Appel à projet, PRC 2016
« Gestion sobre des ressources et adaptation au changement climatique : Suivi intelligent du système terre »

Project: CLIMATOME

Low-frequency CLIMate variability forced by Oceanic Mesoscale Eddies

Principal Investigator: Guillaume Lapeyre

I) Objectifs scientifiques et technologiques

The low-frequency variability (hereafter LFV) of the ocean and atmosphere (decadal to multidecadal timescales) is tightly coupled with high-frequency transient eddies. In the atmosphere, synoptic perturbations define the storm-tracks regions, which can vary on timescales longer than a week, while in the ocean strong currents like Western Boundary Currents (WBC) are associated with a turbulent field of mesoscale eddies with individual timescales of weeks to months. These regions rich in "fast" transients in the atmosphere and ocean are organized by the large-scale circulation, and are generally positioned at the same geographical location: the tropospheric mid-latitude jets and storm-tracks lie above the WBC or the Antarctic Circumpolar current (hereafter ACC).

In addition, it is now recognized that the mean circulation and its LFV are highly dependent on the combined forcing by the transient eddies, both in the ocean and atmosphere. In particular, a number of studies in the last 10 years have shown changes in behavior when increasing the spatial resolution of the atmosphere or ocean models. One crucial element is the representation of the spatial variability attributed to oceanic eddies or oceanic fronts such as WBCs or the ACC. Feliks et al. (2007) and Minobe et al. (2008) have shown that only atmospheric models resolving oceanic features of 50km can reproduce standard patterns of the storm-track (such as enhancement of precipitation along the warm side of WBCs). Moreover, studies by Berloff et al. (2007), Huck et al. (2015) or Sérazin et al. (2015) have shown that the ocean intrinsic variability was enhanced when oceanic mesoscale turbulence was present.

The current global climate numerical models barely resolve structures of 100km in the ocean. It was believed that this was sufficient to represent most climate processes (with the help of a few relevant parameterizations). However it is now apparent that an inclusion of eddy diffusivity does not enable a good simulation of the LFV of the climate system or its response to external forcings.

This project thus aims at understanding how the oceanic mesoscales and high-frequency transients organize and give a more realistic ocean and atmosphere LFV using a hierarchy of models that will capture the main processes of the ocean-atmosphere coupling. The main questions are: how do the high-resolution processes influence the LFV of the climate system? What are the consequences of including these processes in the atmosphere or in the ocean? What components in the air-sea coupling (surface heat fluxes, momentum forcing and Ekman transport, integrated energy exchanges) are necessary to correctly represent the LFV? The results that will be obtained in this project will help climate modelers to interpret and to guide them in their effort to represent ocean-atmosphere processes with increasing resolution and validate their results concerning climate variability.

The project comes in 3 parts: Workpackage 1: the effect of mesoscale sea surface temperatures (SST) on the tropospheric storm-tracks and the tropospheric LFV; Workpackage 2: the oceanic intrinsic variability in high-resolution ocean models; Workpackage 3: the role of the global energy budget constraints in the interactions between the ocean and atmosphere (storm tracks) LFV.

WP1: *Effect of oceanic eddies on the storm tracks*

The impact of the oceanic eddies and of large-scale fronts on the atmosphere has received a lot of attention during the last ten years. On one hand, many studies analysed what occurs in the marine atmospheric boundary layer, such as Chelton et al. (2001) among others. These studies pointed out the relationship between the wind stress and the SST gradients (through a "downward momentum mixing" mechanism, Wallace et al. 1989). On the other hand, other studies addressed the relation between the storm tracks and the large-scale fronts (e.g. WBCs or the ACC), such as Minobe et al (2008) or Nakamura (2008). These studies pointed out the relationship between atmospheric precipitation with the SST Laplacian (through the “backward pressure adjustment’ mechanism, Lindzen and Nigam 1987). In each case, what matter are the oceanic mesoscales through the SST gradient or Laplacian (see also Lambaerts et al. 2013). We can also mention studies such as those by Giordani and Caniaux (2001) and Booth et al. (2012) who highlighted the role of the ocean mesoscales in the development of midlatitude storms.

A truly new area of research concerns the relationship between the oceanic mesoscale eddies, the storm-track and its LFV. These storm-tracks are generated by the nonlinear interactions of the fast transients (e.g. storms with a typical timescale of days) with low-frequency waves (timescale of several weeks). Right now, it is not known what oceanic scales the troposphere does “see” and how surface fluxes, that are modulated by the oceanic mesoscale eddies, affect the storm-track dynamics. The project tries to answer such questions. More particularly, key questions are: i) Are the mesoscale modulations of the surface heat fluxes important in the energy budget of the storm track (in a Lorenz sense) through their influence on surface baroclinicity or surface stresses? ii) What is the role of water vapor processes (as water vapor is an active tracer being evaporated at ocean surface, transported by the storms and subsequent latent heat released at a longer distance)? iii) What about the role of moist convection triggered on the equatorward side of SST fronts?

To this end, we will rely on idealized simulations of a storm-track in a midlatitude channel with a primitive equation model, forced by mesoscale SST and with different spatial resolutions.

WP2: *Intrinsic oceanic variability: spatial patterns and influence of mesoscale eddies*

Several paradigms apply to the decadal to multidecadal climate variability in the North Atlantic, and neither observations nor climate models allow yet identifying the most relevant. While some studies argue for a coupled mode, where the strong atmospheric response to decadal-scale SST anomalies feedback onto the ocean circulation (Timmermann et al., 1998), others point to an oceanic origin where variability in either wind or buoyancy forcing is not necessary to the existence of the variability (Greatbatch and Zhang, 1995). Some authors found instead that low-frequency atmospheric variability associated with the North Atlantic Oscillation drive a significant fraction of the observed variability in the North Atlantic (Eden and Jung, 2001). In this project we focus on one aspect of the dynamics of the North Atlantic climate, the intrinsic decadal-scale oceanic variability, its mechanisms and its sensitivity to crucial processes (such as the turbulent transport of tracers).

Intrinsic oceanic low-frequency variability in stand-alone ocean models forced by constant surface fluxes can arise through different mechanisms. The first one was identified in quasigeostrophic double-gyre ocean models forced by a constant Ekman pumping at the surface: the competition between Ekman pumping and upgradient potential vorticity fluxes at the intergyre boundary drive a "turbulent oscillator" in the strength of the gyres, whose dominant timescale depends on the Reynolds number (Berloff, 2007). The second mechanism, identified for the first time in an idealized planetary-geostrophic ocean model, relies on baroclinically-unstable long Rossby waves and do not require the presence of either wind-forcing or eddies (Colin de Verdière and Huck, 1999). A natural question that remains unanswered is how those two different mechanisms interact when all the components of the surface forcing are represented and in the presence of mesoscale eddies? Is the decadal to multidecadal intrinsic oceanic variability mostly wind-driven or thermally-driven? How does this depend on the model resolution permitting or not mesoscale eddies?

At coarse resolution, intrinsic oceanic variability has been shown to be sensitive to the choice of the surface boundary condition, in particular on temperature (Dirichlet or Neumann) (Arzel et al., 2007). More recently, Jamet et al. (2015) showed that air-sea interactions have a damping influence on the oceanic intrinsic decadal variability in a coarse resolution AOGCM configured in an idealized geometry, in agreement with previous studies based on much simpler coupled models (Arzel et al., 2006, Huck et al., 1999). Is this damping nature of air-sea interaction a robust feature when air-sea interactions occur at the meso-scale? We will determine how much the atmospheric coupling affects the natural oceanic variability on these time scales. This can be done with the help of a simple atmospheric boundary layer (CheapAML, Deremble et al. 2013) as a first step, in presence of eddy turbulence.

WP3: *Energetics constraints on the coupled ocean-atmosphere LFV*

In addition to local dynamical or thermodynamical mechanisms, on long time-scales, the LFV in the ocean and atmosphere are strongly coupled by the total energy budget: the transport of energy by the ocean and atmosphere must on average balance the radiative gain or loss at the top of the atmosphere (TOA). Thus, if the TOA remains constant, a change in the meridional heat transport by the ocean must be balanced by opposite changes in the atmospheric energy transport (Bjerknes, 1964). The atmospheric meridional energy transport is accomplished mostly by eddies (storms) in the mid-latitudes and by the Hadley Cells in the tropics. In both cases, it is strongly coupled with the transport of water vapor, and so with precipitation (Frierson et al., 2013). In the ocean, both the eddies and large-scale circulation (gyres, meridional overturning circulation, MOC) transport heat poleward.

We showed for example in a previous paper (L'Hévéder et al., 2014) using an atmospheric GCM coupled to a slab (inert) ocean, that a prescribed northward heat transport in the Atlantic Ocean, as could be due to decadal changes in the MOC, led to global climate impacts and in particular meridional shifts of the storm tracks. These changes in atmospheric circulation produced anomalous energy transports that compensated the one prescribed in the ocean. Such studies using an inert ocean allow prescribing the energy transport by the ocean, but they ignore a potential response of the ocean circulation (e.g. changes in ocean gyres or shallow cells in response to MOC fluctuations) that could change the Bjerknes compensation mechanism.

We thus propose to investigate in more details how the coupling between the energy transports by the ocean and the atmosphere constrains the structure of their LFV. Some key questions are: (i) How do storm tracks respond (shift, intensification…) to prescribed changes in ocean heat transport? (it should be noted that meso-scale SST fluctuations globally enhance the surface heat fluxes, implying a compensating energy transport in the ocean). (ii) How is this atmospheric response to a given forcing modified in the presence of a dynamical ocean? (iii) At what time-scales do these compensation effects operate?

II) Organisation du projet et moyens mis en œuvre

The project involves the Laboratoire de Météorologie Dynamique (LMD, Ecole Normale Supérieure/CNRS), the Laboratoire d'Océanographie et du Climat – Expérimentation et Approches Numériques (LOCEAN, Université Pierre et Marie Curie/CNRS), both in Paris and the Laboratoire de Physique des Océans (LPO, Université de Bretagne Occidentale/CNRS) in Brest.

The Principal Investigator is Guillaume Lapeyre (LMD) who is a specialist in physical oceanography at mesoscales and in dynamical meteorology, using numerical modelling and theories based on Geophysical Fluid Dynamics. At LMD, Riwal Plougonven and Gwendal Rivière are specialists of storm-tracks and realistic atmospheric modeling at synoptic scales. They benefit from the modeling assistance of Lionel Guez. A PhD student (Alexis Foussard) will also be involved in the project. At LOCEAN, Francis Codron is a specialist in air-sea interactions and climate variability and in global atmospheric modeling. Guillaume Gastineau will provide his expertise in the role of the ocean in decadal variability of the atmosphere. At LPO, Thierry Huck and Olivier Arzel are specialists of low-frequency variability in the ocean and they benefit from the modeling assistance of Patrice Bellec.

All of these scientists will use the high-computing facility of GENCI which provides enough computer resources for the high-resolution simulations that are needed for the project.

One force of this project comes from the sharing of expertise of the different partners in different aspects of the low-frequency variability, high-resolution modelling and mesoscale processes in the ocean or atmosphere. The general objective of this project can be realized only with a hierarchy of models (from idealized to realistic ones) with resolution high enough to represent all processes (mesoscale oceanic eddies, low-frequency variabilities). The team has a long expertise in these classes of models.

Finally it can be noted that the project mostly involves junior scientists (around 40 years old).

WP1: Effect of oceanic eddies on the storm tracks (GL, RP, GR, AF, FC)

The WP methodology is to use the atmospheric WRF model in an idealized set-up of a midlatitude channel of size of ten thousands kilometers length. This model will be, at the beginning, forced by fixed SSTs representing an eddying ocean (in the second step, with a SST field evolving in time, and then with a fully coupled model). The SST field could come from simulations of Klein et al. (2008, JPO) which provide a broad range of scales from the kilometer scale to a thousand of kilometers. Horizontal resolution will vary from 50km to 1km. Such a setting allows resolving both the storm-track (domain of thousands of km) and oceanic eddies (scales of hundreds of km). The challenge is to quantify the atmospheric response and we will need simulations long enough to increase signal to noise ratio (or we will rely on ensemble runs).

We have already obtained a set-up that represents a relatively realistic storm-track in presence of SST anomalies. Different steps are then: i) Performing typical storm life-cycles and investigate the role of surface fluxes, moist processes in the storm nonlinear development (following ideas of LC1/LC2); ii) Assessing the storm-track response to different SSTs (with different spatial resolution), different boundary layer parametrization, etc. iii) Identifying how water vapor processes modify the interactions between the surface and the storm-track. iv) A last step will be to couple the atmospheric model with an active ocean and see how the mechanisms that will be unveiled will be impacted.

WP2: Mechanism of intrinsic oceanic variability (OA, TH, GG)

A first step consists in studying the characteristics and interactions of the wind-driven circulation at large Reynolds number and the thermally-driven circulation at low Reynolds number in generating the oceanic LFV. To this end, we will use different oceanic models (ROMS and MIT GCM) in idealized box-geometry (one- and two-hemisphere Atlantic-like basin) at eddy-permitting resolution. Using different models allows building on existing simulations and using specific coupling options or tools already developed. Also linear stability analysis will be performed, using a series of linear and nonlinear numerical experiments with NEMO and its tangent linear and adjoint model (NEMOVAR). Developments towards extending such analyses to eddy-permitting simulations and also coupled models are planned in collaboration with Florian Sévellec (Lecturer at NOCS). A second step is to assess the damping influence of air-sea interactions on the oceanic intrinsic variability through the use of the MIT GCM coupled to a simple atmospheric boundary layer (CheapAML, Deremble et al. 2013) in the same idealized geometry as the first step. A last step will be be to compare to nonlinear integrations of the MIT GCM in a global configuration at 1° resolution under repeated annual climatological forcing. The sensitivity of the emerging mode to various processes (eddy diffusivities, seasonal cycle) will be analyzed and compared to previous results based on idealized models (in either physics or geometry).

WP3: Energetics constraints on ocean-atmosphere coupling (FC, GG, GL)

We will use the atmospheric GCM LMDz coupled to a hierarchy of ocean models, starting with a simple oceanic mixed layer (slab ocean) in an aqua-planet setup (global ocean). This enables to study the response of the storm tracks, and more generally of the atmospheric circulation and hydrological cycle, to prescribed changes of the ocean heat transport. We are already involved in several international model inter-comparison studies (e.g. TRAC-MIP, driven by Columbia University) using this setup, in which our role is to study the storm tracks and mid-latitude jets.

We will then progressively add complexity in the ocean model: in the physics used (adding the parameterizations of the diffusive and Ekman heat transports illustrated in Codron (2012), then moving to a full GCM) and in the geometry (adding idealized continents to support gyres and MOC, then realistic geometry). We will then compare the coupled response to similar forcings (same implied meridional energy transport).

- ## Most relevant publications

1. **T. Huck**, **O. Arzel**, F. Sévellec, 2015: Multidecadal variability of the overturning circulation in presence of eddy turbulence. *J. Phys. Oceanogr*, 45, 157-173.
2. B. L'Hévéder**, F. Codron**, and M. Ghil, 2015. Impact of anomalous northward oceanic heat transport on global climate in a slab-ocean setting. *J. Climate*,2650-2664.
3. C. Frankignoul, **G. Gastineau** and Young-Oh Kwon, 2013. The Influence of the AMOC Variability on the Atmosphere in CCSM3. *J. Climate*, **26**, 9774–9790
4. J. Lambaerts, **G. Lapeyre**, **R. Plougonven** and P. Klein, 2013*,* Atmospheric response to sea surface temperature mesoscale structures. *J. Geophys. Res.* 118, 9611-9621.
5. C. Michel and **G. Rivière**, 2013, Sensitivity of the position and variability of the eddy driven jet to different SST profiles in an aquaplanet general circulation model, *J. Atmos. Sci.* 71, 349-371.
6. **O. Arzel**, M. H. England, A. Colin de Verdière, and **T. Huck**, 2012: Abrupt millennial variability and interdecadal-interstadial oscillations in a global coupled model: sensitivity to the background climate state. *Climate Dynamics*, 39, 259-275.

- ## CV of PI Guillaume Lapeyre

Education: ***2010*** Habilitation à Diriger des Recherches ; ***2000*** PhD in Oceanography, Meteorology and Environment, at LPO (Brest); ***1995*** Ecole Normale Supérieure (Paris)

Professional Experience: ***Since 2004*** CNRS Associate Scientist (Chargé de Recherche) at LMD; ***2002-2004*** Postdoctoral fellow at LPO, IFREMER (Brest); ***2000-2002*** Visiting Scientist, GFDL, Princeton University

Professional Activities: 37 publications (see http://www.lmd.ens.fr/glapeyre). H-index: 19. Referee for national and international funding agencies (NSF, NSERC, NERC, SNF, ERC), AXA research fund, various scientific journals such as Nature Geosciences, J. Atmos. Sci., J. Phys. Oceanog., J. Climate, J. Fluid Mech;

2012- Scientific Secretary of Section 19 of the “Comité National du CNRS”
Awards: 2008 Journal of Physical Oceanography Editor’s Award.

- **Funding**

At LPO: 1 postdoc for 2 years: 120kEuros. Travel expenses: 10kEuros. Equipment and publication cost: 10kEuros
The postdoc activity will focus on the role of air-sea interactions at mesoscale on the intrinsic oceanic low-frequency variability. This includes the development of numerical simulations with the MIT GCM, implementing the coupling between the oceanic component of MIT GCM and the CheapAML atmospheric boundary layer model (existing package in the MIT GCM), running the model in an idealized box-geometry configuration (2-hemisphere sector of a sphere with Atlantic like dimensions and a southern ocean periodic channel to crudely represent the effect of the Antarctic Circumpolar Current), analyzing the simulations.

At LOCEAN: 1 PhD student for 3 years: 100kEuros. Travel expenses: 6kEuros. Equipment and publication cost: 4kEuros
The PhD student will participate in the analysis of the different simulations, and interact with the other WPs to propose new ones based on their results (surface heat fluxes, eddy energy transports…). He or she would also develop a global configuration of the NEMO ocean model needed for idealized geometries, with the help of the extensive expertise at LOCEAN.

At LMD: 2 Master students:4kEuros. Travel expenses: 16kEuros.Equipment and publication cost: 10k Euros

TOTAL: 280kEuros: 30kEuros (LMD), 110kEuros (LOCEAN), 140kEuros (LPO)

III) Impact et retombées du projet

The atmospheric model configuration with a oceanic mixed layer developed in WP3 and the coupled model configuration LMDZ-NEMO respond to a broader demand at IPSL in particular for deep paleoclimate studies (different continent configurations) or mechanistic studies (idealized continents). These configurations will be integrated into the IPSL modeling center configurations, which would be of great interest for the scientific community.
The issue of the internal atmospheric variability (e.g. weather regimes, storm life-cycles) is often discussed in relation with the forcing by large-scale oceanic anomalies. Here we choose to follow another point of view in viewing the oceanic mesoscales as invigorating (or at least modulating) the atmospheric variability. This could favour positive feedbacks between the atmosphere and the ocean at the intra-seasonal timescales. Actually, oceanic mesoscales will strongly impact evaporation. The advection of moister air from low levels downstream energizes storms and affects anticyclonic blocking (Pfalh et al. 2015). Such synoptic systems will in return modify the underlying SST through large-scale surface fluxes, leading to possible positive feedbacks. Similar feedbacks (but not including oceanic mesoscales) were observed by Cassou et al. (2011) in the case of the summer 2003 European heat wave. Our study could provide some better understanding on atmospheric persistence at the intra-seasonal timescale in relation with seasonal forecasting.
More generally, understanding the mechanism of low-frequency climate variability is fundamental for decadal climate prediction. In the Atlantic Ocean, the large decadal-to-multidecadal variability in SSTs (known as the Atlantic Multidecadal Oscillation) limits our ability to attribute decadal climate change, and to predict North Atlantic climate beyond a decade or so. This project will bring some new elements (influence of mesoscale oceanic eddies, wind-driven and thermally driven circulations, stability of the circulation) regarding the dynamics of intrinsic variability of the Atlantic circulation, which is recognized as a crucial component of the Atlantic climate.
Finally, this project involves different numerical models (WRF/LMDz, NEMO/ROMS/MITGCM). WRF is used for its possibility of doing midlatitude channel simulations (without Hadley cells); LMDz for climate purposes; while ROMS/MITGCM for idealized oceanic box geometries and NEMO for more climate applications. Our study will highlight the advantages and deficiencies of each one concerning the ocean-atmosphere couplings. This will eventually help modelers to know what may occur in more realistic set-ups.