

Case for support part 1: Previous track record

MESoscale Ocean eddies and Climate Predictions (MESO-CLIP)

NOC personnel: Dr Joël Hirschi (Principal Investigator), Dr Chris Wilson, Dr Bablu Sinha, Dr Adam Blaker (researcher), University of Southampton personnel: Dr Florian Sévellec (PI, UoS), Project partners: Dr John Siddorn (UK Met Office), Dr Andy Hogg (Australian National University), Drs Bernard Barnier and Thierry Penduff (LEGI Grenoble, France).

We believe that the team of investigators possess all the necessary skills, expertise and tools to successfully address the research proposed in MESO-CLIP. The problem being addressed requires expertise in high resolution modelling and in the definition of optimal perturbations to the ocean. We have assembled a team of experts who are very experienced in the running and development of ocean models as well as in the analysis of their outputs using novel techniques. The **National Oceanography Centre (NOC)** with its two locations in Southampton and Liverpool, is one of the world's leading marine research institutes, covering ocean circulation and climate, hydrography, air-sea interaction, remote sensing and both ocean-only and coupled ocean-atmosphere modelling. NOC is the national focus for oceanography in the UK with a remit to achieve scientific excellence in its own right as one of the world's top five oceanographic research institutions. NOC activities encompass major ocean technology development, longterm observations, managing international science programmes. Of particular relevance to MESO-CLIP, NOC has a long experience in the development and running of high resolution ocean models. This knowhow which was initially acquired during the development of the OCCAM model now contributes to the development and improvement of the NEMO (Nucleus for European Modelling of the Ocean) model, which is now used in many European research centres and in operational oceanography and which forms the ocean component of the latest UK coupled climate models HadGEM3-H which is developed in a joint effort between NERC centres and the UK Met Office. NOC has its own supercomputing facilities needed for model development runs and has also access to national supercomputing centres. The department of Ocean and Earth Science (OES) at **University of Southampton (UoS)** had 70% of its research rated as "world class or internationally excellent" in the Research Assessment Exercise of 2008. In both quality and volume of research, OES ranked third nationally among Earth and Environment departments. Staff and students in the new Physical Oceanography research group of OES are at the forefront in using world-class models and novel observations for fundamental research.

Dr Joël Hirschi (Principal Investigator), is an experienced numerical modeller who has worked with a hierarchy of numerical models ranging from simple box-models to eddying ocean general circulation models. He has 32 peer-reviewed publications and is in charge of the high resolution ocean modelling subgroup at NOC. His main research interests are the variability and monitoring of the meridional overturning circulation (MOC) and the underlying theory. His work based on numerical ocean models was central to the successful proposal for the pre-operational RAPID MOC monitoring system deployed in March 2004. He currently uses NEMO to study the "chaotic" (i.e. initial condition dependent) variability in the meridional overturning circulation and other ocean currents. He is also interested in atmospheric processes such as large-scale atmospheric circulation and teleconnection patterns linked to the occurrence of particularly warm or cold seasons. He is the lead supervisor of 2 PhD students working on atmospheric teleconnections and on the imprints of oceanic heat divergence on the atmosphere and co-supervises 3 three further PhD students. He is PI of the NOC contribution to VALOR and Co-I on MONACO (both RAPID-WATCH projects).

Dr Florian Sévellec (Co-PI), is a lecturer in physical Oceanography at the University of Southampton. He is an ocean and climate scientist with a growing reputation for research of high quality and impact. He has 8 peer reviewed publications and has presented his work at EGU as "solicited" speaker 5 times over the last 4 years. Prior to his appointment at the University of Southampton, he worked in three other world leading institutions (Laboratoire de Physique des Océans, Brest, France; LOCEAN-IPSL, Paris, France; Yale University, USA). During that time he has built strong international collaborations. His research interests focus on the stability, variability, and predictability of the large-scale ocean circulation, in particular the Atlantic meridional overturning circulation (AMOC). In this context he has developed a method to obtain optimal perturbations of the AMOC in Ocean GCMs at a cheap numerical cost (only twice the numerical cost of a Ocean GCM time integration).

Dr. Sévellec has a thorough and rare expertise in generalised stability analyses and other fields of applied mathematics and computational sciences critical for the success of this project.

Dr Bablu Sinha (Co-Investigator), is a highly experienced scientist, and a specialist in geophysical fluid dynamics and climate science. He has 35 published papers and is Leader of the Climate and Uncertainty subgroup at NOC, in charge of a team of 7 scientists. Relevant to this proposal, two of the main foci of his research career so far have been climate predictability, and the characteristics of oceanic eddies and their influence on mean ocean circulation. He has conducted research into the predictability of ENSO, the North Atlantic Oscillation and the Atlantic Thermohaline Circulation and has worked on mechanisms of predictability such as propagation of sea-surface anomalies and interannual timescale Rossby wave propagation in models and observations. He is currently supervising a student investigating the causes of decadal climate variability and predictability in a variety of climate models. Dr Sinha is involved with running and assessing the ocean component of the HadGEM3 climate model as part of the Met Office INTEGRATE Project under the JWCRP (a joint Met Office-NERC initiative) in particular investigating the effects of SST seasonal cycle biases on the atmospheric storm tracks. and is also a Co-I on the RAPID-WATCH VALOR Project which investigates the impact of assimilating ocean observations on seasonal to decadal climate prediction.

Dr Chris Wilson (Co-Investigator), is a Physical Oceanographer in the Marine Physics and Ocean Climate Group at the NERC National Oceanography Centre (Liverpool). His expertise in mesoscale ocean dynamics and coupled ocean-atmosphere modelling has been developed through previous positions at the Centre for Global Atmospheric Modelling, University of Reading, and at the Department of Earth and Ocean Sciences, University of Liverpool. His recent NERC New Investigator Award has allowed extensive study of the mesoscale dynamics of transport and mixing barriers within the Antarctic Circumpolar Current and their role in climate. This includes several ensemble experiments with the eddy-resolving Q-GCM model on the NOC (Liverpool) cluster and, notably, through optimal combination with two other climate models (Ocean Model for the Earth Simulator and Southern Ocean State Estimate) makes use of the unique insight from the idealised Q-GCM in a powerful and relevant way. This established approach is therefore relevant to this proposed project.

Dr Adam Blaker (researcher), is an ocean and climate modeller in the Marine Systems Modelling group at the NERC National Oceanography Centre, and is based in Southampton. He has 9 years experience running ocean and coupled climate models and has for the past 6 years been conducting post-doctoral research at the NOC and the University of Southampton. His recent work includes running and analysing the NEMO ORCA025 ocean model for the RAPID-VALOR project, with a recent publication which describes how near inertial gravity waves influence the Atlantic meridional overturning circulation, and research into methods to quantify uncertainty in climate model projections within the RAPID-RAPIT project in collaboration with statisticians at Durham University and climate researchers at the UK Met Office and the University of Reading.

National and international project partners Our collaboration with the UK-MetOffice (**Dr John Siodorn**) brings in a vast experience in coupled modelling and forecasting. The MetOffice are leading the development of HadGEM3-H, the most advanced coupled climate model in the UK which will be used in MESO-CLIP. The collaboration with the Metoffice is well established in the framework of the Joint Weather and Climate Research Programme (JWCRP) and the Joint Ocean Modelling Programme (JOMP) which are currently ongoing. The research group at LEGI, Grenoble (**Drs Bernard Barnier and Thierry Penduff**) is working on questions that are highly relevant to MESO-CLIP and vice-versa (NEMO ensembles, intrinsic ocean variability) and our respective approaches will complement each other. LEGI are experts in the running and analysis of NEMO at high (eddy-permitting and eddy-resolving) resolutions. NOC, LEGI and the UK MetOffice all use NEMO in their simulations and all are part of the international DRAKKAR consortium that brings together an international community of NEMO users and developers. **Dr Andy Hogg** from the Australian National University is an expert on the impact of ocean mesoscale eddies on climate variability who has worked extensively with Q-GCM (of which he is the primary custodian). His work based on Q-GCM does suggest a possible imprint of eddies on decadal variability.

Part 2, proposed research: MESoscale Ocean eddies and Climate Predictions (MESO-CLIP)

Summary 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 these highly non-linear MOEs impact the predictability of the climate system. The latest generation of coupled climate models increasingly have eddy-permitting (and soon eddy-resolving) ocean components and there is a need to better understand how much uncertainty MOEs add to forecasts. MESO-CLIP will use eddy-permitting/resolving models to explore how to optimally perturb eddy-permitting/resolving models, and will assess the impact of MOEs on the predictability/variability of ocean and atmosphere on submonthly to decadal timescales.

1 Background and Motivation

Many aspects of the ocean circulation can readily be explained and predicted from the atmospheric forcing (winds, air-sea fluxes). Examples are the positions of ocean gyres with their intensified western boundary currents, or seasonally varying currents e.g. in the equatorial regions or driven by seasonal up- and downwelling along continental coastlines. In addition to the ocean circulation directly attributable to atmospheric forcing there is a less understood and less studied ocean variability that depends on the ocean state (i.e. temperature, salinity and velocity distribution) rather than on direct atmospheric forcing (Penduff *et al.*, 2011, Hirschi *et al.*, 2012). Important and well observed manifestations of such non-linear ocean variability are MOEs which are the ocean equivalent of weather systems in the atmosphere (Williams *et al.*, 2007). MOEs are generated through the same instability mechanisms and play a similar role to weather systems in the transport and mixing of fluid properties, including momentum, heat and freshwater (Jayne and Marotzke, 2002). MOEs have typical scales of ~ 10 to 100 km and days to months compared with ~ 1000 km and hours to days for atmospheric weather. As with high and low pressure systems in the atmosphere the time and location of formation of MOEs depends on initial conditions and their observational uncertainty. In eddying ocean models even a small perturbation in the initial ocean conditions (temperature, salinity, velocities) will eventually lead to a different mesoscale eddy field. As with weather systems, we cannot predict the mesoscale eddy field a long time in advance, even though the areas where MOEs tend to develop (e.g. along the Antarctic Circumpolar Current, in the Agulhas retroflexion region, extensions of the Kuroshio and Gulf Stream) are well known. The dependence of MOEs on initial conditions is illustrated for the North Atlantic in Fig. 1. The longer life times and slower propagation of MOEs compared

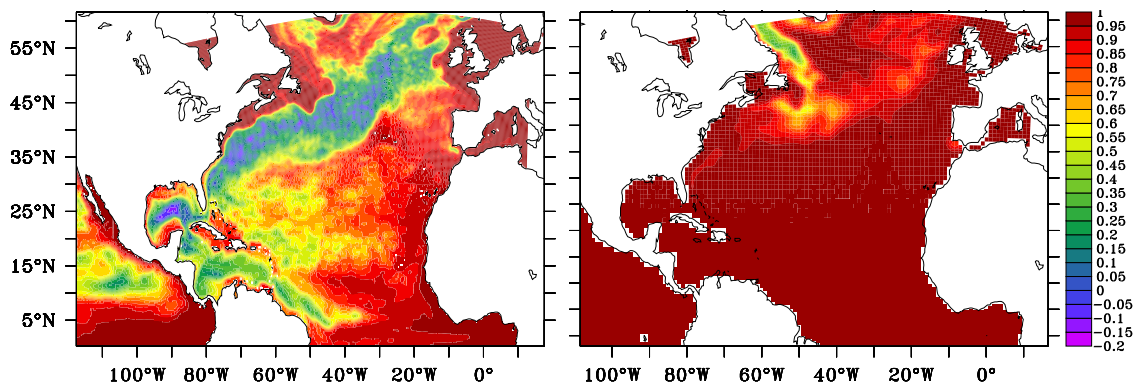


Figure 1: Correlation of sea surface height variability (5-day averages for 1976-2001 period) between twin ocean simulations using the same surface forcing but different initial conditions (Hirschi *et al.*, 2012). **Left:** Eddy-permitting model (NEMO 1/4°). **Right:** non-eddying model (NEMO 1°). In the eddy-permitting model low correlations are found where eddy-activity is high, whereas much higher correlations are found in the coarser resolution model.

with their atmospheric counterparts mean, that despite the decorrelation shown in Fig. 1 (left), there is potential predictability. In some cases MOEs have been shown to have lifetimes of more than one year (Morrow *et al.*, 2004). However, their precise trajectories are difficult to predict. Operational oceanography centres routinely provide weekly ocean forecasts (e.g. MERCATOR (www.mercator-ocean.fr), HYCOM (www.hycom.org/ocean-prediction)). However, on longer timescales (monthly and

longer) the details of the MOE field becomes largely unpredictable. MOEs can also interact with topography (e.g. when they approach a continental margin triggering internal waves (Holloway, 1987, Oey and Lee, 2002) associated with mixing. MOEs also influence the large scale flow (e.g. Marshall, 1984, Stammer, 1998, Hughes and Ash, 2001, Qiu and Chen, 2010). This means that they cannot be ignored; driving us to higher resolution (and more expensive) models.

To date most studies into the predictability of ocean currents such as the meridional overturning circulation (MOC) and of climate in general are based on coarse resolution ocean models where MOEs are not resolved (e.g. Collins and Sinha, 2003, Collins *et al.*, 2006, Hawkins and Sutton, 2009, Zanna *et al.*, 2011, Smith *et al.*, 2007). However, MOEs are ubiquitous, and this raises the question of how much they affect the variability of the ocean circulation and how this will feed back onto the atmosphere. Previous work shows that the presence of MOEs can affect the atmospheric (e.g. Hogg *et al.*, 2006) and oceanic (e.g. Biastoch *et al.*, 2008, Penduff *et al.*, 2011) variability on interannual to decadal timescales - i.e. a time scale that is much longer than the lifetime of MOEs.

The latest generation of coupled climate models currently under development use eddy-permitting ocean components. Examples are HiGEM (Shaffrey *et al.*, 2009), the UK Met Office HadGEM3-H model (Hewitt *et al.*, 2010) or the GFDL CM2.5/CM2.6 models (Delworth *et al.*, 2012). Because of the requirement to explicitly model the eddy field these codes are very expensive, precluding long runs or large ensembles. Currently, little is known about the impact MOEs have on the uncertainty in climate prediction and more work is required if we want to make best use of high resolution models.

2 Objectives

The overarching goal of MESO-CLIP is to assess the influence of MOEs on climate predictions on submonthly to decadal timescales and we will use numerical models to address the following key questions: **(Q1)** How do we optimally perturb ocean models containing MOEs? **(Q2)** How do MOEs affect the predictability of the ocean and of the coupled ocean-atmosphere system? **(Q3)** How large is the imprint of MOEs on the oceanic, atmospheric and coupled ocean-atmosphere variability? **(Q4)** What are the dominant timescales of variability affected by MOEs?

3 Methodology

To answer Q1-Q4 we will use a hierarchy of numerical models: the Nucleus for European Modelling of the Ocean (**NEMO**, Madec, 2008, www.nemo-ocean.eu), the high resolution version of the Hadley Centre Global Environment Model version 3 (**HadGEM3-H**, Hewitt *et al.*, 2010, and the Quasi Geostrophic Coupled Model (**Q-GCM**, Hogg *et al.*, 2003, www.q-gcm.org). We will use the **Generalised Stability Analysis (GSA)** to obtain optimal perturbations for these models.

3.1 Models

NEMO is a primitive equation ocean model and is developed in a collaborative effort between research centers in France (CNRS, OCEAN-IPSL, MERCATOR-Ocean) the UK (NOC, MetOffice) and Italy (Bologna). In NEMO the three-dimensional ocean circulation as well as MOEs can be simulated. In MESO-CLIP we will produce a new set of experiments based on a $1/4^\circ$ version of the model (see Table 1). In addition we will use output from an eddy-resolving ($1/12^\circ$) global ocean simulation (Marzocchi *et al.*, 2012) obtained in the framework of the DRAKKAR project (<http://www-meom.hmg.inpg.fr/Web/Projets/DRAKKAR>). All the NEMO simulations use the ORCA tripolar grid (Madec and Imbard, 1996) and the number of levels is 75. Hereafter, NEMO at resolutions of $1/4^\circ$ and $1/12^\circ$ will be referred to as ORCA025 and ORCA12, respectively.

HadGEM3-H is the latest coupled ocean-atmosphere model currently under development at the UK MetOffice. The ocean component consists of ORCA025 with 75 vertical levels. The atmospheric component HadGAM3 has a horizontal resolution of 0.556° of latitude by 0.833° longitude and 38 vertical levels. With HadGEM3-H we will be able to study interactions between an eddying ocean and the atmosphere (and vice-versa) and to identify possible feedback mechanisms. HadGEM3-H is computationally very expensive and will therefore only be used for short (5-year) runs.

Q-GCM is a quasi-geostrophic model set up to run in idealised configurations (ocean basin, circum-polar channel), and we will run the model with three ocean and three atmosphere layers. Three ocean layers are sufficient to produce good spontaneous MOE generation. Q-GCM is computationally efficient and will allow us to study multidecadal timescales which would be computationally too demanding with NEMO and HadGEM3-H. Q-GCM can represent ocean transports such as an ide-

alised Antarctic Circumpolar Current (ACC) or ocean gyres with their intensified transports at the western boundaries. Q-GCM is a coupled model and we will be able to study interactions between an eddying ocean and the atmosphere (and vice versa). Q-GCM will be set up in a double gyre basin configuration at a resolution resolution of 5 km in the ocean and 80 km in the atmosphere.

3.2 Generalised Stability Analysis (GSA)

Over recent decades GSA has provided new tools for understanding stability and perturbation growth in geophysical fluid dynamics (e.g. Farrell and Ioannou, 1996a, b). Optimal perturbations obtained with GSA are relevant in the context of predictability (Palmer, 1999) and are widely used for ensemble prediction in weather forecasting (Leutbacher, 2005; Magnusson *et al.*, 2005). For the ocean circulation, GSA has been used in a number of applications ranging from mesoscale eddies to the El Niño-Southern Oscillation (ENSO) and the thermohaline circulation (Moore *et al.*, 2003; Tziperman and Ioannou, 2002). Unlike the classical stability analysis that treats asymptotic stability, GSA considers perturbation growth over a finite time and allows for a transient growth in the system. Consequently, this method can consider the sensitivity of climate dynamics on different time scales. However, very few groups in the oceanographic community have so far used this method in realistic settings and only few tangent linear and adjoint general circulation models, originally developed for data assimilation, are available. Ocean perturbations can be confined to the ocean surface, a particular region, or be spatially unconstrained and they can cover one or several dynamically important fields (e.g. temperature or salinity). The optimality is defined with respect to, and will depend on, the chosen measure for the system.

In MESO-CLIP we will use a generalisation of the more classical singular vector analysis (Lorenz, 1965; Farrell and Ioannou, 1996a, b) which originally uses a quadratic norm as the optimization measure (e.g. the Euclidean norm). We can also use linear measures which have the advantage that we can obtain explicit solutions that can be related to actual physical variables. An example of a linear measure that will be used in MESO-CLIP is the divergence of the spatial correlation of sea surface height between two simulations. However, given the linear framework of GSA, even quadratic physical variables (e.g. kinetic energy) are related to first order to linear measures of the system, and only to second order to quadratic measures. This means that even for quadratic variables, we can obtain explicit solutions for both the shape and the amplitude of the perturbations (Sévellec and Fedorov, 2012). GSA also has the advantage of being computationally cheaper than the classical singular vector analysis (Sévellec *et al.*, 2007), and allows us to compute optimal perturbations in ocean GCMs in a realistic setting. To obtain optimal perturbations we will apply a maximisation method using Lagrangian multipliers. This method is extremely general and allows us to maximise any chosen measure. Using the Lagrangian approach, we can also use any additional constraint during the optimization procedure. Further details of the method are described in Sévellec and Fedorov (2010 and 2012).

4 Proposed work

MESO-CLIP consists of three workpackages (WPs) addressing questions Q1-Q4:

WP1: Optimal perturbations in eddying models (Q1)

WP2: Impact of mesoscale ocean eddies on climate predictability (Q2, Q4)

WP3: Quantifying the imprint of mesoscale ocean variability on the ocean and atmosphere circulation (Q3, Q4)

WP1 is concerned with generating perturbations of initial conditions optimised to cause a rapid decorrelation of the MOE field (Q1). Perturbations will be obtained using the global sensitivity analysis (GSA). This technique is available in NEMO and will be applied in Q-GCM. The perturbations from WP1 will be the basis for the simulations proposed in WP2.

In WP2 we will investigate on what timescales and through which mechanisms model trajectories diverge after the application of optimal perturbations. To achieve this goal we propose a new set of ensemble simulations with ORCA025, HadGEM3-H and Q-GCM. The work under WP2 will address Q2 and will contribute to answering Q4.

WP3 will quantify the ocean and atmosphere variability triggered by perturbations to the MOE field once differences between model trajectories have reached a statistical steady state. The work under WP3 will provide estimates of the likely imprint of MOEs on ocean metrics such as the MOC or the

ACC and will address Q3 and contribute to Q4.

4.1 WP1: Optimal perturbations in eddying models

In WP1 we will use GSA to define perturbations optimised to ensure a rapid decorrelation of MOEs.

GSA is already implemented in NEMO (ORCA025). In WP1 the perturbation scheme will also be implemented in Q-GCM. To be able to study the impact of the eddy field on the ocean circulation we need optimal perturbations that maximise the decorrelation of the MOE field between different simulations. In MESO-CLIP we will compute optimum perturbations (of temperature, salinity, velocities) for the following measures: **(i)** the eddy kinetic energy, **(ii)** the divergence of the spatial correlation of zonal sea surface height anomalies, and **(iii)** the divergence of the correlation of zonal potential vorticity anomalies. These measures will be used in NEMO, HadGEM3-H, and Q-GCM. The optimality implies that the perturbation induces the strongest possible transient change in the system measure after a given time delay or over a chosen time interval. We want to achieve an optimised (i.e. fastest possible) decorrelation of the MOE field. Therefore the time interval will be short and we will test intervals ranging from a few days to a few months. The divergence of the measures **(i)-(iii)** will be optimised based on global fields (respectively on the full model domain in Q-GCM). In Q-GCM, we will also use simple (non-optimal) perturbations. Preliminary Q-GCM experiments with two other non-optimal schemes in the form of simple perturbations at ocean/atmosphere boundary over one model time step have shown that one can easily generate an ensemble that exhibits temporal divergence in measures such as ocean transport and kinetic energy. Q-GCM provides an ideal (computationally very efficient) testbed to examine whether GSA extracts extra information from a finite set of climate forecasts in a more efficient way than simpler techniques.

4.2 WP2: Impacts of mesoscale ocean eddies on predictability

The aim of WP2 is to assess how fast and through which mechanisms model trajectories start to diverge after the perturbations defined in WP1 have been applied.

The basis for this work is a new set of numerical experiments listed in Table 1. The simulations will

Experiment	Model	Ocean	Atmosphere	Ensemble	duration [years]
N025 _{control}	ORCA025	free	ERA-Interim	no	1979-2012
N025E	"	free perturbed	"	yes	1994-2012
N12a	ORCA12 NEMO v3.2	free	DFS4.1	no	1978-1989
N12b	ORCA12 NEMO v3.3.1	free	"	no	1988-2007
H _{control}	HadGEM3-H	free	free	no	100
HE	"	free perturbed	free	yes	5
Q _{control}	Q-GCM	free	free	no	150
Q1E	"	free perturbed	prescribed	yes	100
Q2E	"	"	free	"	"
Q3E	"	free perturbed	prescribed	"	"
Q4E	"	(non-optimal) free	free perturbed (non-optimal)	"	"

Table 1: Overview of numerical simulations. The ORCA12 simulations N12a, b have already been completed at NOC and the remaining experiments are proposed new simulations to be run in the framework of MESO-CLIP. Experiments with names ending with "E" are ensembles. The ORCA025 ensemble N025E consists of 10 members for the period 1994 to 2012. Perturbations will be added to ORCA025 for different start dates in 1994. The HadGEM3-H ensemble HE consists of 5 members. As for the ensemble N025E perturbations will be applied for different dates of the same year. Finally the Q-GCM ensembles Q1E-Q4E, consist of 20 members starting in year 50 of the control simulation Q. In Q1E the ocean will be forced by the atmospheric fluxes from years 50 to 150 of Q_{control}. The Q-GCM simulations will be run at eddy-resolving (5km in the ocean, 80 km in the atmosphere) and non-eddy (80 km in ocean and atmosphere) resolutions.

allow us to assess how model trajectories between ensemble members diverge and therefore how the predictability of the ocean and atmosphere circulation is affected by perturbations to the initial MOE field. We will estimate the divergence between ensemble members by looking at statistics of differences $\Delta X(t) = X_i(t) - X^*(t)$, where X is one of the model state variables. The index i denotes the control simulation or ensemble members, and each ensemble member or the control is used in turn as X^* (Collins and Sinha, 2003). As ocean the state variables in NEMO we will use the MOC (Atlantic, Indo-Pacific, Global), the Antarctic circumpolar current (ACC), western boundary currents at locations where the flow is constrained by a strait (e.g. Florida Straits, Kuroshio between Taiwan and Ryukyu Islands), deep western boundary currents, ocean heat content, SSH as well as velocities, temperature and salinities (e.g. longitude-time or latitude-time, see Fig. 2). For the atmosphere (in ensembles HE and Q2E) we will concentrate on the divergence in geopotential height (e.g. at 500 mbar), surface air temperature, precipitation. In HadGEM3-H we will also look at atmospheric indices such as the NAO, SOI. In Q-GCM we will use the barotropic streamfunction, vorticity and interface depth/altitude as state variables.

Experiments forced with prescribed atmospheric conditions (N025, N025E, N12a, N12b, Q1E) will

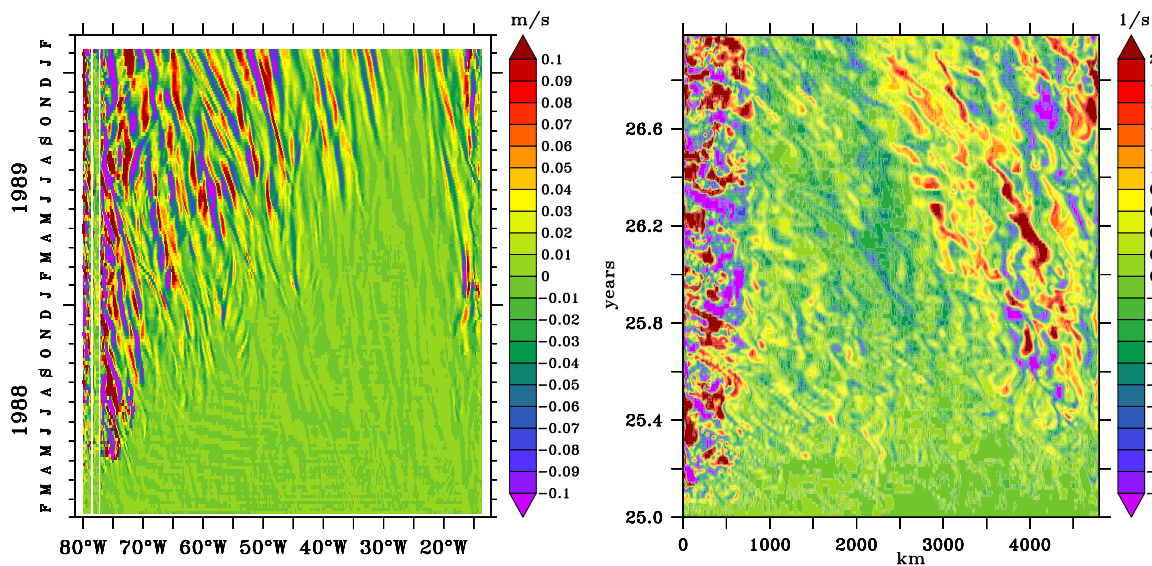


Figure 2: *Illustration of the growth of ΔX . **Left:** difference between the ORCA12 experiments N12a and N12b for the meridional velocity component across 26°N in the North Atlantic. N12a and N12b both experience the same surface forcing. Divergence between N12a and N12 sets in at the western boundary after 3 months, whereas it takes 10 months to see the first changes at the eastern boundary. Interestingly the fastest propagation of anomalies into the basin interior is not due to long, westward propagating Rossby waves but to an eastward propagation of anomalies starting at the western boundary. As the eastward signal crosses the Atlantic it triggers Rossby waves (or MOEs) which travel westward with a speed characteristic of oceanic baroclinic Rossby waves. The mechanism behind the eastward propagation is not yet understood and is one of the aspects we will study in MESO-CLIP based on the ORCA12 simulations. **Right:** Longitude-time section of ΔX for vorticity minus its zonal mean between two coupled Q-GCM simulations. A (non optimal) perturbation (shift of one day) is applied to the atmosphere. ΔX shows a growth pattern similar to that seen in ORCA12: the first response occurs at the western boundary after about two months whereas the first changes occur after 4-5 months at the eastern boundary. The Q-GCM runs are coupled and the atmospheric decorrelation between the two runs explains the noisier and less coherent patterns compared with N12a, b.*

tell us to what extent MOEs affect the trajectory of an ocean in forced mode. No optimised perturbation is used in Experiments N12a, b and differences $\Delta X(t)$ occur because of a switch to a newer version of NEMO in year 1988 of the simulation (for comparison the simulation using the older version of the code was continued for years 1988 and 1989). Nevertheless, the change in the NEMO code introduces slight perturbations that grow with time. With its resolution of $1/12^\circ$ ORCA12 offers an unprecedented insight into the mechanisms leading to the growth of $\Delta X(t)$ (Fig. 2). In analogy

to Sinha *et al.*, 2012 there is a clear difference in predictability between the eastern and western boundary which is most likely linked to wave processes.

The Experiments using HadGEM3-H and Q-GCM will allow us to estimate how ocean-atmosphere feedbacks affect the growth of $\Delta X(t)$ seen in the ocean only experiments. Furthermore, the experiments will show if and on what timescales the changes in initial MOE field feed back onto the large scale atmospheric circulation. The computational demands of HadGEM3-H are such that we will only be able to investigate the divergence on rather short (5 years) timescales. The computationally efficient Q-GCM model will allow us to investigate if $\Delta X(t)$ grows on decadal and longer (multidecadal) timescales and will show if perturbations in the MOE field cascade onto long (decadal and longer) timescales.

4.3 WP3: Quantifying the imprint of mesoscale ocean variability on the ocean and atmosphere circulation

The aim of WP3 is to quantify the amplitude of ocean and atmosphere variability that is caused by MOEs once $\Delta X(t)$ has reached a statistical steady state. Analysis of the experiments listed in Table 1 will allow us to estimate the contribution of MOEs to the variability of the ocean circulation in forced, ocean only and coupled configurations (Q3, Q4).

Once ΔX has reached a statistical steady state (i.e. saturation of the variance of ΔX) it can be used as a measure for the eddy (or the initial condition dependent or “chaotic”) variability of the ocean on timescales that are short compared to the total duration of the simulation (Hirschi *et al.*, 2012). In our experiments we can therefore provide estimates of the “chaotic” ocean variability on subannual to seasonal (HadGEM3-H), interannual (ORCA025) and decadal (Q-GCM) timescales.

The 10 ensemble members in experiment N025E cover the period 1994 to 2012. We will quantify the variability within the ensemble for the ocean state variables listed in WP2. Particular emphasis will be given to the Atlantic MOC at the latitudes around 26.5°N given that this latitude coincides with the RAPID-WATCH AMOC observations (Cunningham *et al.*, 2007, Kanzow *et al.*, 2010) and that our simulations will cover the deployment period of the RAPID mooring RAPID array. What fraction of the very large observed MOC variability is due to MOEs is not yet known. Some studies indicate that the MOE imprint may not be large (Kanzow *et al.*, 2009, Hirschi *et al.*, 2012) but this question has not been investigated systematically yet. The start date of 1994 for the ensemble N025E ensures that a saturation of the variance of ΔX on sub- to interannual timescales is reached prior to 2004, i.e. the difference between the ensemble members is a measure of the “chaotic” AMOC variability. We have already provided an estimate of the “chaotic” MOC variability for the 1976 to 2001 period by comparing a twin experiment with identical surface forcing but different initial conditions (Hirschi *et al.*, 2012, Fig. 3). In MESO-CLIP we will not just look at the AMOC itself but we will also look at the different components (transport through Florida Straits, geostrophic transports, barotropic transports e.g. Hirschi *et al.*, 2007, Blaker *et al.*, 2012) and assess the MOE imprint on each component.

The HadGEM3-H experiments will inform us to what extent the coupling between the ocean and the atmosphere increases the amplitude of the variance of ΔX compared to the ocean only experiment N025E. It will also show if the initial perturbations lead to changes in the daily to seasonal variability of the atmosphere. We will look at the same atmospheric variables mentioned in WP2. Finally, the multidecadal Q-GCM simulations will provide estimates of the eddy-driven variability (in the barotropic stream function, interface depth/height...) on decadal and longer timescales which we cannot address with NEMO and HadGEM3-H because of computational limitations.

5 Project deliverables

WP1, WP2 and WP3 will provide a set of deliverables listed below:

D1: New insights into optimal perturbations of eddying models (WP1). **D2:** Estimate of predictability in eddying ocean-only simulations (WP2). **D3:** Estimate of predictability in eddying coupled ocean-atmosphere models (WP2). **D4:** Estimates of the amplitude of the ocean variability due to MOEs in ocean only models (WP2). **D5:** Estimates of the amplitude of the atmospheric and climate variability due to an eddying ocean (WP3). **D6:** Impact of MOEs on the variability of the coupled ocean-atmosphere system (WP3). The emphasis on each deliverable will be on the similarities and differences between the models and how the findings relate to climate observations.

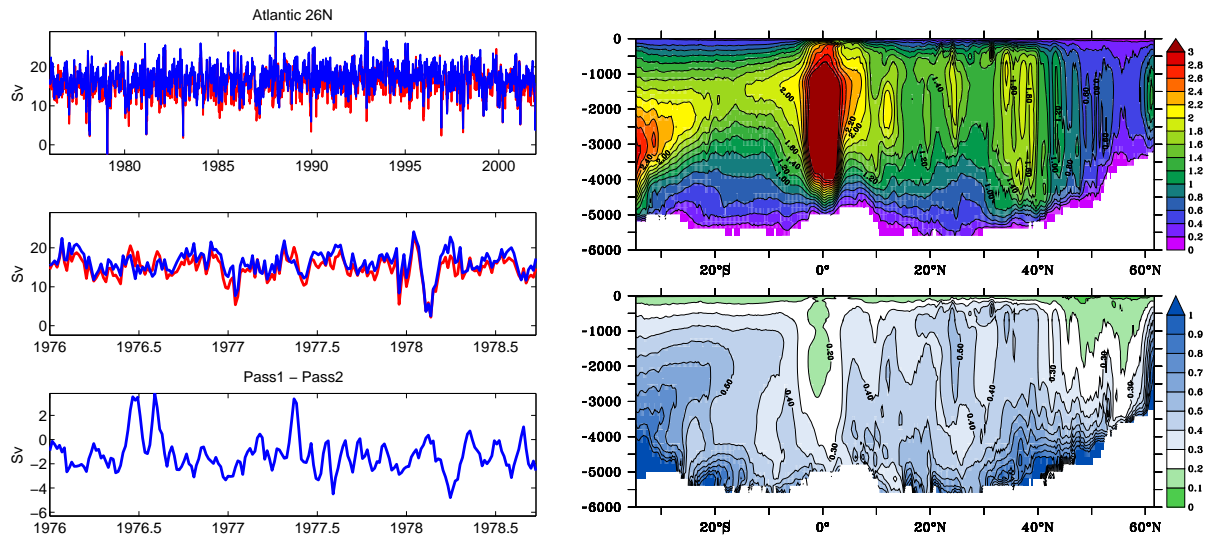


Figure 3: Illustration of initial condition (IC) dependent (“chaotic”) MOC variability in ORCA025 (Hirschi et al., 2012). **Left)** Atlantic MOC transport at 26°N and 1000m depth in two ORCA025 simulations using the same atmospheric forcing but starting from different ICs (top, middle). The difference between the two runs is shown in the bottom panel. **Right)** Standard deviation of the Atlantic MOC difference (in Sv) between the two simulations for the 1976 to 2001 period (top). Values are obtained from 5-day averages. Bottom: Ratio between “chaotic” and total MOC variability (i.e. ratio between the standard deviation shown in the top panel and the standard deviation of the total Atlantic MOC).

6 Project and data Management

The project will be led by Drs Joël Hirschi (PI, NOCS), Florian Sévellec (Co-PI, University of Southampton), Chris Wilson (Co-I, NOCL), Bablu Sinha (Co-I, NOCS) and Dr Adam Blaker (Researcher, NOCS). Hirschi will have the overall scientific overview, Sinha will help with the experiment design and the diagnosis of eddy effects on the circulation. An unnamed PDRA (University of Southampton) will carry out the work required to obtain the optimal perturbations under the supervision of Florian Sévellec. The ORCA025 simulations and analyses will be carried by Adam Blaker and the PDRA. The Q-GCM experiments will be led by Chris Wilson. The Q-GCM simulations will be run on the NOCL cluster and the ORCA025/HadGEM3-H simulations on the ARCHER and MONSOON supercomputers (WP2). The work with HadGEM3-H will be done in collaboration with Dr John Siddorn from the UK Met Office. International collaborators are Drs Thierry Penduff and Bernhard Barnier (Légit, Grenoble, France) for their expertise in both high resolution modelling and the study of intrinsic (“chaotic”) variability in the ocean, and finally Dr Andy Hogg (Australian National University) for his extensive Q-GCM expertise. The model datasets produced in MESO-CLIP will be made available through BADC. Sufficient storage will be required at NOC during the project (see justification of resources).

7 Relevance to UK and international research

The proposed research is directly relevant to the NERC mission “to create understanding and predict the behaviour of the natural environment” as well as to projects such as UK Met Office - NERC Joint Weather and Climate Research Programme (JWCRP), and Joint Ocean Modelling Project (JOMP). Operational oceanography such as FOAM will also benefit from optimal perturbations coming out of MESO-CLIP. The research undertaken in MESO-CLIP will also fit into the scope of CLIVAR. The results from MESO-CLIP will provide valuable knowledge to research groups in the UK and abroad who are developing the next generation of coupled climate models, e.g. the development of HadGEM3-H in CAPTIVATE/INTEGRATE (UK), EC-EARTH (EU consortium), GFDL CM2.5/CM2.6 (US).

8 Schedule of events

MESO-CLIP requests funding for 24 months and the timing of the work in WP1-WP3 as well as the dates for the deliverables D1-D6 is provided in Fig. 4.

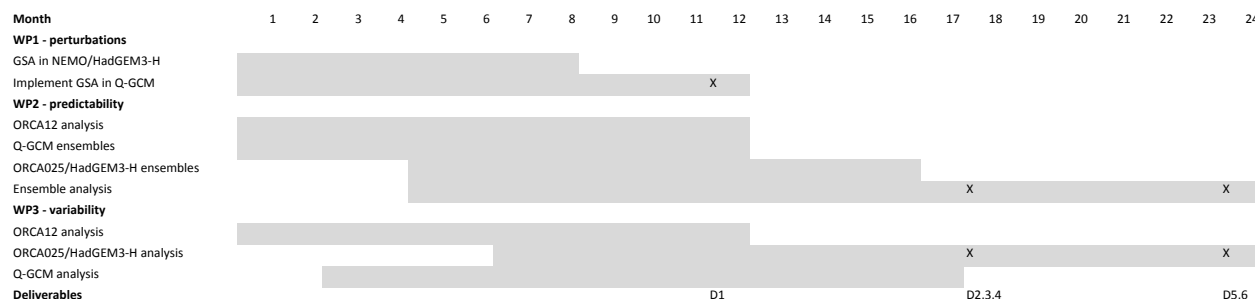


Figure 4: Gantt-chart for the timing of the workpackages in MESO-CLIP. Crosses indicate from which workpackage the deliverables D1-D6 will result.

9 Risk

The work involving NEMO and HadGEM3-H is low risk given that GSA is already implemented for NEMO. For Q-GCM there is a risk that GSA implementation turns out to be more difficult than anticipated (this risk is small given that Sévellec successfully implemented GSA in the more complex NEMO model). The use of non-optimal perturbations in Q-GCM (Q3E, Q4E) mitigates against this risk. For investigating the impact of MOEs on decadal timescales the optimality of the perturbation is less crucial than for the shorter timescale which are at the centre of the NEMO/HadGEM3-H simulations.

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