involved personnel: De Mey, Ayoub, ECOOP post-doc

Collaborations: A. Kurapov, OSU; V. Taillandier, IPSL

Approach:

This Subtask is an extension of Subtask S2.1, both in terms of methodology and personnel. The samples needed for the RMS method will now come from individual members of a Bay of Biscay Ensemble Kalman filter in SYMPHONIE, also used in Tasks T3, T6, and T8 (Subtask S2.1 used stochastic modelling samples instead). The main advantage is the more natural account of the non-stationarity of model error, and the capability to run the RMS method as the assimilation proceeds (therefore over longer periods, which is a precious asset e.g. with altimetry). A collaboration with Alexander Kurapov (OSU) on the structure of representers and on representer-based assimilation is expected to be active throughout the project (Alexander solves weak-constraint DA with the adjoint method, while we solve an approximate form of weak-constraint DA with an Ensemble filter). We will also collaborate with V. Taillandier and his GLIDERS LEFE/ASSIM project in the Mediterranean; one of the topics of his proposal will be the review of statistical criteria, using model error estimates, to assess the relative value of observational network options.

The Ensemble Kalman filter code will be the LEnKF (Local, dual-space EnKF) provided by the BELUGA kernel of SEQUOIA.

Calendar: Years 1 to 4 (background)

4.4.2.3 S2.3 Maintenance of the Bay of Biscay LEnKF and array design methodology

Involved personnel: De Mey, Ayoub, Lamouroux, POC personnel for the maintenance of the SIROCCO suite

Approach:

This is a background task needed throughout the project to maintain the Bay of Biscay LEnKF and the RMS array design methodology. Those tools will be used by several other tasks of this project. In particular, in the framework of the SIROCCO suite of coastal ocean tools which is being set up by POC in the framework of its CSOA service tasks, we wish to set up state-of-the-art benchmark suites which could be subsequently used by companies and organizations for their impact assessment needs (SMEs, also CNES for the future “end-to-end simulator” evolutions). We also wish (1) to test the limits of small, cheap ensembles (O(10) members) for our purposes, (2) to consider optimized versions of the code, and (3) evolutions in the direction of importance resampling filters and genetic filters in order to avoid ensemble collapse and keep enough genetic variance in the population.

Calendar: Years 1 to 4 (background)

4.4.2.4 S2.4 Library of Ensembles for community use

Involved personnel: Ayoub, De Mey, POC personnel for the maintenance of the SIROCCO suite

Approach:

The aim of this Subtask is to give the community of OST investigators access to a library of Ensemble members for their own statistical exploitation: multivariate covariances, representers of satellite or coastal observations, statistical distributions, estimates of representativity errors of satellite observations (e.g. in the high-frequency band).

The target area is the Bay of Biscay, but, depending on availability, ensembles might also be available in other regions covered by this proposal.

Interested groups may include: NOVELTIS, CLS, CTOH, as well as U.S. academic colleagues (OSU).

Our work here will depend on whether and when the engineer at POC who should take care of the SIROCCO community service (CSOA “labellisation” process) will be hired.

- Low option: We will store the most relevant Ensembles on disk and will facilitate access to our network and storage facilities for other groups to copy the data for their own use. All this will be done on a “best effort” basis.
- High option: Same as the low option, but we will also provide a catalog of Ensembles, and will provide the means to distribute the data (on DLT or DVD).

Calendar: Years 1 to 4 (background)

4.4.3 T3: Signature of storms and extreme meteorological events in the Bay of Biscay

Task leader: Ayoub

Rationale:

Altimetric data as provided by current, past and future Jason-2 missions provide a powerful tool to study the ocean circulation in coastal and shelf seas where the periodic and systematic data coverage as well as the high-resolution along-track data are needed probably more than in the open ocean. Besides technical difficulties in recovering the oceanic signal, due for instance to uncertainties in some atmospheric corrections (e.g. wet tropospheric), the question of how to interpret along-track or interpolated sea level (SL) observations in terms of coastal processes is still open. In this study we propose to address this issue in the Bay of Biscay at time scales of a few ten of days during a given period within recent years (probably in 2005). We distinguish two different meteorological contexts: one with ‘regular’ or ‘typical’ atmospheric regimes, one in case of an extreme meteorological event at short time scale (O(1 day)). Climate change is suspected to lead to more frequent extreme events and the understanding, estimation and prediction of the ocean response is critical. Sea surface elevation is a fundamental variable because of the impact of sea level changes (e.g. storm surge) on the littoral and navigation. For both normal and extreme meteorological contexts, we use a data assimilation system based on stochastic modeling to provide estimates of the ocean state as well as insight on covariances between SL and other oceanic and atmospheric variables. In the assimilation method, we aim at including the atmospheric forcing fields in the control vector. The thesis work of Le Hénaff (2007) has proved it feasible in ‘normal’ meteorological conditions. We will explore the way of extending it in stormy conditions where some hypotheses on Gaussian distributions must be relaxed.

The work will be based on the analysis of altimetric data, SST satellite observations and in situ data from ARGO floats and oceanographic cruises (e.g. MOUTON cruises by the SHOM – French Navy). We will use the data-assimilative 2D model configuration set up in Task T2 in the Bay of Biscay.

Calendar: Subtask 3.1: mid-year 1 to end of year 2; Subtask 3.2: years 3 and 4

4.4.3.1 S3.1: Signature onto Sea Level and SST of “Gaussian” atmospheric variability

Involved personnel: Ayoub (subtask leader), De Mey, Lyard, Birol + PEA post-doc

Approach:

We propose to use an existing data assimilation scheme, the SEQUOIA code (De Mey, see Appendix), solving a Local Ensemble Kalman Filter, to provide an estimate of the circulation during the period of study as well as ensemble statistics on the variables of interest. Such a method has been successfully tested with the inclusion of wind and air pressure fields correction in barotropic (Lamouroux et al., 2006) and 3-D (Le Hénaff, 2007) models at LEGOS. Another feasibility study has been done with the SEEK filter and an isopycnal ocean model by Brocquet et al. (2006) at LEGI. Our work will be based on the configuration of Le Henaff (2007) with the SYMPHONIE ocean model. The data-assimilative simulations in Task 2 will provide a basis for our own.

We will explore the possibility to include in the model the effect of tides on vertical mixing in order to improve the representation of tidal fronts. The existing code is designed to assimilate any data type, be it altimetric observations, in situ T/S profiles, or SST for instance. However the impact of additional SST data (from IR satellite measurements) has not been tested in the Bay of Biscay and will therefore be studied here. These extensions with respect to the existing work will likely lead us to perform some sensitivity tests, for instance on the length of the analysis step or on the way of generating the atmospheric perturbations.

The work will include a preliminary task of comparison between the simulated fields (without and with data assimilation) and in situ and satellite observations. We will then compute representers in sea surface height (SSH) from the ensembles in order to characterize the structure of the influence of SSH perturbations on other model variables or quantities. The primary variables we are interested in are SST, temperature and density profiles. We also aim at investigating the impact of the assimilation of altimetric data on the vertical mixing: covariances (representers) between SSH and quantities related to the turbulent energetic budget or to the vertical mixing scheme will be computed.

4.4.3.2 S3.2: Signature onto Sea Level and SST of storms and extreme events

Involved personnel: Ayoub (subtask leader), De Mey, Lyard, Birol

Approach:

This task is an extension of the previous one to a different meteorological context. The occurrence of a strong storm constitutes a non-Gaussian event and a strategy needs to be found to adapt the previous assimilation method, in particular to generate the perturbations on the atmospheric forcing fields.

We will first start by exploring in the non-constrained simulation the signature of the impact of a strong storm on the oceanic surface variables and thermohaline structure. For example, high speed winds accompanying stormy conditions are generating intense vertical mixing: what is the signature on SST and SL? What is the impact of atmospheric low pressure on SL? How are the regional circulation (slope current, fronts) and the hydrological conditions affected? We will also pay a special attention to non-observed (or poorly observed) variables (e.g. vertical velocities) or quantities related to vertical mixing. In parallel, we will try to identify the signature of a strong storm impact in altimetric data, SST satellite observations and, if available, T/S profiles from floats or cruise data.

We will then attempt to characterize uncertainties on the simulated fields due to uncertainties on the storms representation in the atmospheric forcing fields. In particular, we aim at better understanding the sensitivity to the atmospheric fields space-time resolution. We propose to run a small multi-model ensemble forced with two different products from METEO-France with respectively a coarser and a higher resolution: ARPEGE and AROME (note that the domain is such that it is entirely included in the domain of validity of ECMWF, ARPEGE/EUROC, and ALADIN; the AROME domain, which is still an experimental model, must be further clarified). At last, we will explore the use of the Ensemble Kalman filter to perform data assimilation in stormy conditions using the ensemble of atmospheric perturbations defined previously.

4.4.4 T4: Performance of simplified altimetry assimilation schemes in the North-Western Mediterranean

Involved personnel: Lamouroux (task leader), De Mey

Rationale:

In this task, we wish to test the limits of cheap, simple altimetric assimilation schemes as developed within the previous DARSS OST project. The focus will be the North-Western Mediterranean area (Hereafter "NWMED"), which has been extensively studied by the POC group over the years, from *in situ* observations and modelling with SYMPHONIE (e.g. Estournel *et al.*, 2003; Dufau-Julliand *et al.*, 2004). The NWMED regional model has been developed by POC and NOVELTIS for several previous projects. It features a resolution of 3.5km and a sigma-step vertical discretization. It models most of the Northern Current which flows along the shelf break from the Ligurian Sea to the Balearic-Catalan basin via the Gulf of Lions. It has been operated in real time by NOVELTIS during the MFSTEP Target Operational period (http://www.bo.ingv.it/mfstep/). It will be operated by NOVELTIS again in this study.

Approach and calendar:

Most of this Task is common with the ongoing ESA "GOCEAN" work. The SYMPHONIE model will be used under coupling with SEQUOIA with the SOFA analysis kernel in a configuration using multivariate vertical EOFs.

In a first step, we configure the data assimilation system through the assessment of the impact of simulated altimetry observations (T/P, JASON, ENVISAT, GFO) in the framework of Twin Experiments with perturbed initial/boundary values. The usual twin-experiment performance metrics are used.

In a second step, assimilation of real altimetry data in that model will occur. A specific processing of altimetry data will be achieved in our coastal area, using the X-TRACK processing software, also used in task T1. This software has been especially developed to improve the data editing and correction in shelf and coastal areas, and features (1) the editing of 10/20 Hz data with method finer than the ones recommended in the GDR standards users guide, (2) the use of (a) enhanced high-frequency ocean response to atmospheric forcing correction and (b) enhanced tidal correction, both obtained with the barotropic model MOG2D, developed at POC, and (3) the computation of a specific MSS. Performance metrics will emphasize the capability of the system to realistically constrain the Northern Current.

Calendar: Year 1

4.4.5 T5: Improving regional tidal models by Ensemble Spectral OI

Involved personnel: Lyard (task leader), Lamouroux, De Mey

Rationale and approach:

The use of the altimetric data in SCS regions need to improve the present tidal correction capabilities. The strategy developed at LEGOS consists in developing regional models based on the T-UGOm code. Even if the additional resolution and the locally fitted bathymetry allows improving the tidal atlases compared to the usual global databases (such as GOT00 or FES2004), data assimilation is still needed to provide the required accuracy in tidal correction. In the frame of the CNES coastal oceanography project, we have proposed in collaboration with NOVELTIS to set up an Ensemble, spectral OI assimilation over the main SCS in the ocean. This simplified approach has been dictated by the time and cost constraints of the CNES call, still it is known to be robust and efficient to produced accurate tidal atlases. These atlases will be reviewed and validated by the scientists at LEGOS. We will examine whether this can be achieved in the form of a spectral extension of SEQUOIA.

Calendar: Years 1 and 2

4.4.6 T6: Improving regional, high-frequency barotropic models by advanced Ensemble data assimilation

Involved personnel: Lyard (task leader), De Mey

Rationale:

The objective of this Task T6 together with Subtask S7.2 is to set up the SEQUOIA assimilation code for the unstructured hydrodynamic model T-UGOm for shelf and coastal seas (SCS) circulation applications. The SEQUOIA/T-UGO-m system will be designed to be able to deal with real observations and modelling conditions to control model simulations' accuracy and provide observation network assessments. The primary benefit for the Jason program will be the improvement of the HF de-aliasing in SCS regions (VENICE 2006 OST recommendations).

Approach:

The tides are only part of the HF de-aliasing problem. Storm surges are greatly amplified in CSS, and the present corrections are extracted from a global storm surge model. Like for tidal dynamic, the limited resolution and uncertain accuracy of the global bathymetry databases degrades the performances of the global model in the CSS regions. In addition, storm surge accuracy depends upon meteorological forcing quality (namely ECMWF) in terms of resolution and accuracy. Once again, data assimilation is needed to provide the required accuracy. Contrary to the tidal problem, the spectral approach is no more possible and more sophisticated methods are needed. We propose to implement an Ensemble Kalman filter for a regional barotropic HF model, presumably in the Northeast Atlantic (Bay of Biscay). Tide and storm surge dynamics will be both taken into account. Methodological developments will be necessary, in particular for the observation treatment. Following the additional support available, we will take profit of the preliminary implementations developed for Task T5 to generalize the system to the main CSS regions.

Calendar: Years 2 to 4

4.4.7 T7: Applications of Ensemble data assimilation of altimetry and other data in the Bay of Biscay regional, high-frequency 3D model

Task leader: Lyard

4.4.7.1 S7.1 Operational application

Involved personnel: Lyard (subtask leader)

Collaborations: SUDOE (MERCATOR: D. Obaton, Météo-France: J. Hoffmann)

Rationale and approach:

The tidal dynamic has a significant 3D component. The interactions of the tides with the ocean stratification induce a surface elevation signature, either at the high frequency (like internal tides) or at low frequency (annual modulation of the barotropic tides). For the wind-forced ocean motion at high frequency, the upper ocean stratification has an impact on the vertical profile of the horizontal currents. This interaction can be significant for the forecasting of oil spills or object drift. Currently a European inter-regional project (SUDOE frame work) is in preparation in collaboration with Météo-France, Mercator, Noveltis and LEGOS to upgrade the operational storm surge forecasting system at Météo-France (PREVIMAR). Our objectives here are set up a simplified 3D regional model with assimilation, in order to account for the 3D dynamic of the tides and to anticipate on the upgrade for the oil spill and object drift operational system of PREVIMAR.

Calendar: Years 3 and 4

4.4.7.2 S7.2 Finite-element configuration

Involved personnel: De Mey (subtask leader), Lyard

Rationale:

As for any other existing hydrodynamic model, assimilation is needed in realistic simulations to control and improve T-UGO model skills. It is even more essential when considering the development of operational oceanography and marine services applications. On the model point of view, the assimilation techniques are needed to explore and adjust the model parameters (such as ocean bottom roughness, or lateral forcing) and to build consistent initialization fields from general circulation model simulations. For short, the assimilation tool is a mandatory component in T-UGOm ocean modeling system, either for scientific or practical applications.

Approach:

The T-UGOm model is a very recent ocean model and consequently is subject to a rapid evolution. Moreover it is built on flexible architecture to make further changes possible (in discretization and choices in numerical schemes). It will certainly include mesh adaptivity capabilities. In this context, the development of adjoint methods is not a efficient option. On the contrary, the Ensemble approach can accommodate the constant evolution of the hydrodynamic model with very limited constraints. This approach is also known to be extremely efficient for the SCS modeling problem. The interface between SEQUOIA (BELUGA analysis kernel) and T-UGOm will pioneer coupling systems for fully coupled (atmosphere, bio-chemistry etc…) problems. It will be validated on toy models in a first step that will also provide benchmarks for non expert users.

Calendar: Years 3 and 4

4.4.8 T8: Gravity data impact study in the Bay of Biscay

Involved personnel: Lamouroux (task leader), De Mey, Birol

Rationale:

This task is common with the ongoing ESA "GOCEAN" project. It aims at assessing the capabilities and the limits of the use of a satellite-sensed geoid (such as future GOCE products) to improve the shelf and coastal ocean low frequency circulation. The approach consists in using the data assimilation techniques into hydrodynamic models to estimate the present and future benefit of altimetry data use.

Approach:

In this task, the impact assessment will be conducted through assimilation of simulated altimetry and GOCE data in the same Bay of Biscay configuration used elsewhere in this proposal. Focus will be made on the impact of simulated GOCE data onto the topographically-steered flow at the shelf-break and its associated mesoscale and submesoscale field. One of the difficulties with the classic Twin Experiments setup is that results are neither general nor reliable since they depend on a particular pair of runs. Over the last few years, it has been shown by POC (Mourre et al., 2005) that this difficulty can be overcome by the use of the Ensemble Kalman Filter – what we look at then is how well a particular observing system is able to reduce the Ensemble spread when assimilated. The assimilation configuration will be the same as in tasks T2, T3, T6.

We will use GOCE MDT-error covariance estimates provided by G. Balmino. The observation operator for MDT will be an averaging operator acting on the data window.

Calendar: Year 1

4.4.9 T9: Impact assessment metrics

Involved personnel: De Mey (task leader)

Collaborations: D. Obaton, MERCATOR

Rationale and approach:

The MyOcean proposal has been submitted in June 2007 as a response to the GMES Fast Track "Marine Core Services" call. ECOLA/POC participates, *inter alia*, in work package 8 on the IBI (Irish-Biscay-Iberian shelves) coastal ocean system, at several levels. The IBI system is coordinated by MERCATOR (D. Obaton) takes part of MyOcean as a regional model based component. It will be settled to improve, from a global system, the representation of hydrodynamics near the SW European shelf. Its general objectives during the project are:

- To be the regional SW European coastal official contribution to MyOcean running in best effort mode
- To be fully validated and assessed using observations available within MyOcean's Thematic Assembly Centres (TACs)
- To provide products common to all Modelling and Forecasting Centres (MFCs) and others more specific to the area, some of them operationally qualified during the project

We are involved in the definition of regional metrics that will be used to assess the scientific quality of the NEMO 1/36° configuration which will be implemented as part of MyOcean. That configuration has a lot in common with our Bay of Biscay configuration used in this proposal; therefore this work should be mutually beneficial to our Bay of Biscay configuration and to the IBI configuration. The metrics will be an extension to the coastal ocean of the Le Provost et al. (2002) metrics which have been promoted by the MERSEA and GODAE project.

Calendar: Years 1-4 (background)

4.5 Numerical tools

4.5.1 The SYMPHONIE numerical model

SYMPHONIE is a three-dimensional free-surface finite-difference model developed since 1992 by the Coastal Oceanography team at Laboratoire d'Aérologie (Claude Estournel, Patrick Marsaleix, Francis Auclair). This model aims at simulating in three dimensions the coastal ocean circulation in response to atmospheric forcings (wind, pressure, heat and freshwater fluxes), to river runoff, and to boundary conditions (large-scale circulation). The model has a combination of steps and sigma coordinates in the vertical. Validation studies have been completed (Estournel et al., 1997; 2001) on the problem of the dispersal of matters brought by the Rhône into the Mediterranean. More precisely, the model has been validated through the comparison with AVHRR SST and with surface currents observed by VHF radar. As of 2007, SYMPHONIE now exists in parallelized and non-hydrostatic versions.

4.5.2 The T-UGO numerical model

T-UGOm (2D/3D follow-on of MOG2D model) is a time-stepping 2D/3D finite-element/-volume model developed by the ECOLA/POC team at LEGOS (Florent Lyard is the main contact for T-UGOm).

In a 2D mode (external mode), it models the gravity waves forced and modified by atmospheric pressure and winds, the astronomical potential (tides), the loading and self-attraction potentials. The external mode has been validated by comparison with MEDGLOSS tide gauge data as well as with TOPEX/POSEIDON and ERS1-2 altimeter data. Tests show that T-UGOm 2D explains more than 60% of the sea-level variations (excluding tides), understanding that measured sea-level variations contain effects which cannot be modelled in a 2D simulation -- steric effects for instance.

The 3D (baroclinic mode) is based on the non-Boussinesq primitive equation, and is build to integrate non-hydrostatic pressure mode capabilities. Most of state-of-the-art turbulence parameterization and bulk formulae are available in the model. Exogenous modules, such as the sediment transport module developed for the Symphony model, will be adapted and plugged in a near future (for the needs of the ANR AMANDES project). In its standard version, it is partly based on the finite elements (horizontal and vertical velocities, sea surface elevation) and finite volumes (tracers). Its flexible architecture allows for using several classes of discretization and numerical schemes. Layer merging and mesh adaptivity are also planned to implemented in a near future (2008/2009).

4.5.3 The SEQUOIA data assimilation system

Like its predecessor SOFA code (De Mey and Benkiran, 2002), the SEQUOIA system (ECOLA/POC contact: P. De Mey) is a response to the needs of the scientific and operational oceanographic communities for an efficient, modular, multivariate and physically consistent ocean data assimilation tool. It is meant to be useful for large-scale/open-ocean and for coastal/shelf-seas data assimilation problems. For about a decade, the various versions of SOFA have been used to control the state and trajectory of various ocean models in a way which is consistent with multivariate error statistics, and to characterize the predictability of the general circulation, seasonal and inter-annual variability, meso-scale eddies, meanders, sub-basin-scale gyres, and response to wind. As of 2007, SOFA is routinely used by several ongoing Ocean Forecasting projects. In the MFS, SOFA is part of the Mark-II and Mark-III systems. In the MERCATOR project, SOFA is part of the SAM-1 system. The SEQUOIA system uses the best of SOFA, and adds new features, in particular:

- Complete rewriting in Fortran-90
- Support for finite-difference and finite-element unstructured grids
- Support for ensemble operation, i.e. as part of an Ensemble Kalman Filter, on a single machine or on a cluster, with auto-recovery features such as automatic member drop-off when a node fails
- Support for multiple algebrae through modular analysis kernels:
  - The MANTA kernel is based on rank reduction along 3-D multivariate EOFs derived from stochastic modelling. It offers the choice of global or local inversion.
  - The SOFA kernel is based on rank reduction along 1-D multivariate EOFs. It reproduces the algorithm formerly implemented in the SOFA data assimilation code.
  - The BELUGA kernel solves the full-rank analysis equation in dual (observational) space. It can be used as part of a Local, Dual-Space, Ensemble Kalman filter (LDS-EnKF), making use of ensemble representers; alternatively it can be used with any form of reduced-rank covariance modelling such as the methods implemented in the MANTA and SOFA reduced-rank kernels.
- Formalized model interface permitting the use of any numerical model.
- SEQUOIA is distributed under a GPL free software license.

4.6 Anticipated results and significance of the investigation

Very briefly, some of the anticipated **innovative results** of this cross-cutting, leading edge project are the following:

- Development of advanced Ensemble-based data assimilation tools in the coastal ocean, to be used in realistic configurations with multisensor data (both from in situ and space observations) and compared with approaches of other world leading groups
- Development of data assimilation in unstructured-grid models
- Development of state-of-the-art multisensor impact assessment configurations in focus regions
- Methods for objective testing of observational networks with application to future altimeter instruments and multisensor configurations
- A study of the signature of storms and extreme meteorological events in observed variables, as well as in poorly-observed or non-observed ones (surface layer, thermohaline structure, HF transients).

5.Management plan and Cost plan

5.1 Management plan

5.1.1 Calendar

A PI-colored calendar is shown in **Table 2**. Typically Year 1 is expected to start some time in 2008. See also Table 1 (Section 4.4) showing the task labels and task dependencies.

Task specifics:

- The Bay of Biscay SYMPHONIE model with MERCATOR boundary conditions and high-frequency atmospheric forcing used in T2 and in other tasks has been developed by POC as part of M. Le Hénaff's Ph.D. thesis.
- The data-assimilative Bay of Biscay configuration developed in Subtask S2.2 with the Ensemble Kalman filter is a prerequisite for some of the other work in this proposal; it is already being implemented as of this writing and will be available in early 2008.
- Tasks T1, S2.2, S2.3, S2.4, and T9 are background tasks which will last through most of the project.
- Tasks S3.2, S7.1 and S7.2 which start in the second half of the project are prospective, higher-risk tasks which will need to be implemented through *ad hoc* support – CNES will be informed at the end of year 2 on how the investigators plan to implement that work.

Table 2: MICSS calendar

Task leaders: Blue: Birol; Red: De Mey; Indigo: Ayoub; Green: Lamouroux; Grey: Lyard

Task	Year 1				Year 2				Year 3				Year 4			
T1	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
S2.1	Red	Red														
S2.2			Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
S2.3	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
S2.4	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo
S3.1			Indigo	Indigo	Indigo	Indigo	Indigo	Indigo								
S3.2									Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo	Indigo
T4	Green	Green	Green	Green												
T5	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey								
T6					Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
S7.1									Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
S7.2									Red	Red	Red	Red	Red	Red	Red	Red
T8	Green	Green	Green	Green												
T9					Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

5.1.2 MICSS-days

We will organize one MICSS-day at the beginning of each project year. That day-long meeting with scientific presentations will provide an opportunity to exchange between us on the progress of each task, optimize task interactions, launch collaborations, and prepare the material for the annual CNES reviews of the project.

5.1.3 Links with other OST proposals and collaborations

Oregon State University's OST proposal (Alexander Kurapov) : We have had preliminary talks lately about a very promising collaboration between MICSS and their proposal, but given the fact that they will submit theirs much later (Oct. 31) than this one, they have not yet details of what their proposal will cover, and on the other hand it is difficult to include them here as Co-Is since they must have their own proposal to get funded. Alexander Kurapov is working on weak-constraint representer-based data assimilation for coastal stratified flows using the adjoint of their numerical model. The two groups are among the only ones in the world to think in terms of representers. We could (1) carry out a comparative analysis of model error covariances for altimetry sea level obtained from representer analysis (OSU) and ensemble filtering/smoothing (MICSS), (2) compare both representer-based assimilation methodologies: weak-constraint adjoint assimilation (OSU) and dual-space EnKF (MICSS), and in the later stages of this project (3) perform comparative analyses of eastern boundary coastal systems off U.S. West coast and the geographical domains included in this proposal as they come out of altimetry data assimilation. Some code exchange could also be considered. Contact: Alexander Kurapov and John Allen (OSU).

"Calibration and validation for multi-mission and high precision altimetry" OST proposal: Near the end of this project, depending on anticipated improved quality and availability, we may wish to test the assimilation of the "improved" CLS altimetric products with the new correlated observational error estimates and feedback to CLS (the advanced assimilation schemes used in this proposal are compatible with any form of correlated observational errors). Contact: Claire Dufau (CLS).

"MARINA" OST proposal: The advanced assimilation activities planned in the Bay of Biscay in this proposal could be ported to the Mediterranean region as part of the MARINA proposal. We at POC propose to set up a benchmark package in that region (model + assimilation) which could be expanded by MARINA to meet their needs. Contact: L. Roblou (NOVELTIS).

“SWOT” and “CTOH” OST proposals: We will see how our activities could benefit, and benefit from, these proposals. Contact: Nelly Mognard (LEGOS/CNES) and Florence Birol (LEGOS).

5.1.4 International and national collaborations outside OST

European RTD projects ECOOP (FP6) and MyOcean (FP7, GMES/Marine Core Services) – Some of the investigators also participate in those RTD projects, in particular on data assimilation in coastal models and assessment of observational networks (in ECOOP, as part of a collaboration with the Danish met. Institute – Contact: Jun She, and with Puertos del Estado – Contact Enrique Alvarez), and on modelling performance metrics in Bay of Biscay modelling and data assimilation (in MyOcean, as part of a collaboration with MERCATOR – Contact: Dominique Obaton)

GOCE geoid impact study on continental shelves (ESA “GOCEAN” R&D project) with participation by LEGOS and NOVELTIS. Contacts: Florent Lyard (LEGOS) and Julien Lamouroux (NOVELTIS).

Existing and active links with NOVELTIS and CLS activities in coastal altimetry:

- Improvement of altimeter data in coastal areas
- Development of the X-TRACK altimeter processing software (NOVELTIS).

SHOM (French Navy) projects : Programme d’Etudes Amont (see Appendix), MOUTON cruises in the Bay of Biscay, EPIGRAM project on the Bay of Biscay

LEFE/ASSIM project “GLIDERS”: Contribution to the optimization of glider arrays in the Mediterranean by the Representer Matrix Spectra method (Contact: Vincent Taillandier, IPSL) – also linked with the MARINA OST project above

European inter-regional SUDOE project: Upgrading of the operational storm surge forecasting system at Météo-France (PREVIMAR).frame work) (Contacts: Joël Hoffmann, Météo-France and Dominique Obaton, MERCATOR)

T-UGO network – in particular with David Greenberg (BIO)

INTAS project ALTICORE – Contact: S. Vignudelli (CNR)

ANR project AMANDES, in which several LEGOS researchers are involved.

5.1.5 Computing

We will compute on the POC cluster of dual-node Opterons acquired from several funding sources in the recent years, and which is specifically dedicated to stochastic coastal modelling and Ensemble assimilation. The system support is ensured by LA system engineers. In this project we ask for two more nodes in order to be able to run the array assessment methodology (RMS) during the course of ensemble assimilation. On the scientific computing and numerical aspects, we will also have of the support of a POC Ingénieur de Recherche (CNRS NOEMI), Cyril Nguyen.

5.2 Cost plan

5.2.1 Existing or expected funding

The investigations listed in this proposal have applied for separate funding or are already funded in projects listed in the text. The main sources of external funding, and which parts of this proposal they cover, are summarized below:

- The colleagues listed as “external collaborators” will obviously not request any funds through this proposal
- T1: F. Birol expects to have her costs entirely covered under the separate CTOH OST proposal.
- S2.1/S2.2: Post-doc funding for 9 months is secured through the ECOOP FP6 proposal (work package 1). Additional nodes will be needed for the existing POC cluster.
- S3.1: One year of post-doc fellowship is funded by SHOM on the Programme d’Etudes Amont grant of N. Ayoub (an extension in S3.2 will be sought under MICSS funding – see **Section 5.2.3**). N. Ayoub’s PEA proposal aims at better understanding the impact of the assimilation of SST data in a North Atlantic model. The first part (finished) was a large-scale study in the North Atlantic (Lucas et al., 2007). In the second part, starting in October 2007 and planned for a year and a half, the objective is to estimate the impact of the assimilation of SST satellite observations in a coastal model of the Bay of Biscay. This second part will be done in parallel to Subtask S3.1 but with an emphasis on SST.
- Funding by the European Space Agency of much of the work contained in Tasks T4 and T8 related with the GOCEAN project is gratefully acknowledged.
- Six months of Post-doc/CDD funding is being requested for Task T5 within the CNES Coastal Altimetry AO (“AO Côtier”), separate from this one.
- T7: A response to the European inter-regional SUDOE project is in the making (MERCATOR/MétéoFrance/POC). Funding will be sought in that framework but will not cover manpower. Advanced assimilation in unstructured-grid models is a challenging research topic which could benefit from a Ph.D. thesis (start in Year 2).

- T9: Funding (including manpower) has been requested within the MyOcean European project (GMES/Marine Core Services). The outcome should be known by 2008.
- Most of the work in the background tasks S2.3 and S2.4 will be carried out without additional personnel, but additional disk storage will be needed for S2.4.

5.2.2 CNES funding

The additional cost with respect to the existing or expected funding will consist in :

1. Participation in 4 OSTST meetings for the PI and 2 OSTST meetings for 3 co-Is (Lyard, Ayoub, Lamouroux) over the total span of the project
   ➔ Assumed mission cost: 2k€/person (this is a weighted average assuming ½ France, ½ USA locations)
   ➔ Total for a 4-year project: 20k€
2. Participation in one AGU meeting in Europe or USA, or another international satellite conference, on T-UGO related conference, for two investigators per year
   ➔ Total for a 4-year project: 16k€
3. Two 5-day trips to Oregon State University for collaboration on coastal ocean representers: 3k€ each
   ➔ Total for a 4-year project: 6k€
4. Publications : 2 publications per year
   ➔ Assumed publication cost: 2.5k€
   ➔ Total for a 4-year project: 20k€
5. Two dual-Opteron (or equivalent) cluster nodes with 4Gb memory each on Year 1
   ➔ Total: 8k€
6. Contribution to disk silo for the Ensemble Library (Subtask S2.4): 2Tb @ 3k€ ea. on Year 2
   ➔ Total: 6k€
7. Contribution to consumables and small equipment: 3k€/year
   ➔ Total: 12k€

The funding requested from CNES, not including the hired manpower (see below), is summarized in **Table 3**.

Table 3: Detailed cost schedule

Year 1	OSTST = 5.0k€ Other conference = 4.0k€ Publications = 5.0k€ Equipment = 8.0k€ Consumables = 3.0k€	25.0k€
Year 2	OSTST = 5.0k€ Other conference = 4.0k€ U.S. collaboration travel = 3.0k€ Publications = 5.0k€ Equipment = 6.0k€ Consumables = 3.0k€	26.0k€
Year 3	OSTST = 5.0k€ Other conference = 4.0k€ Publications = 5.0k€ Consumables = 3.0k€	17.0k€
Year 4	OSTST = 5.0k€ Other conference = 4.0k€ U.S. collaboration travel = 3.0k€ Publications = 5.0k€ Consumables = 3.0k€	20.0k€
Total		88.0k€

5.2.3 "CDDs" and Post-Doc Fellowships

In addition, we will apply for TOSCA funding of CDDs/Post-Docs on the following items:

- In Year 1, F. Lyard will apply for 12 months on Task T6, "Improving regional, high-frequency barotropic models by advanced Ensemble data assimilation"
- In Year 2, N. Ayoub will apply for 12 months on Task T3, " Signature of storms and extreme meteorological events in the Bay of Biscay", in continuation to the 13-month post-doc fellowship provided by SHOM (PEA project)
- In Year 3, F. Lyard and P. De Mey will apply for 18 months on Task T7, " Applications of Ensemble data assimilation of altimetry and other data in the Bay of Biscay regional, high-frequency 3D model".