I. CHAOCEAN : COVER SHEET

Proposal No. _____________________ (Leave Blank for EUMETSAT/CNES Use)

Title: CHAOCEAN (low-frequency intrinsic variability in the eddying ocean : observations, simulations and processes)

This project is tightly connected with the US CHAOCEAN OST/ST project submitted to NASA/ROSES.

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Budget (for French Investigators only):
1st Year: **46k€.** 2nd Year: **46k€.** 3rd Year: **45k€.** 4th Year: **45k€.** Total: **182k€**

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* Co-funded by Région Midi-Pyrénées

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III. IDENTIFYING INFORMATION

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IV. INVESTIGATION AND TECHNICAL PLAN

IV.1 Summary

The advent of satellites has led to an explosion of ocean observations at unprecedented resolution and has illuminated the rich spatial and temporal character of upper ocean variability. There has also been recent, concomitant growth in subsurface observations due to the Argo and Rapid arrays and other major observational programs. Ocean General Circulation Models (OGCMs, i.e. primitive equation models implemented in realistic settings and forced by comprehensive atmospheric products) have contributed importantly to the synthesis and interpretation of this information. In turn, the observations show that realistic models have grown in skill. Dynamical understanding of ocean variability has also grown over the last few decades through a number of insightful process-oriented analyses. Accurate model-based climate projections constitute a significant societal need, and the above elements naturally benefit this goal.

The aim of this proposal is to exploit the above advances with a view to low-frequency ocean variability, motivated by evidence that both external (atmospheric) and intrinsic sources contribute importantly to the ocean variability observed by altimetry and other means, that the latter is poorly known (and is indeed absent from current climate models), and that analyses and projections of climate variability are likely sensitive to it. The foundations for these statements will be outlined below, where we argue that **distinguishing the internal (intrinsic) and external (atmospherically-forced) components of the ocean variability is central to understanding and using observational (altimeter and other) timeseries for ocean/climate science: climate monitoring, climate reconstruction/projection, and detection of climate change in the ocean.**

The improvement of OGCMs is evidenced in the convergence of model statistics towards observations, in particular sea level variability (Penduff et al., 2010). In order to analyze the features and origin of the observed signals, we propose to simulate and extract the low-frequency intrinsic ocean variability from ensemble-like OGCM simulations, and study its dynamics using dynamical concepts developed in process-oriented settings. The objectives of this French project are to **(1) categorize interannual-to-decadal ocean variability according to its forced/intrinsic origin, (2) quantify the imprint of both contributions in observational datasets, (3) explore the dynamics of this variability, and (4) assess the sensitivity of these results to model construction.**

Accordingly, this proposal, along with its American counterpart that was just submitted to the partnered NASA/ROSES OST-ST program, gathers French, European and American scientists/engineers who work on the ocean variability from complementary perspectives: namely ‘realistic‘ ocean modelers, making routine use of altimeter/satellite/in-situ observations, specialists in non-linear dynamics and dynamical systems theory with insights into the foundations of ocean variability, and experts in statistical analysis of large datasets applied to climate. Our international group will produce, share and analyze an ensemble of observed/simulated fields and will take advantage of the complementarity between their own approaches to address several scientific questions with operational relevance (ocean/climate observation, monitoring, reconstruction, modeling) on climatic timescales. The PIs will coordinate the collaboration between French and American members, who will meet at least once every year at OST-ST meetings.

IV.2 General context

The ocean is sampled by complementary satellite and subsurface observing systems. Thanks to their relatively high spatio-temporal resolution, global coverage and record length, sea-level anomaly (SLA) and sea-surface temperature (SST) data have proven invaluable to the study of ocean variability, to climate monitoring and numerical investigations over a wide range of scales. Subsurface measurements of 3D T/S structures, currents and transports, and of the Atlantic Meridional Overturning Circulation (AMOC, monitored at 26°N by the RAPID array) are also crucial. Along with the expansion in quantity and quality of observational data, dedicated model studies have proven essential for the depiction, understanding, and attribution of the observed ocean variability.

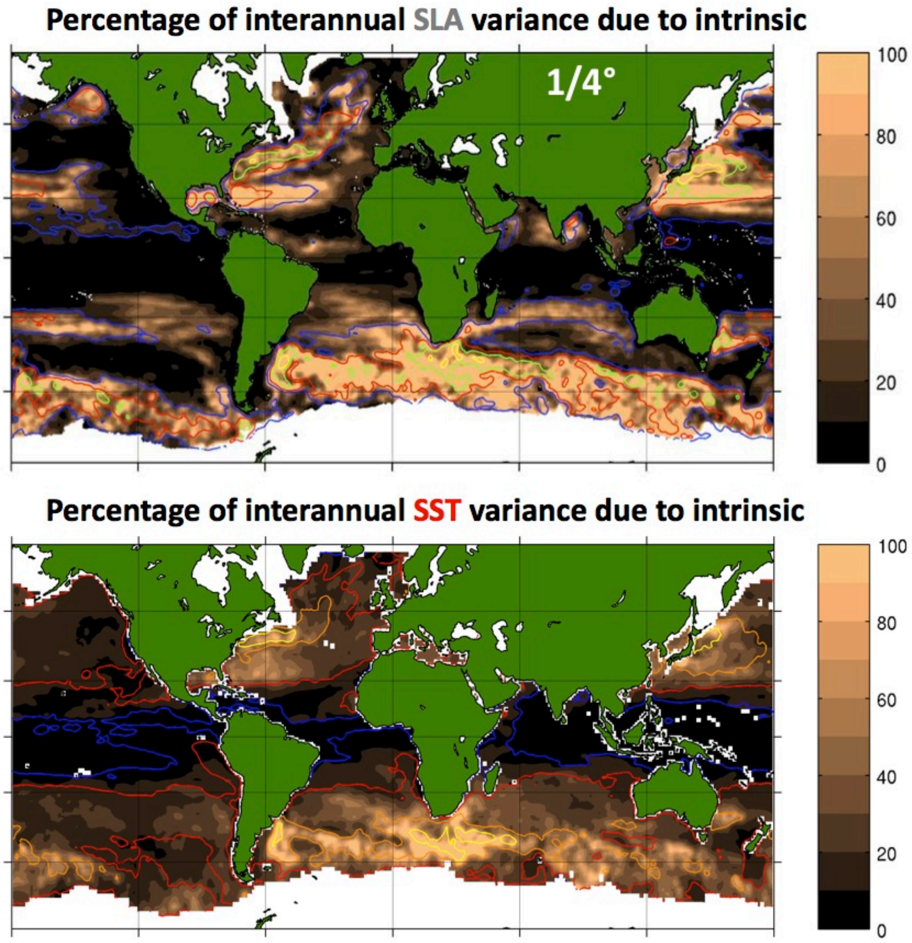

Figure 1: Contribution (in %) of intrinsic/chaotic ocean processes in the interannual variance of Sea Level Anomaly (a) and SST (b), as estimated from global eddying ocean simulations (Penduff et al, 2011).

a) A poorly known low-frequency chaotic variability affects satellite/in-situ observations

At monthly timescales, recognized spatio-temporal patterns of the observed ocean variability include a deterministic component (the direct oceanic response to the atmosphere) and a chaotic, intrinsically-generated component (mesoscale turbulence) that strongly contributes to the total variance. At interannual-to-decadal timescales, however, OGCM-based and observational studies of variability are mostly restricted to (and hence understood as) the direct oceanic response to the atmosphere. The residual is often large, but has received much less attention; it is considered as low-frequency "background noise". However, OGCMs have recently shown (e.g. Cabanes et al., 2006; Taguchi et al, 2007; Penduff et al, 2011, noted *P11* hereafter) that when mesoscale eddies are (even partly) resolved, a large part of the observed 1-10 year variability (**LFOV**)[1] of Sea Level Anomaly (SLA) has a chaotic character, and is intrinsically generated by the ocean (i.e. it is simulated without any interannual forcing). The intrinsic fraction of LFOV SLA variance, as shown in Fig. 1a, exceeds 40% over half of the global ocean, and 80% over one fifth of the globe. Included in the latter are the regions of the separated Gulf Stream and Kuroshio, interestingly also the locations of the largest air-sea heat exchanges in the global ocean. In addition, Figure 1-b shows a preliminary estimate (probably an underestimate) of the same ratio for SST and is suggestive that intrinsic ocean variability might, in turn, *drive* interannual atmospheric variability in these frontal regions of strong air-sea interactions through its upper ocean thermal signature (also see Feliks et al., 2011).

P11 also showed that low Reynolds number flows, like those simulated by laminar ocean models currently used for climate prediction, are devoid of intrinsic LFOV, as already shown in idealized studies. We argue that this ignored chaotic ocean variability may substantially affect the coupled climate system (Brachet et al., 2011; Feliks et al, 2011; Deremble, 2011). Eddying OGCM simulations also provide evidence that major climatic indices are significantly impacted by intrinsic LFOV; examples include e.g. the Agulhas eddy low-frequency modulation of the AMOC[2] reaching as far north as the northern tropics (Biastoch et al, 2008), or the Florida Current transport low-frequency variance, 40% of which is of intrinsic origin according to recent DRAKKAR/NEMO simulations.

Besides these few studies, however, very little is known about the origin, time-space (4D) structure and magnitude of the intrinsic LFOV in global realistic contexts. Its imprint on satellite observations, subsurface data and climatic indices is also largely unknown.

To summarize, low-frequency oceanic variability importantly involves ocean-generated "noise" that cannot be extracted from observations alone. The features, magnitudes, dynamics and observational imprints of this intrinsic LFOV component are unknown. The overarching objective of the proposed study is to assess the importance of intrinsic LVOF in the oceanic variability.

b) Studying this observed chaotic ocean variability requires realistic eddying simulations

Considerable effort is being applied to monitoring and understanding the variability of climatic indices (e.g. SLA, SST, AMOC, sea-ice cover, air-sea fluxes, etc). However, intrinsic and forced LFOV are entangled in the real ocean, and hence in observational datasets. Since collecting an ensemble of real observational timeseries is impossible, we are forced to perform ensembles of realistic ocean simulations driven by different forcings in order to separate and study both components. Long eddying ocean-only OGCM simulations are mandatory to investigate the multivariate, spatio-temporal structure of this overlooked variability which is present in real observations in various regions and at various scales. This particularly applies to altimetric data, which blends the surface signatures of poorly-known, intrinsic and forced signals.

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[1] 'Low frequency' will generally refer to the 1-10 year range of timescales in this proposal.

[2] An RAPID-like array is planned to monitor the AMOC at 34.5°S in the Atlantic (SAMOC).

Ocean variability identification from realistic OGCMs is a new effort and has promising perspectives, but has little in the way of existing literature upon which to build. In contrast, there is a rich literature on nonlinearity and intrinsic dynamics in process studies with reduced dynamics, such as quasi-geostrophy in simplified geometries, or shallow water studies in square basins. Such studies/theories have produced very interesting concepts, tools and dynamical hypotheses; we assert these can be ported to OGCMs, although diagnoses so inspired are few. Studying intrinsic LFOV in realistic contexts using these solid concepts will shed new light on climate variability, on the imprint of LFOV on altimeter and other observational datasets, place OGCM solutions in the framework of existing theories, and extend the latter to the real ocean complexity.

Ocean-atmosphere coupled climate models are at the moment transitioning from IPCC-class, laminar ocean components (devoid of intrinsic LFOV) to “eddy permitting” resolutions. This transition will make SST variability more chaotic (see Fig. 1b), and will likely modify the simulated climate variability substantially. We see this important issue as a perspective for the present proposal: characterizing the structure, dynamics and surface thermal fingerprint of this poorly known intrinsic LFOV in ocean-only settings is a requisite first step towards anticipating and interpreting future climate projections.

Several observational and operational issues are also concerned: knowing the contribution and structure of ocean intrinsic variability should help set error bars when comparing ocean simulations with satellite/subsurface observations, better constrain ocean reanalyses and forecasts, and better separate atmospherically-forced climate change signals from the intrinsic variability present in oceanic observations.

The abundance of observations and computational resources make it now possible to study the structure, magnitude, observational imprint and dynamics of intrinsic LFOV in the realistic context of global eddying simulations. The benefits of such a study include an improved knowledge of deterministic and chaotic signals recorded in altimetric and other datasets, a better understanding of LFOV and its contribution to climate variability, the interpretation of observational datasets, and material for useful “operational” outcomes (i.e. monitoring, detecting, hindcasting and forecasting climate). Besides OGCM modelers, our group includes experts in the methods and concepts used to study intrinsic LFOV in idealized frameworks; these complementary talents will be focused on the production of realistic simulations and on their statistical and process-oriented analysis in strong connection with satellite and in-situ observations.

IV.3 Dynamical background

a) Dynamics of the intrinsic LFOV

What is known about intrinsic variability dynamics has come almost solely through the study of highly simplified numerical oceans. Quasi-geostrophic (QG) or shallow-water models have often been used because they can be integrated for long periods at very high resolution to yield robust statistics and inspire dynamical hypotheses.

Hasselmann (1976) and Frankignoul et al. (1997) showed that an atmospheric wind variability with a white energy spectrum *linearly* forces a red oceanic spectrum. In a linear ocean, however, no LFOV can appear in response to an atmospheric forcing without low-frequency variability. Nonlinearity is required to generate variability at periods longer than the forcing periods (as found by *P11*). High-resolution models simulate high

Reynolds number (strongly nonlinear) eddying flows, with marked frontal structures. Whether the eddies and/or steep isopycnal fronts drive intrinsic LFOV remains unclear.

Do eddies directly drive intrinsic LFOV? Analyzing altimeter observations, along with idealized and realistic simulations, Arbic et al. (2012) recently argued that nonlinearities in the momentum equations (i.e. eddy-eddy interactions that are resolved at high resolution) can efficiently flux this O(1month) mesoscale energy to longer *time* scales; the mesoscale eddy field may thus generate intrinsic LFOV through a spontaneous *temporal* inverse cascade. Using eddying process ocean models, Spall (1996), Dewar (2003) and Berloff et al (2007) identified eddy PV fluxes and turbulent rectification as possible nonlinear processes directly sustaining intrinsic LFOV. In other words, Berloff's "turbulent oscillator" approach, as well as Dewar's and Spall's PV budgets diagnose in physical space how eddy processes feed intrinsic LFOV at larger time and space scales; Arbic's temporal inverse cascade provides a complementary view in frequency space.

Does the intrinsic LFOV feed on the mean PV structure? In contrast, Huck and Vallis (2001), Dijkstra and Ghil (2005), or Hazeleger and Drijfhout (1999) suggest that intrinsic LFOV may not be directly fed by eddies but by large-scale instabilities and/or nonlinear interactions between slow variability modes and the background (potential vorticity) state. Dynamical systems theory (DST) suggests that the LFOV is due to chaotic transitions of the large-scale circulation between multiple stable equilibria, which may be predicted from the mean potential vorticity climatology.

To summarize, idealized and realistic models show that turbulence and steep PV fronts (i.e. high resolution model features) favor intrinsic LFOV, but which drives LFOV is not clear. In the realistic context of OGCM runs and in the real ocean, the answer might depend on the regions and scales considered. In any case, central to LFOV studies is nonlinearity (e.g. Arbic's study), and potential vorticity, either through eddy redistribution, or in its large-scale structure upon which the instabilities driving the variability feed.

These dynamical hypotheses will be investigated in CHAOCEAN, for the first time in a realistic context and in close connection with observations. European and American scientists having complementary views/tools (PV budgets, nonlinear energy cascades, DST approaches) will study the same realistic runs; this may help better understand the origin of intrinsic LFOV.

b) Timescales

CHAOCEAN is primarily focused on 1-10 year intrinsic ocean variability. Our reasons for this choice range between the theoretical and the practical. First, intrinsic variability emerges in this frequency band in the presence of mesoscale eddies (Dijkstra and Ghil, 2005; *P11*). The roots and consequences of this phenomenon have not yet been examined in realistic OGCMs. Second, computational resources are now such that long, global high-resolution simulations can now be performed. To reproduce this 1-10 year variability thus requires multi-decadal realistic runs in the eddying regime. Such considerations have led to the design of our proposed numerical work, to be outlined below.

The process study literature on LFOV is mostly focused on adiabatic experiments in which basin-scale gyres fluctuate spontaneously under a constant wind forcing. Given the qualitative resemblances mentioned by *P11* between intrinsic LFOV features in realistic and (adiabatic) idealized setups, and given Dijkstra and Ghil (2005)'s review on intrinsic LFOV timescales, it is very likely that interannual-to-decadal intrinsic LFOV is mostly controlled by adiabatic dynamics in OGCM simulations as well (unlike at multi-decadal frequencies where diabatic processes might have a stronger contribution).

c) Focus Regions

We will address observational issues with a global scope but focus most of our in-depth dynamical investigations on the North Atlantic, the best-known mid-latitude basin. We choose this region because [i] our previous studies show that the mid-latitude North Atlantic within and south of the Gulf Stream/North Atlantic Current (GS/NAC) system is subject to a strong 1-10 year intrinsic LFOV; [ii] the in-situ observational coverage is densest and longest there; [iii] process-oriented double-gyre studies are obviously applicable there; and [iv] most importantly, the direct or indirect climatic impacts of the oceanic intrinsic variability are potentially strong there (e.g. through air-sea fluxes, MOC, meridional heat transport, etc). We will attempt to compare our model results with observations in other regions (e.g. Southern Ocean, North Pacific) as much as possible.

d) Remaining experimental issues

P11 used a simple strategy, i.e. a *pair* of global eddying simulations, to estimate the intrinsic contribution to the observed sea level variance. Their first simulation was driven by a realistic ("full") forcing, containing all atmospheric timescales; their second was driven by a repeated seasonal cycle. The first one was compared to AVISO and proved realistic regarding most features of SLA low-frequency variability. Despite the absence of direct interannual forcing, the second simulation did exhibit a strong sea-level LFOV hence referred to as "intrinsic", that was subsequently compared to the "full" LFOV obtained in the first simulation (Fig 1). Our strategy in CHAOCEAN will still rely on sets of experiments in which sources of variability are selectively withheld. We will use a somewhat more sophisticated approach to test certain assumptions made by *P11*:

1. Although the DRAKKAR/NEMO model has passed several tests, such as hindcasting SSH and SST variances comparable to observations, we do not genuinely know if Fig. 1 is the "right" answer. The only viable test for this is to conduct the same calculation in independently coded OGCMs and subject the results to rigorous comparison. European CHAOCEAN partners will use NEMO; American partners will use HYCOM and MITgcm.

2. *P11* made the assumption that the "total" SLA variance in the first run was the sum of the forced and intrinsic components. However, *a posteriori* testing of this assumption showed it was not valid in certain regions of strong mesoscale activity. This suggests that intrinsic LFOV can be modified by forced variability, a point in need of study that will be adressed in CHAOCEAN. Our strategy (see IV.6 below) will address this issue.

3. 1/4^{o} simulations omit part of the mesoscale and all of the submesoscale. CHAOCEAN will investigate the (likely substantial) contribution of smaller scales in the sustainance of intrinsic LFOV from ¼°, 1/12° (and 1/36° in the US) realistic simulations.

Other issues can also be raised viz. the results in *P11*, but we identify the above as the most pressing. This proposal has been designed to address the above three points.

IV.4 Experimental and scientific objectives

We have emphasized in previous sections the need for an analysis of LFOV in realistic models and our capacities for performing the needed calculations. We have mentioned assumptions implicit in our past work and how those assumptions might be tested.

➔ In view of these points, we hypothesize that:

H1. Pairs of seasonally forced and interannually forced runs analyzed in a manner like that appearing in Fig. 1 will yield 3-dimensional measures of the percentage of intrinsic variability in observed variances. **We expect intrinsic variability will compare in amplitude to forced variability** (at least at the surface). We further expect that **the 3D patterns of intrinsic variability resemble those of the forced variability in regions where they interact, and that our simulations will identify them.**

H2. Intrinsic variability has large-scale fingerprints on observational databases, which will be less sensitive to model construction than model resolution (1/4°, 1/12° and 1/36°)**.** We expect that these differences will be identifiable from intercomparisons of synthetic[3] observations extracted from various OGCMs.

H3. The large-scale features of the intrinsic LFOV diagnosed in model runs (via e.g. EOF analyses) **will resemble the eigenvectors found in the linear stability analysis of the background climatological state** (i.e. Dynamical Systems Theory). We also anticipate that **the linear stability of large-scale ¼° and 1/12° 3D climatologies will be similar, i.e. that the intrinsic LFOV at 1/12° will be modified by mesoscale effects.**

H4. Our 3D statistical analyses will highlight links between the intrinsic LFOV's surface and subsurface expressions, as well as with climate indices; this may help assess the imprint of LFOV on the three-dimensional ocean circulation from altimeter data.

➔ To test these hypotheses, the European CHAOCEAN objectives are the following[4]:

A. Extract and statistically characterize the 4D intrinsic LFOV (space-time structure, frequency spectra and fluxes, scales, amplitude, signature on surface variables, etc.) in NEMO simulations in the eddy-permitting and eddy-resolving regimes (H1, H4)

B. Quantify, globally and regionally, the imprints of intrinsic LFOV on satellite/subsurface observations (SLA, SST, air-sea fluxes, etc.) **and climate-relevant observations** (climate indices[5], e.g. MOC at RAPID[6], OVIDE[7], etc.) (H1, H2, H4)

C. Assess in the North Atlantic the relative contributions of eddies and large-scale PV structure in driving intrinsic LFOV through DST analyses and Berloff's "Turbulent Oscillator" approach. (H3)

D. Compare intrinsic LFOV features in NEMO, HYCOM and MITgcm to assess their robustness, and their sensitivity to model parameters (hybrid vs. geopotential, resolutions) **with the design of future climate models in mind.** (H1, H2, H3, H4)

E. Make raw and post-processed (e.g. synthetic/real collocated observations, statistics) **NEMO outputs available to the EU/US CHAOCEAN group, to the OST/ST community and beyond.**

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[3] Fields from realistic simulations subsampled where and when real observations were collected. This operation is routinely performed through online or offline multi-linear collocation.

[4] These item purposedly complement and partly overlap the US CHAOCEAN group's.

[5] chosen among those recommended by CLIVAR panels (see section IV.8).

[6] http://www.noc.soton.ac.uk/rapidmoc/. Note that Joel Hirschi (NOCS, UK) and William Johns (RSMAS, USA) are both involved in RAPID and will contribute to CHAOCEAN.

[7] http://www.ifremer.fr/lpo/ovide/

➔ These objectives respond to the OST/ST requirements by:

- investigating the physical content of altimeter data (+ other satellite/subsurface data).
- capitalizing on satellite observations to perform research about fundamental processes, climate variability, observation strategies, and numerical ocean modeling.
- jointly investigating and relating satellite and subsurface observations.
- preparing for wide swath altimetry by studying O(1-10km) dynamics and their low-frequency climatic impacts.
- providing possible operational outcomes: constraining the uncertainties associated with climate monitoring, hindcasting, and projections.

IV.5 General approach

Our strategy involves realistic ocean simulations as well as real and synthetic satellite/subsurface observations. These data will be analyzed jointly to study the structure and origin of intrinsic LFOV using various statistical and physical diagnostics.

Long OGCM simulations, based on 3 state-of-the-art primitive equation models, will simulate total (full forcing) and intrinsic (seasonal forcing) LFOVs in a realistic eddying regime. Their solutions will be collocated with, and assessed against, real observations. The 3D structure (Obj. **A**) and observational fingerprint (Obj. **B**) of modes of intrinsic variability will be studied from fully sampled model outputs and synthetic observations, respectively. The 'realistic' ocean modelers involved in the project use three types of OGCMs. This partly reflects our modeling backgrounds (see IV.7.c below). This variety of models also allows us to directly address H3 about model-based sensitivity of LFOV[8] and Obj. **D**. This will strengthen links between various ocean modeling communities.

All CHAOCEAN simulations will be driven via bulk formulae using the same "full" and seasonal atmospheric forcing fields. LEGI scientists (BB, TP, JMM, etc) have developed such fields in projects supported by OST/ST-CNES continuously since 2008: the "DRAKKAR Forcing Sets" (DFS), are used by several modeling groups in Europe. These 54-year hybrid forcing fields are based on reanalyzed and satellite atmospheric fields that are calibrated, corrected for known biases, tested and equilibrated using long, dedicated NEMO runs (see Brodeau et al., 2010). We will use the same strategy as *P11* (see their section 2) to design and apply CHAOCEAN seasonal and interannual forcings.

Computational and storage resources as necessary will be requested from GENCI (IDRIS/CINES) computational centers, and potentially from PRACE (www.prace.eu).

IV.6 Experimental and work plan

During the first 1-2 years of the project, we will perform and assess the simulations appearing in the table below, which is followed by some clarifying comments (in italics). We discuss the rational for this experiment set and the planned diagnostics afterwards.

TABLE OF MAIN PROPOSED RUNS

Resolution, Model	Domain	Seasonally-Forced	Fully Forced
¼° NEMO	global	400 year (Run α)	1958-2011x4 (Run β)

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[8] Some have been seen in previous model intercomparisons (Griffies, et al, 2009).

1/12° NEMO	global	54-year	1958-2011
¼° HYCOM(*)	global	54-year	1958-2011
1/12° HYCOM(*)	global	54-year	1958-2011
1/36° MITgcm(*)	N. Atlantic	54-year (a)	1958-2011(a)
1/36° MITgcm(*)	N. Atlantic	54-year (b)	1958-2011(b)

(*) experiments to be conducted by American CHAOCEAN partners

<u>Comments:</u>

The long duration of Nemo ¼° Run α will serve several purposes:

- *Characterize in the absence of forced LFOV the 3D structure and magnitude of intrinsic LFOV during (years 10-100) and after (years ~200-400) the adjustment of oceanic background states. Obj.* ***A B C D E.***

- *Build significant statistics (covariances, modes, spectra, eigenmodes, stability analyses) describing variability over the range 1 month-10 years. These results are a first requisite to extractand study intrinsic LFOV in fully forced runs. Obj.* ***A B C D E***

The modes extracted from Run α will then be used to generate optimal perturbations and initialize the 4 passes of Run $\boldsymbol{\beta}$. These 54-year fully forced simulations will be started from dynamically consistent but mutually independent initial conditions. Both NEMO and HYCOM β runs will yield various passes of interannually forced "trajectories" with different intrinsic variabilities. Deviations from these 4-member ensemble means will then yield 3D characterizations of the intrinsic LFOV in the presence of forced interannual variability. The intrinsic LFOV signatures as deduced from the β runs will be characterized in terms of spatial patterns, typical periods, etc., using statistical methods (e.g., Canonical Correlation Analysis (CCA), Empirical Orthogonal Function (EOF) projections). The comparison of intrinsic LFOVs with and without forced LFOV (β and α) will allow us to go beyond P11's analysis (see second item in III.3): the regions where, and degree to which, intrinsic LFOV is affected by forced LFOV permit the study of interactions and possible resonances between both (see e.g. Taguchi et al 2007) with a link to observations.

The HYCOM seasonally- and interannually-forced simulations will use the same grid, land mask, topography, initial state and forcing as NEMO simulations. The same subgrid-scale parameterizations will be used in both models when possible, although their different formulations imply certain distinctions in model physics (e.g. vertical mixing) and numerics (e.g.advection schemes).

Atmospheric forcing will be applied in a manner that ensures the mean and seasonal cycle of the air-sea fluxes will be consistent between the α and β runs. We propose to force all CHAOCEAN pairs of simulations with the 54-year DFS#5 forcing fields.

Both MITgcm 1/36° (a) runs will employ seasonal boundary conditions, while both (b) runs will use interannual boundary conditions. This will allow us isolate local from remote sources of intrinsic and forced variabilities.

The proposed strategy will have additional advantages :

(i) pairs of runs will be produced by various models at various resolutions, thereby assessing the robustness of our results to model formulation and resolution (Obj. ***D****).*

(ii) As shown by Hirschi (2012, in preparation), differences between passes yield a characterization of intrinsic variability along an interannually forced trajectory. J. Hirschi, and T. Penduff with S. Gregorio have started independent investigations of the AMOC intrinsic LFOV in NEMO ¼° runs. Preliminary results suggest that both P11's approach and multiple-pass diagnostics provide interesting and complementary insights in the dynamical phenomenology (obj. ***A B****).*

(iii) from the finest resolution simulations, we will get a first look at the role of the submesoscale in climatically relevant settings, in the surface, subsurface and near topography.

a) Numerical strategy

The objectives listed above will be addressed using realistic runs, synthetic and real observations (see section b below)

- The OGCMs setups will be identical (HYCOM and NEMO will use the same model grids, topographies, forcings, initial states —provided by LEGI from DRAKKAR experience), or similar (MITgcm). Note that some ¼° and 1/12° model fields, as well as real/synthetic observations will be shared across the Atlantic for joint EU/US investigations (e.g. statistical analyses, inverse cascades, etc. See American CHAOCEAN proposal). The models will be run in the eddying regime at 3 target resolutions:

- "Eddy-permitting" ¼° global NEMO (and HYCOM) models partly resolve the low/mid-latitude turbulent spectrum. Because of their moderate computational cost, they are planned as part of the next generation of global coupled climate prediction systems. This emphasizes the need to assess their chaotic behavior in forced mode first. Both models are well suited for the long integrations necessary to compute significant statistics at low frequencies and for ensemble strategies. Their simultaneous use will also allow us to directly assess the model-based sensitivity of LFOV.

- We will then move to 1/12^o for 54 year runs of seasonally and fully forced settings. The initial conditions for both will come from an interpolation of the seasonally forced, ¼^o solution to minimize the model drift. Horizontal/isopycnal dissipation operators will be adjusted in both models to match the threefold increase in resolution. The 1/12° runs will of course represent more of the mesoscale energy spectrum, and provide a more accurate view of altimeter/satellite/in-situ observations. ¼° and 1/12° global NEMO (and HYCOM) runs will be compared (obj. **D**).

- The 1/36° (2.5km at 35°N) MITgcm model (run at FSU) will resolve mesoscale and part of the submesoscale processes in the North Atlantic over several decades. The comprehensive coverage of the North Atlantic at these scales will allow for the first time a thorough study of the entire Gulf Stream system and its adjacent mode waters. These regional simulations will provide a computational context in which to anticipate the results of planned, future high-resolution, wide swath altimetric missions.

The NEMO ¼^o Run α will be integrated for several centuries (nominally 400 years) under climatological seasonal forcing. We will not use a constant atmospheric forcing as done in most idealized adiabatic numerical studies (e.g. Spall 1996), since a seasonal cycle is required to maintain mean states (stratification, PV structure, water masses) in an 'Earth-like' regime[9]. This experiment needs to be long to produce significant statistics about the intrinsic 1-10 year LFOV.

However, long integrations tend to integrate small model errors and discrepancies, potentially yielding long-term drifts. Experience shows that O(200 year) spinups lead to mean states that are more adjusted dynamically, yet further away from the observed ocean. We shall carefully examine these trends in Run α[10], compare them with the evolu-

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[9] The impact of seasonal forcing on intrinsic LFOV will be addressed by P. Berloff in QG runs.

[10] The NEMO/DRAKKAR group has recently tested and validated two possible strategies that will reduce the main long-term drifts found in the earlier *P11*'s 327-year seasonal experiment without jeopardizing relevant dynamics; one of these solutions will be used in NEMO Run α.

tion of model-climatology mismatches over centuries, and then choose the adequate spinup period after which initial conditions for Runs β will be generated.

The North Atlantic domain of the regional MITgcm experiment extends from 0° to 55°N. The northern boundary is chosen to avoid areas where sea-ice cover is likely; it nonetheless completely encompasses the GS/NAC system, the subtropical gyre and parts of the subpolar gyre. The proposed regional modeling sequence is different from that planned for the global experiments due to the lateral boundary conditions. We have 4 possible forcing scenarios, all of which are planned for study. We will develop climatological boundary conditions, filtering out interannual variability, in a manner analogous to the surface fields. The boundary data will come from interpolated HYCOM or NEMO 1/12° fields. The available forcing combinations then can be composed from seasonal or interannual boundary conditions, with seasonal or interannual surface conditions.

b) Link with observations — Diagnostic methods and tools

Observational issues (obj. **B E**) will be addressed by CHAOCEAN groups (mostly by LEGI and NOCS in Europe, COAPS and B. Arbic in the USA) by collocating model fields onto real observational data. Associated methods and tools have been designed during the SSINOC 2008-2012 OST/ST project (PI T. Penduff), and described in Juza & Penduff (2007). Real/synthetic collocated datasets may be compared mutually and with the fully-sampled model outputs using specific metrics and existing tools. Several DRAKKAR simulations have been collocated on observational data: AVISO altimetry, ENACT-ENSEMBLES 1956-present dataset (individual T/S profiles from CTD, XBT, Argo, floats, moorings, etc.), AVHRR sea-surface temperature fields, RAPID MOC timeseries, current meter recordings, sea-ice satellite maps and local thickness measurements, etc.

The production and use of collocated fields has at least 3 interests: [i] providing quantitative comparisons between various observations and one particular simulation (Koch-Larrouy et al, 2010; Hasson et al, 2012); [ii] comparing various models and assess model sensitivities in tight link with observations (Mathiot et al 2010; Penduff et al, 2010, 2011); [iii] study how the observational subsampling may degrade the signals present in the fully-sampled model outputs (observability studies, e.g. Juza et al, 2011, 2012). CHAOCEAN will take advantage of these 3 potentialities; collocation will be performed by TP, GS, JH (in the USA by EC, AM, NW).

The other, complementary post-processing tools and methods used in CHAOCEAN are presented in more detail in section IV.7, and have users in both CHAOCEAN groups. Those related to DST approaches will be used by TH and HD (and BD in the USA). Statistical analyses will be made by LT, TP, GS (and in the USA by SK, MG, DK). Nonlinear eddy fluxes will be investigated by PB (and in the USA by BA, WD, BD).

c) Work plan

(Objective) Partners	**2013**	**2014**	**2015**	**2016**
(E) JMM,AL,TP,BB	Produce new 1/4° NEMO runs	Produce new 1/12° NEMO runs	Build and maintain EU/US observ./model databases. Develop & support diagnostic tools	
	Exchange data/investigations w/ CHAOCEAN team, OST-ST, others(1)			
(A,B) TP,BB,LT,GS,SG,JH	Characterize 4D LFOV from			Syntheses, publications
	present 300-yr 1/4° run	new 400-yr 1/4° run	new 400-yr 1/12° run	
		Observational imprint, process studies		
(C) TH, PB, HD	Build/Adapt tools(2)			
	Study(3)			Syntheses, publications
	present 300-yr 1/4° run	new 400-yr 1/4° run	new 400-yr 1/12° run	

(1) *e.g. DRAKKAR runs have been distributed to over 140 scientists worldwide over 2008-2011*

(2) *QG model configuation, diag. tools for linear stability analyses, eddy fluxes, etc*

(3) *Feeding of intrinsic LFOV by large-scale PV field vs. turbulent fluxes*

Notes: *Yearly CHAOCEAN meetings will take place just before or after OST-ST meetings*
French/US computing resources will vary each year and may modulate our plans
Most phases have counterparts in the US: interactions will take place continuously.

IV.7 Individual contributions — Synergies within the CHAOCEAN group

a) French teams

- **MEOM-LEGI, Grenoble, France [TP, BB, JMM, AL, GS, SG]**

TP will coordinate the French activities, the interactions with the 3 European experts (PB, HD, JH) and with the American CHAOCEAN partners (in tight connection with W.K. Dewar, PI of the American CHAOCEAN project). The LEGI group will design, calibrate and perform global NEMO *pairs* of simulations at 1/4° (ORCA025) and 1/12° (ORCA12), extract synthetic observations from their outputs and compare them to altimeter, satellite and in-situ observations in order to assess the simulations. MEOM research engineers [JMM and AL] have a strong expertise in ORCA025, which has been computationally optimized, whose outputs have been largely distributed and proven realistic. ORCA12 is currently being optimized and assessed and is proving promising in terms of realism. LEGI will also provide raw and post-processed model outputs to the OST-ST community and beyond.

We shall quantify how and where the intrinsic LFOV "contaminates" observational data and major climate indices, at 1/4° then at 1/12° resolution. P11's approach will be extended to a variety of satellite/in-situ synthetic observations (collocated model outputs) and to important climate indices (chosen among those recommended by CLIVAR panels: e.g. latitude-dependent AMOC, mass transports of main currents and overflows, mode water characteristics, mixed layer depths). This will provide us and observationalists with 3D maps of the aforementioned "noise" level in various satellite/in-situ datasets, thus quantifying the actual decorrelation between the atmospheric forcing and the oceanic variability, and guiding investigations on the forced oceanic response and on predictability.

We will first extract observable surface fields (e.g. SSH, SST, SSS, air-sea fluxes) from the existing pair of 1/4° DRAKKAR runs. Band-pass analyses of the variance of these fields in both runs will reveal at global scale the distribution of intrinsic LFOV (seasonally-forced run) and its contribution to the total variability (fully-forced run) in various frequency bands. Slightly different approaches will then be followed using the ENACT-ENSEMBLES historical collection of ~8.10^6 in-situ T/S profiles (including XBTs, CTDs, TAO, Argo, etc). The intrinsic and total 3D fields of T and S variances will be collocated on all archived profiles, hence providing the absolute magnitude of intrinsic and total temperature/salinity LFOV variances as well as the intrinsic/total variance ratio simulated by the fully-forced model, at the time and location the actual measurement was made. These various collocated model-derived quantities will be added to the original ENACT-ENSEMBLES T/S data file. These profile-dependent estimates of the atmospherically-forced and intrinsic signals will allow subsequent users of this dataset and the oceanic reanalysis community to go beyond the sole recorded data.

The robustness of our main 1/4°-derived results will finally be assessed from 1/12° runs when available (2013-2014). Differences will reveal in a realistic context how the grid Reynolds number impacts the intrinsic LFOV, and potentially how future high-resolution observing systems (e.g. SWOT) may be "contaminated" by the intrinsic LFOV.

These investigations will provide information on the observability of 3D intrinsic LFOV modes from satellite, on locations where the forced LFOV ("signal") may be masked by intrinsic LFOV ("noise"). Attributing signal-to-noise ratios to observational data/locations should also help improve ocean model assessment metrics (e.g. Koch-Larrouy et al, 2010) by setting error bars on mismatches between observed and simulated local variabilities, potentially help better design climate change monitoring systems and improve data assimilation techniques for reanalyses.

- **SUC-CERFACS, Toulouse, France [LT, GS[11]]**

The SUC-CERFACS has a strong expertise in the statistical analysis of climate variability from large model simulations. In collaboration with LEGI (and in parallel with American partners), the leading 3D modes of intrinsic LFOV and their temporal behavior will be computed in key regions from the existing and planned seasonally-forced DRAKKAR run. Statistical analyses[12] will first be produced and compared to characterize the intrinsic LFOV without interannual forcing, with a specific attention to surface variables. These intrinsic variability modes will then be sought in the fully-forced 1/4° simulation by projecting its leading EOFs on the fully-forced solution and reconsruct time series of intrinsic variability in the presence of forced variability.

The intrinsic LFOV is likely to be modified to some extent by the interannual forcing (because of e.g resonances or nonlinear interactions, see P11 and Taguchi et al 2007). The differences found between the intrinsic LFOV's found in the ensemble of fully-forced runs and the seasonally-forced run will help identify regions where the forced variability distorts and modifies intrinsic variability modes.

- **LPO, Brest, France [TH]**

The ¼° and 1/12° global simulations planned in CHAOCEAN will express intrinsic LFOV that will be statistically analyzed (e.g. from EOF analyses). Provided that this variability

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[11] G. Serazin's PhD thesis will be co-advised by TP and LT. He will contribute to LEGI/SUC efforts.

[12] e.g. multivariate Empirical Orthogonal Function (EOF); Canonical Correlation(CCA); Multi-Channel Singular Spectrum (MSSA)

feeds upon the background mean potential vorticity (PV) field, its structure may also be predicted from the modelled mean state using a dynamical system analysis (e.g. a linear stability analysis). Comparing the predicted and actual modes of LFOV will therefore be useful to assess the role of eddies vs the large-scale mean PV structure in generating this variability. Such analyses of model climatologies, performed on their native 1/4 —1/12° grids, are expected to select the most unstable structures with scales near the first Rossby radius at which the growth of mesoscale baroclinic instability is fastest. We propose to perform linear stability analyses of high-resolution climatologies after their interpolation on coarser grids (ie 2°, 1°) to select unstable modes with larger spatial scales, and presumably lower frequencies (periods from years to decades). Existing studies show that global NEMO simulations at 2° do not yield any significant intrinsic LFOV (Penduff et al 2011) and only a weakly damped decadal mode (Sévellec & Fedorov, in revision); both findings are consistent with weak isopycnal slopes and available potentiel energy at 2°. High resolution yields much narrower mean fronts and steeper mean isopycnal slopes, and we expect much more unstable, large-scale low-frequency modes can be predicted from high-resolution solutions degraded in resolution.

The linear stability results will be analyzed in terms of observable fields, namely sea surface height (alternatively Sea Level Anomaly for the modes) and thermal structure of the upper ocean. Indeed, if the low-frequency large-scale mode dynamics is based on baroclinic Rossby waves as expected (see Penduff et al 2011), these observable indicators are particularly pertinent. We will extract the mean seasonal cycle (harmonics or monthly means) of temperature, salinity and velocities from the high resolution simulations (1/4°, 1/12°). These fields will be used as the mean periodic trajectory for the computation of the most unstable modes through a Poincaré section analysis. Linear stability analysis methods have been implemented so far in a 2° NEMO configuration, using the tangent linear and ajoint package OPATAM, but we should be able to adapt the method to regional North Atlantic configurations at higher resolution (1°, maybe 1/2°). The selection of the modes is based on their growth rate, hence promoting large scale modes based on the scale selection of the diffusion parameters (viscosity and/or tracer diffusivity that have comparable influences on potential vorticity). These analyses will be performed in collaboration with Dr. Florian Sévellec, Lecturer at NOCS, Southampton, UK, that T. Huck supervised for his PhD and with whom the linear/adjoint stability analysis tools have been developped based on OPATAM (OPA Tangent Linear and Adjoint Model, Anthony Weaver, CERFACS). For more information, see Huck & Vallis (2001), Huck et al (2001), Ben Jelloul & Huck (2005), Sévellec et al (2008).

b) European experts

- **Joël Hirschi, NOCS, Southampton, UK**

The forced and intrinsic MOC variability will be studied in 1/4 ° and 1/12° NEMO simulations. We will perform, respectively have already performed simulations where the same surface forcing is applied over successive passes (e.g. 1958 to 2001 at ¼°, 1988-1989 and 2004-2009 at 1/12°). These passes then essentially differ in their initial conditions which leads to mesoscale eddy fields that are decorrelated (Hirschi et al. in prep.). The variability of the difference (e.g. in SLA, SST or or MOC) between model passes can then be used as a measure for the intrinsic ocean variability on timescales that are short compared to the length of the time period covered by the model passes. We will study the forced vs intrinsic variability in the different components of the MOC (geostrophic, Gulf Stream and Ekman contribution). Besides surface variables, the intrinsic variability will be most clearly seen in the Gulf Stream transport and in the geostrophic transport obtained from cross-basin zonal density gradients. Much smaller differences are expected for the Ekman transport (same wind applied in all passess), although differences in the mesoscale eddy field will result in slightly different wind stresses in model passes. The analysis will not be confined to 26.5°N where direct MOC observations are available but we will also look at the meridional and vertical structure of the forced and intrinsic MOC variability for the full Atlantic and Indo-Pacific basins.

The results of this analysis will provide an estimate of how much of the observed MOC variability is intrinsic (objectives **A B**). The results will also show how much the amplitude of the intrinsic MOC variability depends on the resolution (obj. **D**). Current work is showing that there is a markedly higher intrinsic MOC variability in NEMO ¼° compared to NEMO 1°. Is a similar increase found when moving from ¼° to 1/12°? Is there a further change in intrinsic variability if we look at the regional 1/36° model from FSU or does the intrinsic variability saturate?

Our main focus is subanual to interannual timescales, but it will be interesting to also apply the MOC decomposition to the long climatological NEMO ¼° simulation performed at LEGI. The seasonal forcing means that intrinsic MOC variability found on interannual to decadal timescales in this run will be found in the geostrophic component. The findings will be relevant for studies aiming at inferring the MOC from surface forcing (e.g. Josey et al., 2009; Grist et al., 2009) where the intrinsic MOC variability is not included.

- **Pavel Berloff, Imperial College, London, UK**

We will address in idealized contexts various dynamical issues relevant to CHAOCEAN's realistic experiments. We will perform and analyze baroclinic quasigeostrophic double-gyre ocean simulations, which over the last 30 years have proven successful for the study of physical processes involving oceanic mesoscale eddies. A novelty is that our ocean model will be integrated for long periods in regimes with extremely detailed resolution of the eddies and their effects. We will carry out and analyze very high resolution simulations in simplified geometries, with the focus on:
- The sensitivity of intrinsic LFOV to the seasonal forcing (an issue which has not been studied yet but is crucial for realistic simulations);
- The correlations between the forced and intrinsic variabilities, an issue that has been raised (but not solved) by Taguchi et al (2007) and P11 in realistic simulations;
- The dynamical impact of submesoscale processes on the intrinsic LFOV (this will help interpret the transition between 1/12° and 1/36° OGCM simulations);
- The contribution of high baroclinic modes in the eddy stresses that are likely driving intrinsic LFOV ;
- Dynamic and kinematic analyses of the eddies, Eddy backscatter mechanism, and improvement of the theory of intrinsic large-scale low-frequency variability.

These activities (see details in VII.2) will contribute to the CHAOCEAN project through systematic process studies of fundamental processes underlying the generation of intrinsic LFOV in the eddying regime and in a realistic context.

- **Henk Dijkstra, University of Utrecht, The Netherlands**

We are interested in the decadal variability in the North Atlantic that has been found in many climate models and in observations. From studies with low-resolution three-dimensional ocean models, it is shown that this variability arises because the Atlantic Meridional Overturning Circulation (MOC) is destabilized through a multidecadal mode (Te Raa and Dijkstra, JPO, 2002). The spatial patterns associated with this mode in a realistically shaped basin look reasonably good when compared to observations and the westward propagation of temperature anomalies are also found in GCMs (see Frankcombe et al., 2010).

The main question is what happens to this variability when the ocean models allows for strong eddying flow fields, in particular because now also other modes of variability (of the gyres) become important as well as the effect of the eddies. By comparing the 10-30 year variability in high-resolution and low-resolution model results we want to determine whether the large-scale spatial pattern of variability arises through an instability of the time-mean state (as low-resolution models suggest) or whether the eddy variability is crucial to generate the variability. The temporal behavior of the flow will become complicated, but the main issue is whether the spatial pattern of this variability is still controlled by large-scale processes (so still westward propagation, etc.) and if so, why (inverse cascades, etc.).

c) Synergies among/between the French, American and European partners

For several years TP, BB, JMM and JH (+EC in the US team) have been leading and involved in realistic modelling projects projects focused on the ocean variability at meso-to-global daily-to-multidecadal scales, in observational and operational research (TP, BB, JMM have been OST-ST Pis or co-Is over the last years; BB is co-leading the main French effort in terms of global eddying ocean reanalyses). JMM is leading the development of global and regional Drakkar configurations with NEMO; he and AL will be the engineers in charge of producing and optimizing simulations (WD, NW, EC, and AM will lead the HYCOM and MITgcm simulations in close coordination with the French team). Members from LEGI, NOCS, and LPO are experts in the development and use of NEMO; Chassignet (COAPS-FSU) is a specialist in HYCOM, while Dewar/Deremble/Wienders are very experienced in downscaled applications of the MITgcm.

LT (+MG, DK and SK in the US) has a long experience in statistical analysis techniques applied to ensemble simulations and climate science, in jointly analyzing observational and model data. Their expertise will allow us to characterize the complex structure of intrinsic and variability modes. Also, SUC-CERFACS will use LEGI's NEMO-based global ¼° model (ORCA025) for the next generation of IPCC coupled runs (AR6 exercise).

TH and HD (+MG, BD, DK in the US) have had significant contributions in studies of climatic and oceanic intrinsic variability generation, using Dynamical System Theory approaches. Besides, PB (+BA and WD in the US) have investigated this issue from a complementary viewpoint rooted in potential vorticity analysis and statistical mechanics. Gathering these two "schools" around the analysis of realistic simulations should help assess e.g. the direct vs indirect driving of intrinsic LFOV by the eddies.

TP, HD and WD are associated to PB's research project soon to be submitted to NERC. This process-oriented study will complement our observation-oriented project by assessing a number of mechanisms influencing intrinsic variability and its surface imprint.

IV.8 Anticipated results

- A thorough description of the overlooked chaotic component of the ocean variability
- The imprint of the intrinsic variability on altimeter timeseries (including at resolutions close to expected wide-swath future data), SST, air-sea fluxes, currents' transports, etc.
- The connections between its observable surface patterns and subsurface structure.

- The genesis of LFOV through Reynolds Stresses (Turbulent Oscillator), inverse temporal cascade, mean PV state (Dynamical Systems theory), and atmospheric forcing.
- The sensitivity of these results to model design and resolved range of scales
- The potential change in future climate predictions with high-resolution ocean models.

IV.9 Significance of the investigation

- This project has been designed to address several observational and dynamical issues that have recently been recognized as important, but remain largely unknown in the real ocean. It works at the extremes of what is possible given modern computational power: we take the next steps in multi-centennial (1/4°) and multi-decadal (1/12°) global simulations; CHAOCEAN will perform multi-model and multi-resolution simulations, and diagnostics, that will provide us with new and complementary viewpoints. We will address a number of practical and theoretical questions associated with ocean modeling and the role of oceanic nonlinearities in climate projections. This is a first step towards understanding mid-latitude feedbacks on coupled climate variability and is essential to the construction of confidence estimates for climate reconstructions and projections.

- In the clarification of intrinsic versus forced variability in the ocean we expect to contribute to the understanding of climate signals captured by altimeters, other satellites and in situ arrays, and potentially help design future observational systems. We also anticipate advancing the prediction of subsurface ocean structures from surface observations. We will also provide computational standards that can be used in planning for and anticipation of the upcoming high resolution, wide swath, satellite missions.

- We will share our simulations and analyses among the EU/US group, and distribute them within the OST/ST community and beyond to stimulate research on additional questions (e.g. atmospheric response to low-frequency SST signals generated by the eddying ocean, possible implications for data assimilation, climate change detection, etc.).

- Studying small-scale processes and their climatic impacts from long eddy-resolving simulations is also a step towards future SWOT observations, whose range of resolved spatial scales will compare to our simulations. This project affirms a long-term commitment to the OST/ST community.

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- _Sévellec, F., T. **Huck**, M. Ben Jelloul, N. Grima, J. Vialard, and A. Weaver, 2008: Optimal surface salinity perturbations of the meridional overturning and heat transport in a global ocean general circulation model. Journal of Physical Oceanography, 38, 2739-2754._
- _Sévellec, F., and A. V. Fedorov, 2012: Interdecadal variability of the North Atlantic in an Ocean General Circulation Model. In revision._
- _Scott, RB and Wang, F., 2005: Direct evidence of an Oceanic Inverse Kinetic Energy Cascade from Satellite Altimetry, Journal of Physical Oceanography, 2005, 1650-1666._
- _Scott, R.B., and B.K. **Arbic**, 2007: Spectral energy fluxes in geostrophic turbulence: Implications for ocean energetics, Journal of Physical Oceanography 37, 673-688._
- _Shriver, J.F., H.E. Hurlburt, O.M. Smedstad, A.J. Wallcraft, and R.C. Rhodes, 2007: 1/32° real-time global ocean prediction and value-added over 1/16° resolution, Journal of Marine Systems, 65, 3-2_
- _Spall, MA, 1996: Dynamics of the Gulf Stream/Deep Western Boundary Current Crossover. Part II: Low-Frequency Internal Oscillations, Journal of Physical Oceanography, 26, pp. 2169-2182._
- _Taguchi, B., SP Xie, N Schneider, M Nonaka, H Sasaki and Y Sasai, 2007: Decadal Variability of the Kuroshio Extension: Observations and an Eddy-Resolving Model Hindcast, Journal of Climate, 20, 11, pp. 2357-2377._

VI. MANAGEMENT AND COST PLAN

V.1 Management plan

a) Management

Coordination will be supervised by T. Penduff at the French level, and coordination with the US partners will be done in strong interaction with W.K. Dewar (CHAOCEAN American OST-ST Project). The French partners (LEGI, LPO, SUC-CERFACS) will strongly interact together (note that TP and LT are co-advising GS's PhD thesis on CHAOCEAN themes). Interactions with the three European experts will be ensured by regular videoconferences and yearly visits of French scientists to NOCS, Imperial College and University of Utrecht. French and American partners will collaborate through regular video/phone conferences, and will meet every year during CHAOCEAN meetings ; these meetings will take place just before or after the OST-ST meetings. A 2k€/year support is requested to CNES in order to support the management/coordination/gathering costs.

b) Facilities and equipment

The European CHAOCEAN team requires:

- Computer resources. They will be requested to GENCI by LEGI as done routinely in the Drakkar context. Dedicated proposals will be submitted to run and store the CHAOCEAN NEMO simulations. Access to the Tier-0 CURIE supercomputer for CHAOCEAN NEMO simulations is also being considered in the context of PRACE.

- Data storage. NEMO outputs will be stored at GENCI computing centers. We will need additional storage that is accessible to all (French, European, American) CHAOCEAN partners: subsets of the NEMO database; selected HYCOM and MITgcm outputs for comparisons; real/synthetic collocated data from various instruments (including altimeter) and models; post-processed products (statistical modes, multivariate EOFs, etc), etc. 6k€/year are requested to CNES during 3 years to invest in this equipment (about 15 TB) which will be installed and operated at the OSUG computing center (Grenoble).

- small computer equipment (1 laptop + 1 workstation = 6k€) is also requested to CNES.

V.2 Cost plan

45.5k€/year on average are asked to CNES by the whole French CHAOCEAN team (4 research scientists, 2 research engineers, 1 postdoctoral researcher, 1 PhD student).

FRENCH CHAOCEAN TEAM	2013	2014	2015	2016
TOTAL (k€ per year)	46	46	45	45

- Support for NOCS Southampton, University of Utrecht, and Imperical College London is not accounted for, as it concerns non-French investigators.
- Six 4-day missions are asked each year in order to allow 6 of us to attend the CHAOCEAN meetings that will be organized just before of after yearly OST/ST meetings. These meetings take place in the USA and Europe alternately, hence the oscillating budget.
- Three 5-day missions (1k€/mission) per year are asked to CNES to support the trip and stay of 3 French scientists or students (LEGI, LPO or SUC) with our British and Dutch partners. This budget will be managed at LEGI-CNRS.
- Computing resources for French activities will be requested to GENCI and PRACE.

LEGI (k€ per year)	**2013**	**2014**	**2015**	**2016**
TRAVEL				
AGU or EGU meetings (2 pers. x 5d)	4	4	4	4
CHAOCEAN+OST/ST meetings (4 pers. x 4d)[1]	4	8	4	8
Visits to European experts (3 pers x 5d)[2]	3	3	3	3
MATERIALS				
Raid hard disks[3]	6	6	6	0
Computers[4]	6	0	0	0
Contribution to MEOM's functioning fees[5]	8	8	11	11
OTHER				
Publication fees	5	5	5	5
Grants for Master internships	2	2	2	2
Contribution to France/USA coordination[6]	2	2	2	2
TOTAL LEGI	40	38	37	35

[1] *takes place in the USA and in Europe alternately.*

[2] *may be used by LEGI, LPO or SUC as needed.*

[3] *NEMO runs + post-processing (LEGI) produce large outputs. We will invest in 6 TB/yr of storage*

[4] *one laptop for TP + one workstation for GS.*

[5] *Contribution to the maintenance by the MEOM team of their 80TB server + 25 workstations, to the team secretary, phone bills and office renting. The increase in 2015 corresponds to the whole MEOM team moving from LEGI to LGGE on the Grenoble campus around that date: this move will induce an increase in infrastructure costs and rental, for which we ask some support from CNES.*

[6] *expenses for CHAOCEAN meetings, coordination international phone calls, video-conferences, etc.*

LPO (k€ per year)	**2013**	**2014**	**2015**	**2016**
TRAVEL				
AGU or EGU meetings (5d)	2	0	2	0
CHAOCEAN+OST/ST meetings (4 pers. x 4d)[1]	1	2	1	2
Visits to Grenoble (5d)[2]	1	1	1	1
OTHER				
Publication fees	0	0	2	0
TOTAL LPO	4	3	6	3

SUC-CERFACS (k€ per year)	**2013**	**2014**	**2015**	**2016**
TRAVEL				
AGU or EGU meetings (5d)	0	2	0	2
CHAOCEAN+OST/ST meetings (4 pers. x 4d)[1]	1	2	1	2
Visits to Grenoble (5d)[2]	1	1	1	1
OTHER				
Publication fees	0	0	0	2
TOTAL SUC-CERFACS	2	5	2	7

VII. APPENDICES

VII.1 Profiles of French Investigators

• Thierry Penduff (PI on the French side)

42 years old. CR1 CNRS in the MEOM team, LEGI, Grenoble, since Oct 2001.

Education

1992 : Engineer in Aeronautics, ENSICA , Toulouse.
1994 : DEA in Physical Oceanography, LPO, Brest.
1998 : PhD in Physical Oceanography, LPO, Brest. *Dynamical study of the Northeastern Atlantic using a regional model*. Advisors : A. Colin de Verdière, X. Carton.

Research in Physical Oceanography

Physical processes (*weekly-to-multidecadal variability, intrinsic variability, turbulence/waves, atmospheric forcing, dynamics/thermodynamics, currents/water masses, topographic effects, air-sea fluxes, etc*). Numerical ocean modelling (*schemes, parameterizations, resolution impacts, open boundaries, forcing*). Joint uses of simulations, observations, reanalyses (*collocation/assessment metrics, model-model and model-observation comparisons, data assimilation*)

Visiting positions

Oct 1998-Sep 2000 (postdoc) : *MEOM team (data assimilation and ocean modelling)*
Oct 2000-Dec 2001 (postdoc) : *Center for Ocean-Atmospheric Prediction Studies, Tallahassee, FL*.
Aug 2008-Jul 2011 (visiting scientist) : *Dpt Oceanography, Florida State University, Tallahassee*.

Recent Students

2011-2013 : S. Gregorio (Postdoc) *: Low-frequency variability of the MOC*
2009-2011 : M. Juza (PhD) : *Ocean models and observations: development of interfaces, assessment of simulations and observing systems, dynamical investigations.*
2006-2009 : A. Lecointre (PhD) : *Interannual to decadal variability in the North Atlantic and the Nordic Seas: combined study of ocean observations, reanalyses and simulations.*
2004-2007 : G. Hervieux (PhD) : *Numerical study of current-topography interactions in ocean circulation models*

Scientific Projects

2003-present : Cofounder & member of the DRAKKAR Ocean Modelling group.
2005-present : Principal investigator of two OST-ST research projects (NASA/CNES)
Ex-member of LEFE-IDAO scientific committee

29 Rank A papers/book chapters. 5 most significant papers in the 5 last years

- Penduff, T., M. Juza, B. Barnier, J. Zika, W.K.Dewar, A.-M. Treguier, J.-M. Molines, and N. Audiffren, 2011: Sea-level expression of intrinsic and forced ocean variabilities at interannual time scales. J. Climate, 24, 5652–5670. doi: 10.1175/JCLI-D-11-00077.1.
- Dufour C, Le Sommer J, Penduff T, Barnier B, England MH, 2011: Structure and Causes of the Pulsation Mode in the Antarctic Circumpolar Current South of Australia. *J. Phys. Oceanogr.* 41, 253-268.
- Penduff, T., M. Juza, L. Brodeau, G.C. Smith, B. Barnier, J.-M. Molines, A.-M. Treguier and G. Madec, 2010 : Impact of global ocean model resolution on sea-level variability with emphasis on interannual time scales. Ocean Sci., 6, 269–284.
- Koch-Larrouy A., Morrow R., Penduff T. and Juza M., 2010: Origin and mechanism of Subantarctic Mode Water formation and transformation in the Southern Indian Ocean. Ocean Dyn., 60(3), 563-583.
- Lombard, A., Garric G., and Penduff T., 2009: Regional patterns of observed sea level change: In-sights from a 1/4° global ocean/sea-ice hindcast. Ocean Dynamics, 59, 433-449.

- **Bernard Barnier**

57 years old. DR1 CNRS in the MEOM team, LEGI, Grenoble. Bernard Barnier (PhD in Geophysical Fluid Dynamics from the Florida State University) is the Head of the MEOM Team. He is an expert in ocean modelling, air-sea fluxes and atmospheric forcing of ocean models. He is coordinating (with Dr. A-M Treguier from LPO) the international DRAKKAR consortium. He also coordinates (with Dr. N. Ferry from MERCATOR-Ocean) the GLORYS ocean reanalysis project and has a leading role in the reanalysis activities carried out in the European project MYOCEAN. Presently President Elect of the Ocean Sciences Division of EGU, B. Barnier is also member of various international scientific committees (e.g. the Global Synthesis and Observation Panel of CLIVAR, or the Working Group on Air-Sea Fluxes of WCRP).

>80 Rank A papers/book chapters. 5 most significant papers in the 5 last years:

- Barnier B., Penduff T., Langlais C., 2011: Eddying vs. laminar ocean circulation models and their applications. *Operational Oceanography in the 21st Century.* Schiller, Andreas; Brassington, Gary B. (Eds.)1st Edition., 2011, X, 450 p., ISBN: 978-94-007-0331-5.
- Venaille, A, J Le Sommer, JM Molines, B Barnier, 2011. Stochastic variability of oceanic flows above topography anomalies. *Geophys. Res. Lett.*, 38, L16611, 5PP., doi:10.1029/2011GL048401.
- Jourdain N, Mathiot P, Gallée H, Barnier B, 2011: Influence of coupling on atmosphere, sea ice and ocean regional models in the Ross Sea sector, Antarctica. *Clim. Dyn.*, DOI10.1007/s00382-010-0889-9.
- Mathiot, P., B. Barnier, H. Gallée, J.-M. Molines, J. Le Sommer, M. Juza, and T. Penduff, 2010: Introducing katabatic winds in global ERA40 fields to simulate their impact on the Southern Ocean and sea-ice. *Ocean Modelling*, 35, 146–160.
- Brodeau L., B. Barnier, T. Penduff, A-M. Treguier, S. Gulev, 2010: An ERA40 based atmospheric forcing for global ocean circulation models, *Ocean Modelling*, 31, 88-104.

- **Jean-Marc Molines**

55 years old. IR0 CNRS in the MEOM team, LEGI, Grenoble. Jean-Marc Molines, PhD in Fluid Mechanics form Univ. of Grenoble, is a CNRS Research Engineer specialized in high performance computing. Member of the NEMO developing committee, he is an expert in the development and implementation of ocean model configurations. He coordinates the technical activities of the international DRAKKAR consortium, which includes optimisation of model configurations on supercomputers (> 1000 procs), the development of ocean model configuration managers, simulation monitoring and diagnostic tools.

5 most relevant publications in the last 5 years:

- Treguier AM, Le Sommer J, Molines JM, de Cuevas B, 2010: Response of the Southern Ocean to the Southern Annular Mode: Interannual Variability and Multidecadal Trend. *J. Phys. Oceanogr* 40, 1659-1668.
- Laanaia N., Wirth A, Molines J.M., Barnier B., and Verron J., 2010: On the numerical resolution of the bottom layer in simulations of oceanic gravity currents. *Ocean Science*, 6, 563572.
- Melet A., Gourdeau L., Kessler S., Verron J. and Molines J.-M., 2010: Thermocline circulation in the Solomon Sea: a modeling study. *Journal of Physical Oceanography*, 40, 1302-1319.
- Girard L., Weiss J., Molines J.M., Barnier B. and Bouillon S. (2009): Evaluation of high-resolution sea ice models on the basis of statistical and scaling properties of Arctic sea ice drift and deformation. *J. Geophys Research*, 114, C08015, doi:10.1029/2008JC005182, 2009.
- Jouanno J., Sheinbaum J., Barnier B., Molines J.M., Debreu L. and Lemarié F., 2008: The mesoscale variability in the Caribbean Sea. Part I: simulations with an embedded model and characteristics. *Ocean Modelling,* 23, 82–101.

- **Laurent Terray**

51 years old. Senior scientist at CERFACS. Laurent Terray is active in the field of climate modeling for more than 15 years, working on ENSO, on the tropical Pacific Ocean, as well as on climate variability over the North Atlantic and Europe. He is also studying the detection and attribution of anthropogenic climate change and related impacts at global

to regional scales using innovative techniques to estimate forced and intrinsic variability. He has been pursuing modeling research activities on these themes within several ANR (ESCARSEL, CLIMATOR, SCAMPEI) and GICC(IMFREX, REXHYSS) projects and has(is) also been involved in many European projects (e.g. PREDICATE, ENSEMBLES and COMBINE). L. Terray is also a member of various scientific committees (e.g. current co-chair of the CLIVAR Atlantic Implementation Panel).

5 most significant papers in the 5 last years:

- Terray, L., Corre, L., Cravatte, S., Delcroix, T., Reverdin, G., and A. Ribes, 2012: Near-surface salinity as Nature's rain gauge to detect human influence on the tropical water cycle. J. Climate, in press
- Hoerling, M., J. Hurrell, A. Kumar, L. Terray, J. Eischeid, P. Pegion, T. Zhang, X. -W. Quan, and T. Y. Xu, 2011: On North American Decadal Climate for 2011-2020. J. Climate: Volume 24, Issue 16 (August 2011) pp. 4519-4528. doi: 10.1175/2011JCLI4137.1
- Corre L, Terray L, Balmaseda M, Ribes A, Weaver A (2011) Can oceanic reanalyses be used to assess recent anthropogenic changes and low-frequency internal variability of upper ocean temperature ? , Climate Dynamics, doi:10.1007/s00382-010-0950-8, on-line
- Minvielle M., C. Cassou, L. Terray, R. Bourdalle-Badie, 2011: A statistical-dynamical scheme for ocean downscaling in the Atlantic. Part II: Methodology, validation and application to high resolution ocean models. *Clim. Dyn.,* doi:10.1007/s00382-010-781-7, 3-4, 401-417
- Swingedouw D., Terray L., Cassou C., Voldoire A., Salas-Melia D. and Servonnat J., 2011: Natural forcing of climate during the last millennium: Fingerprint of solar variability. *Clim. Dyn*., doi:10.1007/s00382-010-0803-5, 7-8, 1349-1364

- **Thierry Huck**

42 yr old. Research scientist at CNRS, Laboratoire de Physique des Océans, Brest. Thierry Huck investigates the role of the ocean in climate variability, using a large range of numerical tools from idealized models (box, quasigeostrophic, shallow water) to realistic general circulation models (NEMO, HYCOM, ROMS), as well as dynamical system theory (tangent linear and adjoint models, stability analysis, optimal perturbations, ...). He has mostly contributed on the intrinsic variability of the ocean thermohaline circulation on multidecadal time scales, a mode possibly related to the Atlantic Multi-decadal Oscillation described in the observations. He has participated and leaded several projects of the CNRS/INSU PNEDC and LEFE, and Coriolis/Mercator GMMC programs over the last 12 years.

5 most significant papers in the last 5 years:

- Arzel, O., M. H. England, A. Colin de Verdière, T. Huck, 2011: Abrupt millennial variability and interdecadal-interstadial oscillations in a global coupled model: sensitivity to the background climate state. Climate Dynamics, in press, DOI: 10.1007/s00382-011-1117-y.
- Lherminier, P., H. Mercier, T. Huck, C. Gourcuff, F. F. Perez, P. Morin, A. Sarafanov, A. Falina, 2010: The Atlantic Meridional Overturning Circulation and the Subpolar Gyre observed at the A25-OVIDE Section in June 2002 and 2004. Deep-Sea Research I, 57, (11) 1374-1391, doi:10.1016/j.dsr.2010.07.009.
- Sévellec, F., T. Huck, M. Ben Jelloul, and J. Vialard, 2009: Non-normal multidecadal response of the thermohaline circulation induced by optimal surface salinity perturbations. Journal of Physical Oceanography, 39, 4, 852-872.
- Huck, T., A. Colin de Verdière, P. Estrade, and R. Schopp, 2008: Low-frequency variations of the large-scale ocean circulation and heat transport in the North Atlantic from 1955-1998 in-situ temperature and salinity data. Geophysical Research Letter, 35, L23613, doi:10.1029/2008GL035635.
- Sévellec, F., T. Huck, M. Ben Jelloul, N. Grima, J. Vialard, and A. Weaver, 2008: Optimal surface salinity perturbations of the meridional overturning and heat transport in a global ocean general circulation model. Journal of Physical Oceanography, 38, 2739-2754.

VII.2 Profiles of the European experts associated to CHAOCEAN

• Pavel Berloff

44 years old. Professor (Reader) in Applied Mathematics at the Imperial College London, Department of Mathematics and the Grantham Institute for Climate Change, UK. I am a physical theoretician and applied mathematical modeller, with main research interests in *Ocean and Climate Dynamics*, *Geophysical Fluid Dynamics*, and *Turbulence*. My research focuses on understanding fundamental physical processes in the ocean, particularly those that involve ocean turbulence and impact climate. I have developed an extensive network of collaborators involving leading scientists from a range of countries, including the USA, UK, Australia, Russia, and Ukraine. In recognition of these efforts, I have been awarded 13 competitive research grants over the last 10 years. I have published more than 30 papers in highly-rated journals. The list of my recent publications can be found on my webpage http://www2.imperial.ac.uk/˜pberloff. I review articles for 18 high-impact journals and participate in various panels of experts at National Science Foundation (USA), Natural Environment Research Council (UK), etc.

5 most significant papers in the last 5 years (related to the topic):

- Berloff, P., A. Hogg, and W. Dewar, 2007: The turbulent oscillator: A mechanism of low-frequency variability of the wind-driven ocean gyres. J. Phys. Oceanogr., 37, 2363–2386.
- Kamenkovich, I., P. Berloff, and J. Pedlosky, 2009: Role of eddy forcing in the dynamics of multiple zonal jets in the North Atlantic. J. Phys. Oceanogr., 39, 1361-1379.
- Hogg, A., W. Dewar, P. Berloff, S. Kravtsov, and D. Hutchinson, 2009: The effects of mesoscale ocean-atmosphere coupling on the large-scale ocean circulation. J. Climate, 22, 4066--4082.
- Karabasov, S., P. Berloff, and V. Goloviznin, 2009: CABARET in the ocean gyres. Ocean Modelling, 30, 155--168.
- Marshall, D., J. Maddison, and P. Berloff, 2012: A framework for parameterizing eddy potential vorticity fluxes. J. Phys. Oceanogr., in press.

• Henk Dijkstra

51 year old. Professor of Dynamical Oceanography at Utrecht University, the Netherlands. My main line research is on theory development for phenomena of ocean-climate variability within a complex (dynamical) systems framework. The main contribution of my group over the past decade has been the development and application of novel numerical techniques to analyse the behaviour of large-dimensional (stochastic) dynamical systems, such as those derived from ocean-climate general circulation models. Apart from this main line of research, I have been, and still am, involved in projects on palaeoclimate modeling using state-of-the-art climate models, phytoplankton dynamics, mathematical theory of stochastic dynamical systems vegetation dynamics, distributed (super)computing and ocean upper-layer turbulence (observations and theory). In 2005, I received the Lewis Fry Richardson medal from the Division Nonlinear Processes in Geophysics of the European Geophysical Society (EGU) for “his outstanding work in developin the nonlinear dynamical systems approach to oceanography and especially for his study of the role of ocea circulation in palaeoclimate” I have been member/chairperson of several international committees and boards. Currently, I am president of the Division on Nonlinear Processes in Geophysics of the EGU (and EGU Council member and member of the Program Advisory Group of the UK-RAPID program.

5 most significant papers in the last 5 years (related to the topic):

- Frankcombe, L. M., Dijkstra, H. A. and von der Heydt, A. S., Subsurface signatures of the Atlantic Multidecadal Oscillation, Geophysical Research Letters, 35, L19602, doi:10.1029/2008GL034989, (2008).
- Frankcombe, L. M., Dijkstra, H. A. and von der Heydt, A. S., Noise-induced multidecadal variability in the North Atlantic: Excitation of normal modes. J. Physical Oceanography, 39(1), 220-233, (2009).

- Frankcombe, L. M., von der Heydt, A. S. and Dijkstra, H. A., North Atlantic Multidecadal Climate Variability: An investigation of dominant time scales and processes, J. Climate, 23, 3626–3638, (2010).
- Frankcombe, L. M. and Dijkstra, H. A., Internal modes of multidecadal variability in the Arctic Ocean, J. Physical Oceanography, 40, 2496–2510, (2010).
- Frankcombe, L. M. and Dijkstra, H. A., The Role of Atlantic-Arctic Exchange in North Atlantic Multidecadal Climate Variability, Geophysical Research Letters, 38, L16603, doi:10.1029/2011GL048158, (2011).

• Joel Hirschi

42 years old. Senior Research Fellow, National Oceanography Centre, Southampton, UK, since 2004. He is head of the high resolution ocean modelling subgroup at NOCS. Since 1999 he has been working on the North Atlantic dynamics and connection with the overlying atmosphere at eddy-to-basin and subdaily-to-centennial scales using analytical, numerical and observational approaches. He is an active member of the RAPID project and has contributed to design monitoring techniques of the MOC from in-situ instruments (his model-based work was central to the successful proposal for the pre-operational RAPID array deployed in March 2004), altimeter-based indicators of the MOC variability, its underlying processes in the presence of mesoscale eddies, and on the contribution of the intrinsic variability and the atmospheric forcing in the observed MOC variability.

5 most significant papers in the last 5 years (related to the topic):

- Cunningham S.A., Kanzow T., Rayner D., Baringer M.O., Johns W.E., Marotzke J., Longworth H.R., Grant E.M., Hirschi J.J.-M., Beal L.M., Meinen C.S., Bryden H.L., 2007. Temporal variability of the Atlantic Meridional Overturning Circulation at 26°N. Science, 317, 935-938, doi:10.1126/science.1141304.
- Kanzow T., H. Johnson, D. Marshall, S.A. Cunningham, J.J.-M. Hirschi, A. Mujahid, H.L. Bryden, W.E. Johns, 2009: Basin-wide integrated volume transports in an eddy-filled ocean. J. Phys. Oceanogr., 39, 3091-3110.
- Hirschi J. J.-M., P.D. Killworth, J.R. Blundell, 2009: Sea surface height signals as indicators for oceanic meridional mass transports. Journal of Physical Oceanography, 39, 581-601.
- Lucas, M., J.J.-M. Hirschi, J. Marotzke, 2010: Response of the meridional overturning circulation to variable buoyancy forcing in a double hemisphere basin Climate Dynamics, 34, 615-627
- Blaker, A., Hirschi, J J.-M., Sinha B., de Cuevas B, Alderson, S., Coward A., Madec G. 2012 Large near-inertial osciallations of the Atlantic meridional overturning circulation, Ocean Modelling, 42, 50-56
- Hirschi, J., A. Blaker, B. Sinha, A. Coward, B. de Cuevas, S. Alderson and G. Madec, 2012, Forced and internal variability of the meridional overturning circulation on subannual to interannual timescales, to be submitted.

VII.3 Proposals submitted by the 3 European experts associated to CHAOCEAN

• ***"Turbulent Oscillator: intrinsic eddy-driven decadal variability of the Ocean"*** submitted to NERC. **PI : P. Berloff** (Imperial College London, UK)

The main goal of this Project is to reach new level of fundamental understanding of the large-scale low-frequency variability of the midlatitude ocean. The main motivation comes from the observational studies showing that the North Atlantic and North Pacific possess basin-scale variability on the interannual-to-interdecadal timescales. The main result of this Project will be theory that explains intrinsic mechanisms of the large-scale low-frequency variability in midlatitude ocean, as well as the roles played by transient mesoscale eddies in these mechanisms. The main practical applications of the proposed fundamental research will be in terms of: (a) guiding comprehensive, oceanic general circulation models towards better representation of the key physical processes and (b) guiding observational programs towards more optimal measurement strategies for direct assessment of the eddy processes influencing and driving the large-scale low-frequency variability.

We put forward the central hypothesis that significant fraction of the observed oceanic variability is intrinsic, that is, driven by the intrinsic dynamics of the ocean rather than by variations of the external forcings. Some of this variability is likely to be explained in terms of the transient linear modes of the climatological mean circulation, but most of it — and this is our second hypothesis — is likely to be driven and controlled by the transient mesoscale eddies that constitute synoptic variability of the ocean and strongly interact with the large-scale circulation. The broader impact is in terms of understanding the global climate variability, with the ultimate goal of acheiving more accurate predictions of the global climate change. The broader context is that the underlying nonlinear mechanisms are likely to be pertinent to other parts of the global ocean.

- ***“Multidecadal Variability in a Strongly Eddying Atlantic Ocean”*** submitted to the Dutch Science Foundation (NWO). **PI : H. A. Dijkstra** (Utrecht University, The Netherlands)

The Atlantic Multidecadal Oscillation (AMO) is a dominant pattern of climate variability with a time scale of 20-70 years. This variability has an impact on precipitation over the continental USA and on Summer temperatures in Europe. In addition as it is an important mode of natural climate variability, it plays a role in the discussion on human induced climate change. In this project we build on earlier work with idealized models in which the AMO is viewed as an instability of the Atlantic Ocean circulation through a normal mode, a so-called thermal Rossby mode. Using a high-resolution strongly eddying ocean model, we aim to study the mechanism of multidecadal variability in the presence of the effects of meso-scale eddies. Our aim is to investigate whether 20-30 year variability can be found in such a model and if so, whether the origin of this variability is related to the thermal Rossby mode mechanism.

- ***“MESO-CLIP”*** submitted to NERC. **PI : J. Hirschi** (NOCS, UK)

The goal of MESO-CLIP is to study how mesoscale ocean eddies affect climate predictability using high resolution models. Mesoscale ocean eddies (MOEs) are ubiquitous in the world ocean. They play a crucial role in the transport and mixing of heat and fresh water, and their momentum transfer steers current systems such as the Gulf Stream. However, it is largely unknown how MOEs impact the predictability of the climate system. The latest generation of coupled climate models increasingly uses eddy-permitting (and soon eddy-resolving) ocean components and is therefore computationally very expensive. MESO-CLIP will use a combination of three models to explore strategies to efficiently perturb initial conditions in eddy-permitting/resolving models and assess the forecast uncertainty due to MOEs on submonthly to decadal timescales. MESO-CLIP will thus determine the potential impact MOEs could have on the predictability of ocean and atmosphere in present and future climate models.

VII.4 Letters of Support

Brest, April 9 2012

Dr T. Penduff, LEGI, BP 53

Grenoble 38041, cedex 9

Dear Thierry,

I have read with great interest the CHAOCEAN OST-ST proposal. The question of the origin of the decadal variability in the ocean is central in climate issues since the atmosphere by itself has difficulties to generate such low frequencies. As the proposal points out, there are at least two possible ocean related origins, (i) large scale instabilities favored under certain coupling conditions such as flux boundary conditions, (ii) rectifications of the powerful mesoscale eddy motions. These two sources have not been studied together and yet their interactions are crucial to climate predictions.

This proposal aims at remedy this gap in our knowledge, a study made possible by a combination of skills, numerical modelers, dynamical systems specialists, observational scientists and by a combinations of methods. It is indeed becoming increasingly possible to integrate eddy resolving models on the long time scales necessary to find out the origins of multidecadal variability. At the same time satellite products are beginning to be able to tackle such long time scales (22 years since the launching of Topex-Poseidon). In situ oceanic products such as the Rapid Array and the float ARGO program also become products aimed at the longer periods.

This joint effort at a considerable problem has adopted a good scientific strategy and I am sure that the quality of the team involved is a guarantee to obtain strong results. I support very warmly this piece of research to the CNES selection committee.

Alain

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01 April 2012

Dr Thierry Penduff

Dear Thierry,

I strongly support your proposal CHAOCEAN project, and I look forward to contribute to it through the proposed collaboration. As you know, I have been working on the dynamics of intrinsic, eddy-induced low-frequency variability in the ocean gyres for many years. Understanding phenomenology and mechanisms of this variability is one of the most important and challenging problems in the ocean and climate sciences. Your project is a great and a timely opportunity to tackle this problem in the context of observations and comprehensive general circulation models. My own research agenda – basic process studies and theory – compliments yours very nicely, and, thus, provides the natural basis for collaboration.

Sincerely,

P. Berloff

Pavel Berloff

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Utrecht, 31/03/2012

Dr. T. Penduff
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Dear Thierry,

This letter is to show strong support for your proposed Chaocean project. The low-frequency intrinsic variability of the oceans is an important example to test theories of climate variability. My particular interest in the project is the origin of the large-scale patterns of internal variability, in particular on multidecadal time scales, and whether they can be related to normal modes of the time-mean flow.

This work fits very well into the research efforts of my group at IMAU and I will be happy to collaborate with you in this project. I have submitted a related proposal for long-term high-resolution ocean model (POP, 0.1^0) simulations to the Dutch Science Foundation (NWO) and will hear about funding of this proposal by May 1.

Henk

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Thursday, March 29, 2012

Dear Thierry,

It is a pleasure for me to provide a letter of support for CHAOCEAN. This is an exciting project which covers a range of topics that are central to the research we do at NOC. CHAOCEAN will enable a lively exchange of ideas with other institutions across Europe and in the US. Our research group at NOC specialises in the development and running of high resolution models and currently we are running a global 1/12° model (NEMO in the ORCA configuration). The output from the simulations performed at NOC will be available to CHAOCEAN.

The meetings and visits that the project will enable will allow us to get a better understanding of the nature of the variability that such a model can simulate (also in comparison to HYCOM which is run at the same horizontal resolution but which has different vertical coordinates). We are currently assessing the importance of chaotic (internal or intrinsic) variability in the oceans and in the climate system. Of particular interest for us is to understand what fraction of the variability in major ocean currents such as western boundary currents or the meridional overturning circulation (MOC) is directly attributable to variability in the atmospheric forcing or to processes such as mesoscale ocean eddies and internal waves. This clearly fits with one of the main goals of CHAOCEAN which is to gain a better insight into the in chaotic (intrinsic) ocean variability.

Little is currently known about how big the imprint the chaotic ocean variability is on ocean observations. An example are the RAPID observations from 26.5°N in the Atlantic which are led by NOC. The first 7 years of MOC observations show a large sub- to interannual variability – even for components that are not necessarily highly correlated with the atmospheric forcing (geostrophic variability, Gulf Stream). In order to understand the observed MOC variability we need to know how much of this variability is likely to be chaotic. The current observations do not allow us to address this question. However, the ocean simulations that will be used within CHAOCEAN (e.g. runs with different initial conditions) will provide useful estimates of what the chaotic MOC variability is likely to be.

In summary, I think that you have brought together strong partners to address highly relevant questions in oceanography. I very much look forward to our collaboration in the framework of CHAOCEAN.

Regards,

Joël Hirschi