New Large Projects

IPSL has a number of advantages compared to other international climate research centers: its ability to address issues in a comprehensive manner on all compartments of the climate system, understanding the variability of climate on various scales time (past and future) via simulation, observation and paleoclimatic reconstructions, its ability to analyze forcings, feedbacks, and impacts of climate change (CC) on some sectors of society or some natural environments.

A strategy has been defined in 2014 on issues that the LABEX should focus over the last half of the program. It was proposed that IPSL build three ambitious projects, involving all WPs LABEX, for the last part of the LABEX (until 2019):

LP1) Investigating, from observations and modeling, steep interglacial climatic changes of the last ice age (MIS3) and the last interglacial maximum.

LP2) Understanding of 20th century climate and the allocation of its variability, by reconstructing its forcings and a set of simulations

LP3) Investigating the emergence of a few impacts and associated uncertainties

In addition the L-IPSL pursue its support to the global climate model development, under a 4th project

LP4) Climate model development

These "large projects" are now detailed in the following sections, as well as their preliminary results.

Finally, the LABEX wants to keep the possibility to invite foreign scientists. It is scheduled that **two 2-3 month visits per year could be funded and organized**. A first call was issued in 2016 and another call will be launched in 2017.

1- LP1: Abrupt and large climate variability

Project leads: Christophe Colin (GEOPS) & Amaëlle Landais (LSCE)

Participants

Teams	**L-IPSL contributors**	**External collaborators**
Marine cores and corals	Franck Bassinot (LSCE) Ioanna Bouloubassi (LOCEAN) Christophe Colin (GEOPS) Delphine Dissard (LOCEAN) Stéphanie Duchamp-Alphonse (GEOPS) Aline Govin (LSCE) Catherine Kissel (LSCE) Claire Lazareth (LOCEAN) Elisabeth Michel (LSCE) Luc Ortlieb (LOCEAN) Marie-Alexandrine Sicre (LOCEAN) Giuseppe Siani (GEOPS) Sophie Sepulcre (GEOPS) Claire Waelbroeck (LSCE)	Renato Salvatteci (Germany) Olivier Esper (Germany) Jeremy Hoffman (USA)
Terrestrial sites	Anne-Marie Lézine (LOCEAN) Sébastien Nomade (LSCE) Hervé Guillou (LSCE) Denis-Didier Rousseau (LMD) Christine Hatté (LSCE) Abdel Sifeddine (LOCEAN) Dominique Genty (LSCE) Dominique Blamart (LSCE) Uli von Grafenstein (LSCE) Amaëlle Landais (LSCE) Anaïs Orsi (LSCE) Valérie Masson-Delmotte (LSCE)	Alexander Prokopenko (USA) Chronis Tzedakis (UK) Sophie Verheyden (Belgique) Russell Drysdale (Australie) Giovanni Zanchetta (Italy) Haï cheng (Xi'an Jiaotong University) Emilie Capron (University of Cambridge) Sune Rasmussen (University of Copenhagen)
Modeling	Pascale Braconnot (LSCE) Didier Roche (LSCE) Masa Kageyama (LSCE) Adriana Sima (LMD) Jean-Claude Dutay (LSCE) Laurent Bopp (LSCE) Yves Balkanski (LSCE) Camille Risi (LMD)	Louise Sime (UK) Marie Jose Gaillard (Sweden) Louis François (Belgium) Tilla Roy (ECOCEANA, France)

Main participants to this project at the writing stage.

Project summary

Documenting past climate and environmental changes is essential to increase our knowledge about the Earth System behavior in varied climatic conditions, and to test the climate models which are used for projections. This project focuses on two aspects of past climate change that are directly relevant for the simulation of future climate change:

1- The last interglacial period (LIG; ~130 000 to 115 000 years before present): warmer climate and mean global sea-level values 5 to 9 m higher than today.

2- The abrupt variability of the last glacial period (70000 to 20000 years before present): succession of rapid climatic changes within decades (temperature increases of 10-15°C in Greenland, large temperature and precipitation changes in the mid to low latitudes).

The goal is to build new data bases for the periods of interest in this project, to improve our models and their capacity to compare their results with data and to perform these comparisons. This will yield a better knowledge or the processes at stake during the last interglacial warm period and the abrupt climatic changes of the last glacial period.

The strategy follows a model-data approach. To do so, we proposed to initiate two actions in parallel over the next 3 years: (1) the data synthesis and (2) the development of model interfaces for tracers representation. These actions should be carried out in parallel to deliver a comprehensive data – model intercomparison, including the spatial variability, over the last interglacial and the abrupt climate variability of the last glacial period. These two actions builds on the previous developments performed within WP5 in L-IPSL: the isotopic paleo-data-base (Tim Bolliet, Bolliet et al., 2015) and the multi-archives dating tool DATICE (Bénédicte Lemieux-Dudon and Lucie Bazin, Lemieux-Dudon et al., 2015).

<u>Axis 1: Data syntheses: Deliverables D1, D2 (+ participation to D4 and D5)</u>

- Compilation and implementation in the L-IPSL paleo data-base of the high to low latitude records with their respective dating constraints for the last interglacial period and the abrupt millennial variability of the last glacial period encompassing H2 and/or H4.

- When needed, adding targeted missing data (sequences of tracers or dating constraints) for key climatic periods or geographic zone.

- Harmonisation of chronologies: synchronization tests in specific geographic zone or by type of tracers using the multi-archive version of DATICE as well as modelling experiments performed using intermediate complexity models (connection with axis 2). We will emphasize the use of non-climatic chronological tie-points.

- Production of coherently dated time series for the investigated intervals.

Since the strategy and tools are the same for the different global data syntheses, one long (2+1 years) post-doctoral position is devoted to the realisation of tasks associated with deliverables 1 and 2. This post-doctoral fellow should strongly interact with the different experts listed in table 1 to ensure their active involvement in the project for selection of the appropriate archives records, additional data acquisition, additional dating constraints on key intervals, dating synchronization tests, … In addition, workshops are set up to review key sequences and dating constraints in the different geographic zones for the production of the syntheses. Finally, the possibility of funding a limited number of M2 internships will permit to fill the gap in key identified sequences of data.

<u>Axis 2 - Model interfaces - Deliverables D3, D4 (+ participation to D5)</u>

- Implementation of an interface based on the BIOME4 model so that the iLOVECLIM and IPSL model output can be compared to pollen data.

- Implementation of an interface for the FORAMCLIM model to be used with both the IPSL and iLOVECLIM model. This will also involve some evolution of the iLOVECLIM marine biogeochemistry model, so that its output can be used as input data for FORAMCLIM.

- Implementation of dust in interactive mode for paleoclimate experiments using the IPSL model.

As for axis 1, the strategy is to fund a 2+1 year post-doctoral position, which gives enough time for the different developments and for their valorisation. Some developments will also be realised by permanent staff of L-IPSL such as the implementation of dust in interactive mode in the IPSL model using outputs from axis 1 (reliable dated synthesis of loess records for a robust estimate of mass accumulation rate associated with dust deposition during the last glacial period).

Axis 3 - Comparison between model outputs and data over selected time periods (D5)

- Application of the modelling tool on LIG and abrupt climate variability of the last glacial period with newly built data bases from Axis 1. These should lead to major publications on these periods.

The exploitation of model simulations and comparison to data synthesis will be performed in the frame of master 2 internships with involvement of permanent staff from labex L-IPSL. This should also be done within dedicated workshops or invitations of external experts

Progress so far

The project started in the course

Axes 1 and 3:

- Organization of the workshop "Climat et Impacts" (C. Colin, C. Hatté) at Orsay the 15th and 16th of November 2016 with sessions dedicated to the model and multi-archives data integration over the periods of interest (session 1: propagation des changements climatiques globaux: processus et rétroactions; session 2: Variabilité climatique décennale à millénaire de l'Holocène et des periods chaudes du passé; session 4: variabilité actuelle et passé du climat des hautes latitudes: role de la cryosphere, rétroactions et impacts).

- Lucie Bazin Troussellier is hired since the 3rd of November.

Axis 2:

- Bret Metcalfe and Carmen Alvarez-Castro will begin their post-doc positions at the end of 2016 or very beginning of 2017.

Axis 3:

- Hans Renssen is invited for one month by labex L-IPSL for model-data confrontation. The invitation is made through the senior scientist invitation program

Program until 2019

1- Data syntheses (axis 1)

1-a- Data synthesis of the last interglacial period (November 2016 – April 2018)

1-a-i – Compilation of the mid to low latitude records covering the last interglacial period with dating constraints (Nov 2016-January 2017).

We will gather the mid to low latitude records (speleothem, marine cores, corals…) with a resolution better than 2000 years. We will select sites with available information on temperature (quantitative estimates), stable isotopes (quantitative estimates) and precipitation (qualitative estimates) as well as dating constraints. A workshop will be held at the beginning of the project (Climat et Impacts, Orsay, 15-16 November 2016) to promote collaborations with research team outside of the labex to complete the available records at L-IPSL.

1-a-ii- Evaluation of dating constraints and harmonisation of chronologies by geographic zones (Feb-Sept 2017)

First, we will perform a thorough evaluation of dating constraints of the sequences identified in the previous section. Second, the validated data gathered in previous section will be separated in different geographic zones (Mediterranean Sea – North Atlantic – Asia – Southern ocean). This will enable synchronization tests. We will thus use the DATICE multi-archives dating tool to incorporate these non-climatic dating constraints within each region to evaluate the robustness of the classical hypotheses of synchronicity of events among the various archives tracers. These tests will permit a quantification of the lags between similar events recorded in different tracers (e.g. lag between change in pollen concentration in response to a change in precipitation archives in $\delta^{18}O$ of speleothem).

1-a-iii – Production of a coherently dated sequence of the last interglacial period (Oct 2017-March 2018)

We will start from the coherent chronology of marine and terrestrial records from the Mediterranean region. We will then extent it to the optimized chronologies of the North Atlantic region, by synchronizing paleomagnetic records (e.g. Blake and post-Blake events) of marine sediments from both regions, checking the coherence of temperature changes to the south and west of the Iberian Peninsula and the coherence with Greenland ice core records. Coherence will be checked and optimized with South America speleothems. In addition, coherence within the Southern Ocean region will be achieved by optimizing marine sediment paleomagnetic records, chronological constraints and low latitudes proxies of ice cores and available speleothems in New Zealand. Finally, the coherent time frame will be transferred to the Indian and Pacific Oceans (using paleomagnetic and benthic foraminifera $\delta^{18}O$ records) for which less records are available.

Once all selected paleoclimatic records are placed on the globally coherent time frame, we will produce time slices for specific time periods to map the spatial distribution of temperature and stable isotopes anomalies.

1-b Data synthesis of the abrupt climate variability

1-b-i- Review of the high to low latitude records with robust dating constraints covering H2 and H4 (April 2017-July 2018)

A workshop will be held in mid 2017 to gather the different data sets available within L-IPSL and from the existing databases. In the following months (mid 2017 – mid 2018), an in-depth work on the reliability of dating constraints to be used over this time period will be assessed by experts in dating techniques within L-IPSL (e.g. ^{14}C correction).

At the end of 2018, a final selection of the high resolution records will be performed. This will be done by choosing the higher resolution records (one reference by large geographical zone) for rapid event H2 and H4.

1-b-ii Acquisition of new data on targeted periods (2017-2018)

The data acquisition addressed by this project should concern key dating constraints or archives with high resolution (200 years minimum around H2 and H4) and for which chronological constraint already exist or are currently acquired. Target projects for master 2 students within L-IPSL will be proposed for spring 2017 and 2018.

1-b-iv- Chronology improvements and synchronization tests by proxies or geographic zones (August 2017-June 2018)

In order to use the loess records for the global synthesis, we need to improve their chronological framework by using the dating tool DATICE multi-archives in which we will implement the possibility to deal with hiatus or erosion as well as complex chronological trends (opposed time evolution in eolian units and paleosols). This will also enable us to assess robust sedimentation rates and thus to constrain the IPSL-CM model for a realist and quantitative estimate of the dust-climate retroactions.
Second, the data gathered in previous section will be separated in different geographic zones (e.g. Mediterranean, North Atlantic, Asia, Southern Ocean). This will enable first synchronization tests as for the interglacial period.

1-b-iv – Production of a coherently dated sequences over H2 and H4 (July-Sept 2018)

The method for the production of the climatic and environmental sequences is exactly the same as the one given in part 1-a-iii. We will especially use the paleomagnetic signal around the Laschamp event (~40000 years before present) for H4 and test the connexion between the Mediterranean region and N. Atlantic region with some available tephras.

2- Model interfaces (axis 2)

2-a FORAMCLIM

2-a-i Implementation of a FORAMCLIM interface so that it is easily run with IPSL, and eventually iLOVECLIM output (Jan – June 2017)

Currently, running FORAMCLIM requires many steps including corrections for present-day biases and regridding. The way FORAMCLIM was written makes its use very time-consuming if we want to use it for long simulations/high resolution model output. The model will therefore be adapted for an easier use with large input files. This work can directly be applied for first analysis of existing IPSL simulations for mid-Holocene, early Holocene, MIS3 and MIS4 stages (the LGM simulation has aleady been performed).

2-a-ii- Implementation of a method enabling the use of FORAMCLIM with the outputs of iLOVECLIM (July 2017- June 2018) and applications (July – Dec 2018).

There are a few variables missing from the marine biogeochemistry model implemented in iLOVECLIM that are required as inputs for FORAMCLIM. The objective here is therefore to compute these variables, either by working on the marine biogeochemistry model itself, or by building simple rules from available output from the IPSL model.

2-b BIOME (Jan – Dec 2017)

The comparison between paleodata on vegetation (pollens) and vegetation model outputs (ORCHIDEE) are limited because ORCHIDEE models the presence and productivity of different plant functional types which are not directly comparable to pollen counting. We will implement and use the BIOME model in the IPSL-CM to generate outputs that are coherent with pollinic records on the abrupt events of the last glacial period. Specific output from climate model usually require special post-treatment if we want to use a model such as BIOME. We will create an interface to use BIOME with IPSL and iLOVECLIM output and test different methods for these bias corrections. The tool will also enable the study of the influence of single factors (CO_2, single climate variables) on the vegetation so that the processes leading to its evolution are better understood. The outcome can be compared to more complex dynamical vegetation models such as ORCHIDEE but our aim here is really to build a tool with which we can easily compare with pollen data.

2-c Dust in interactive model for paleoclimate experiments using the coupled model (Jan-Dec 2018)

The configuration LMDZORINCA of IPSL-CM forced by sea surface conditions obtained by the iLOVECLIM model will permit an improved understanding of dust emission and deposition under various climatic conditions. Calibration and validation of the model through results on dust sedimentation obtained within axis 1 will enable us to run the IPSL-CM in an interactive mode with dust. This task will be realised by permanent staff of L-IPSL and does not require specific manpower.

3 - Comparison between model outputs and data over selected time periods (2019).

The exploitation of model simulations and comparison to data synthesis will be performed by master 2 internships with involvement of permanent staff from labex L-IPSL (especially for publications).

Deliverables for 2016-2019

In the next five years, our goal is to build new data bases for the periods of interest in this project, to improve our models and their capacity to compare their results with data and to perform these comparisons. This will yield a better knowledge or the processes at stake during the last interglacial warm period and the abrupt climatic changes of the last glacial period. We thus propose the following sub-challenges or deliverables:

Deliverable D1 - A **well-dated** and **global** data synthesis of the last interglacial (temperature, precipitation, stable isotopes) with (1) well-dated temporal evolutions of climatic records (with propagated age and tracer errors) and (2) snapshots of climatic state for selected time slices (e.g. 130, 125, 120 and 115 ka – kiloyears before present -, in addition to the 127 ka and 116 ka time slices selected as part of the PMIP4 and CMIP6 projects).

Deliverable D2 - A **well dated** (200 years relative uncertainty) and **global** synthesis **integrating new targeted measurements** over two abrupt events of the last glacial period :

- Heinrich 2 : this event occurs in a full glacial context (maximum ice sheet extent, ~ 25 ka)
- Heinrich 4 : this event occurs in an intermediate glacial context (intermediate ice sheet extent, ~ 40 ka)

Deliverable D3 - Integration in climate models of two interfaces for climatic tracers:

- **FORAMCLIM** : an ecophysiological model for growth and distribution of foraminifera (Lombard et al., 2011) to (i) link the relative abundance of various species of foraminifera (a major proxy in marine archive) to climatic parameters and (ii) study the impact of habitat on paleoceanographic records.

- BIOME : a biome model enabling the reconstruction of the natural vegetation at equilibrium and a direct comparison to the observed and measured pollen distributions (the BIOME classification has been used in the analysis of many pollen records).

Deliverable D4 - Realistic implementation of the interactions between dust, vegetation and climate in the coupled model in order to run paleoclimate simulation including **dust in interactive mode**.

Deliverable D5 - Model-data confrontation on the key time periods of this project (last interglacial period, one abrupt event in full glacial context, one abrupt event in intermediate glacial context). This will particularly enable us to test the different hypotheses leading to abrupt climatic change (freshwater flux, change of sea-ice regime in northern Atlantic, changes of ice-sheet extent through iceberg discharges, bipolar seesaw or tropical – high latitudes teleconnections, …).

2-LP2: Reconstructing and attributing climate variability since the early 20th century

Project leads : Slimane Bekki, Frédérique Cheruy, Marjolaine Chiriaco, Eric Guilyardi, Juliette Mignot *(alphabetical order)*

Participants

LMD – EMC3, ABC(t), DPAO
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LOCEAN – PARVATI, NEMO
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LATMOS – SHTI, SPACE
Marjolaine Chiriaco, Slimane Bekki, Alain Hauchecorne, Marion Marchand, Franck Lefèvre, Sophie Bastin

METIS
Florence Habets, Laurence Lestel

IPSL- SIRTA
Martial Haeffelin, Jean-Charles Dupont, Sophie Cloché

LSCE- PALEOCEAN, GLACCIOS, PISP
Pascal Yiou, Philippe Naveau, Valérie Masson-Delmotte, Anne Juillet-Leclerc

External collaborators: Didier Swingedouw (EPOC, Université de Bordeaux)

Project summary (goals, methods)

Understanding, perception and recognition of climate change due to human activities are complicated by internal variability that occurs over a wide range of time scales (from days to several decades). This internal variability arises from the chaotic nature of fluid motions and from the interactions between the components of the climate system (atmosphere, ocean, cryosphere, continents and biosphere). It comes in addition to externally forced variability from both natural (solar activity and volcanism) and anthropogenic sources (emissions of greenhouse gases –GHG, sulfate aerosols etc.). The weight of internal versus forced components increases from global to regional scale (Deser et al 2012). **The overall goal of this project is to understand the relative role of external forcing and internal variability in shaping the climate variations since 1900, at the global, regional and local scales**. For this, we promote reconstructions of the climate over the historical period where internal variability is constrained to observations, taking benefit of the unprecedented amount of high quality observations during the last decades in some specific areas. First, the reconstructions will provide the basis for analysis of the climate at various scales, providing a unique opportunity for identifying trends and processes of decadal variability. Second, analysis performed in this project provide ideal test-beds for reducing persistent biases and systematically testing parameterisation which otherwise remain, in some places, quite empirical. This project also paves the way for the contribution of IPSL to climate services, including the initialisation of decadal forecasts and providing more reliable reconstructions to test the models developed for impact studies.

These reconstructions require a detailed review of the external forcings themselves (solar, volcanic, aerosols, dust) as well as a methodological work on how to best drive the model components by observations. This is performed in a first set of tasks (task 1), The second set of tasks (task 2) aims to understand the relative role of external forcing and internal variability in shaping the climate variations since 1900, at the global, regional and local scales. The atmosphere-only reconstructions, a central and common tool within the project, will be further extended (coupled reconstructions, regional simulations, downscaling…) as well as compared to ensembles of free (no nudging) simulations to address specific science questions. The goal is to identify how external forcing influences the statistical distribution of climatic events, in order to understand how these distributions may evolve in the future as external forcing changes. Analysis of the nudged simulations together with observations available at IPSL will also provide test cases for process-oriented evaluation of the model's physics. Hence, task 2 will not only feed from the developments performed in task 1 but it will also feed back to the latter for subsequent improvements. Let's emphasize here that the aim of the project is not to produce an additional climate reanalysis while several centres already do so with dedicated tools. The idea here is to gather expertise and scientific questions around the use of the IPSL climate model, using (among others) the common reconstructions tool for various scientific questions, and feeding back onto the model and forcing implementation developments from different space and time scales perspectives.

Note that the methodology proposed here has slightly evolved over the year, after inputs of external reviewers and internal discussions.

Progress so far

The different tasks of the project are still progressing rather independently. Year 2016 has primarily been devoted to advancing on task 1.2. A report regarding volcanic activities (which ended in August 2016) has been sent separately. Regarding the solar forcing : the objective of the study is to test how the chemistry-climate IPSL model reproduces satellite-derived correlations between solar forcing and atmospheric composition, with a specific focus on the ozone and more generally to test its capacity to reproduce links between solar variability, stratospheric ozone and climate. For this, the chemistry-climate IPSL model is forced by different solar reconstructions.

The figure below shows the links between solar variability and ozone for the period 10/1991 to 8/2007. It shows the average ozone response to UV variability (here named sensibility) in an ensemble of 5 chemistry-climate simulations. The mean sensibility profile changes little over 3 year intervals. This shows that the response is not sensitive to the phase of the 11 year cycle. Nevertheless, the dispersion of the 5 simulations is clearly weaker during the maxima of the cycle.

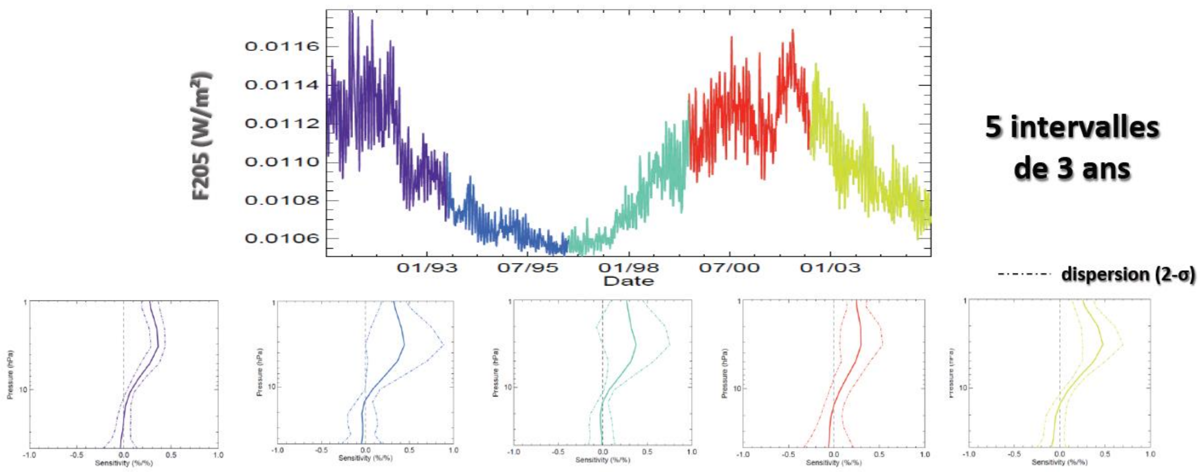


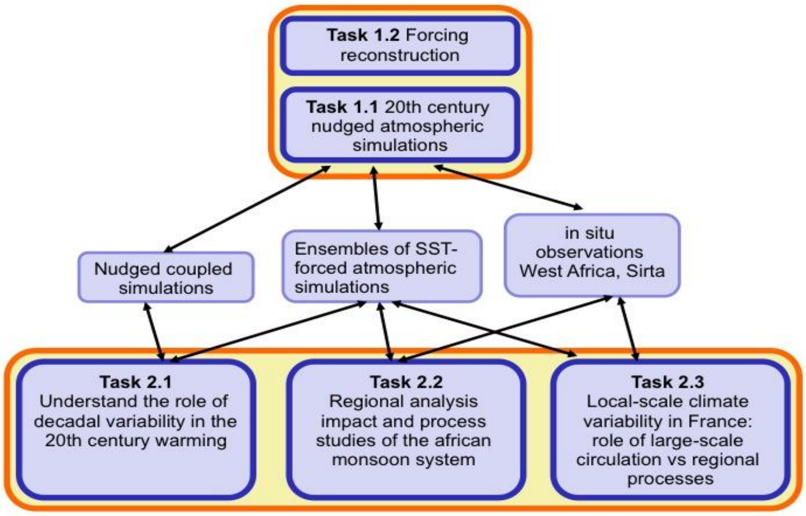
Figure : (top) time evolution of the incoming flux at 205 nm (F205 en W/m2) over the 18 years period; (bottom) vertical profiles of sensitivity to stratospheric ozone (% of the ozone variations for 1% of F205 variation) for each 3 years interval of this 18-years period, from 10/1991-9/1994 (descending phase of the cycle 22) to the period 9/2004-8-2007 (descending phase of the cycle 23). The dashed lines show the dispersion (2-sigma) around the mean of the 5 members The 5 intervals of 3-yrs are shown with different colors.

Atmospheric climate reconstructions with the atmospheric and land-surface models under development for CMIP6 are in construction for the (1958-2014) period (task 1.1). For the nudged reconstruction, the large-scale dynamics is constrained to the ERA-40/ERA-Interim re-analysis in order to reduce large scale biases from large scale dynamics misrepresentation. These reconstructions are carefully analysed to evaluate the realism of the near surface climate especially over land and identify sources of uncertainties.

As of task 2.1, one of the strategy foreseen to guide the climate model in coupled mode has been fully examined in perfect model configuration and published (Ortega et al 2016). This new strategy is based on the use of sea surface temperature only to constrain the model, with a variable restoring coefficient which increases proportionally to the mixed layer. The constraint is thus stronger when the surface signal has to be incorporated on a deeper physical layer. As indicated in the document, task 2.2 deserves some internal discussion and coordination probably with LP3. It will thus start later. Task 2.3 will begin as soon as possible when the post-doctorant will arrive. Datasets to be used in this task are already available, so the scientific analysis will start immediately. The first step of the analysis will consist in characterizing meteorology at local scale, using temperature and precipitation distributions for a given large-scale circulation, and studying the relation between these two parameters at different scales, and their evolution.

Program until 2019

The project in itself has to take off during 2017 and the program until 2019 is essentially to achieve the different tasks proposed in the project. This figure recalls how the tasks depend on and feed each other.



Deliverables for 2016-2019

D1.2	Delivery of a set of atmosphere-only reconstructions of the global climate since the early 1950s, earlier if relevant	Task 1.2
D1.1	Delivery of a set of novel, in-house, physically based solar, volcanic, tropospheric aerosols (e.g. dust) external forcings and implementation method in the IPSL climate model	Task 1.1
D1.3	Delivery of a protocol for the coupled reconstructions of the global climate for the last decades	Task 2.1
D1.4	Delivery of publication proposing a validation of the atmosphere-only and coupled reconstructions against observations on the west African monsoon region.	Task 2.2
D1.5	Delivery of scientific publication on the understanding of climate variability at local scale, over Paris Area	Task 2.3

3-LP3: Impact of climate change

Project leads: C. Rabouille and B. Sultan

Participants

Teams	L-IPSL contributors	External collaborators
SP1	Marco Gaetani (LOCEAN) Serge Janicot (LOCEAN) Benjamin Sultan (LOCEAN) Ben Parkes (LOCEAN) Dimitri Defrance (LOCEAN) Moïse Famien (LOCEAN) Frédéric Hourdin (LMD) Cyrille Flamant (LATMOS) Mathieu Vrac (LSCE)	
SP2	Christophe Grenier (LSCE) François Costard (GEOPS) Antoine Séjourné (GEOPS) Catherine Ottlé (LSCE) Masa Kageyama (LSCE) Mathieu Vrac (LSCE) Albane Saintenoy (GEOPS) Anne Jost (METIS) as InterFrost participant	Alexander Fedorov (Russie) Pavel Konstantinov (Russie) Ivan Khristoforov (Russie) > 20 InterFrost participants (France, UK, Germany, Sweden, USA, Canada)
SP3	Vincent Thieu (METIS) Marie Silvestre (METIS) Josette Garnier J(METIS) Gilles Billen (METIS) Ludovic Oudin (METIS) Christophe Rabouille (LSCE) Laurent Bopp (LSCE) Josiane Ronchail (LOCEAN) Claire Lazareth (LOCEAN) Vincent Chaplot (LOCEAN) Robert Vautard (LSCE) Mathieu Vrac (LSCE)	Alberto Borges (Belgique) Nathalie Gypens (Belgique Pierre Regnier (Belgique) Goulven Laruelle, (Belgique) Ronnie Lauerwald (Belgique) Philippe Cugier (IFREMER, France)

Project summary (goals, methods)

In 2014, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has confirmed that the increase in anthropogenic greenhouse gases emissions has produced (and will continue producing) global climate change with potential impacts on natural resources, ecosystems and human's activities. These impacts and the necessary adaptation of most vulnerable regions are addressed in a separate volume of the AR5 report written by Working Group II "Impacts, adaptation and vulnerability". As said in this report "Climate change is projected to amplify existing climate-related risks and create news risks for natural and human systems". It is now clear that Climate change has emerged from natural variability on a global basis for temperature, but changes in precipitation intensity and seasonal patterns do not reach a consensus especially when regional scales are investigated. Yet, the water cycle at the regional scale and its changes are the main drivers that control impact on human populations and ecosystem's sustainability. Therefore, it is a great challenge to assess at the regional scale the time when **climate change impacts will emerge from present-day climate variability. This is particularly relevant in some regions that are highly threatened by climate change like the Arctic regions, the Mediterranean and for populations from developing countries who highly depend on natural resources like in West Africa.** In this project our goal is to tackle three different types of climate impacts in different regions where IPSL has expertise and L-IPSL initiated activity through previous projects. The large project will build upon these to develop methodologies for emergence of impacts.

In West Africa, for example, deciphering between climate variability and climate change and their impacts on societies through agriculture is a very challenging task. As global warming in this region of the world will affect numerous sectors such as energy, agriculture, water use and health, the time of emergence can differ and some sectors and/or some populations can be affected faster than some others. Knowing which sector will be first affected by climate change can help to support adaptation policies. In the warming Arctic and subarctic where permanently frozen soils dominate water and soil retention, climate change has already impacted the thermal structure of the surface soils. It is thus essential for the potential positive feedbacks that thawing permafrost can provide on the carbon cycle to understand how this impact will propagate on the permafrost thermal state, affecting water catchment hydrology, groundwaters and the mechanical stability of the soils in Arctic and subarctic regions. In addition, in all regions impacted by climate change, it is also crucial to assess the vulnerability of ecosystems to climate change, due to the importance of ecosystem services and goods (food production, water quality, soil retention and transfer downstream, connectivity between ecosystems). In this regard, aquatic ecosystems are of main importance as they transfer water, nutrients, carbon and particles downstream to the coastal zone and sustain in itself a large productivity that serves as food reserves for a large share of the world population (>50% for freshwater bodies, Kummu et al, 2011).

Several challenges have to be achieved in the coming decade concerning impacts of climate change. Simulations of regional climate are increasingly becoming available and, combined to impact models, their use to adapt/mitigate the impact of climate change is required in key regions. The assessment of the time of emergence (ToE) for climate change impacts will provide an estimation of the time available before the consequences of climate change become too severe for the humans/ecosystems of vulnerable regions. At L-IPSL, we have targeted three specific regions with impacts of climate change:

- West Africa where water resources and agriculture are largely dependent on climate and its variability/change
- Arctic and subarctic regions where the water cycle, from surface to groundwaters, is impacted by climate change with potential feedbacks on greenhouse gases
- Densely populated mid-latitude regions where water quality and aquatic ecosystem services from land to coastal ocean are threatened

The main question raised when mitigation or adaptation is concerned is the time of emergence of these impacts from the variability linked to climate variations. When will these impacts reach a critical treshold? How can human societies or ecosystems adapt to the new situation in a changing climate?
Our challenges in Labex-IPSL will be to tackle this issue by implementing these three research sub-projects in a collaborative manner through series of workshops in order to share knowledge and metrics of the Time of Emergence (ToE). The exchange of experience on this common goal applied on different climate change and impacts will strengthen the L-IPSL community working on impact of climate change and deliver a reflexion/methodology to tackle ToE questions.

Sub-project 1: Impact of climate change on water resources and agriculture in West Africa : a time-of-emergence approach (started in October 2016)

Uncertainties affecting climate model simulations are reflected in impact studies, which are based on climate models outputs. Global climate models display a significant spread in prediction over West Africa due to their divergent capabilities to model the West African Monsoon (WAM), which is the main rain carrier in the region. Therefore, reducing (or being able to quantify) the uncertainty of climate models in West Africa would provide impact models with more constrained inputs. The main objective of this study is the reduction of the uncertainties affecting the definition of the time of emergence of the climate change signal in impacts, through the understanding of the uncertainties in climate models. The definition of critical metrics to evaluate climate models, based the sensitivity to specific mechanisms and/or forcings, and the subsequent classification, appears crucial in this respect (see below).

Sub-project 2: Impact of climate change on arctic and subarctic regions : the impacted water cycle from surface to groundwaters (started in 2016, post-doc to be hired in 2017)

The project will be based on a combination of an international modeling benchmark project and the development and of a unique reference field database on surface and subsurface hydrology in the Siberian Lena River Basin. The study of the system in the context of climate change will thus benefit from well validated and optimized codes to represent coupled Thermo-Hydrological codes operating at the scale of a landscape unit with the full complexity of field conditions. The international InterFrost code inter-comparison project hosted at LSCE (wiki.lsce.ipsl.fr/interfrost/) was launched in November 2013. Its intention is to provide a platform for the evaluation and optimization of coupled heat and water transfer codes and activate the modeling community around climate change impact issues requiring rapid development of efficient and validated codes. So far, academic test cases were considered with some validation experiments performed in a cold room at GEOPS. For the next phase to come, more realistic and complex test cases have to be developed and modelled, especially including non-saturated water flow conditions. In this purpose, time series measurements (started since 2012) performed in Central Yakutia (East Siberia) will be continued and compiled into a unique reference river-valley monitoring setup and database. A transect through a river and its underlying permafrost is instrumented in collaboration with the Melnikov Permafrost Institute in Yakutsk to continuously monitor the hydrological and thermal state evolutions. This dataset will be further prepared to become a reference InterFrost test case with web site publications and submitted to the InterFrost community.

The key parameter studied will be permafrost temperature and put in relation with the evolution of climate conditions. Its evolution is complex, e.g. depending on land cover, presence of a water body, presence of ground ice. The key issues addressed are here water resources evolution (all year round liquid water is only available below water bodies where the unfrozen bulb, called talik, will increase and might become a through-talik, able to connect surface and sub-permafrost water with very different geochemical properties) and landscape evolution (Yakutsk area is a ground-ice rich region where propagation of summer heat at depth can reach the ice rich layer of the ground thus causing liquid water to be released and the triggering of ground subsidence leading to the creation of thermokarst lakes).

The time of emergence of climate change will be studied for various key parameters covering all typical sub-units of the valley-river system (0°C isotherm propagation, permafrost temperatures at distinctive locations) taking past monitoring data into account (air temperatures since 1830, ground temperature series beginning in 1930 as well as recent monitoring at Syrdakh river site) and past and future regional climate simulations issued from CMIP5 and Arctic CORDEX. Some key ToE issues will be proposed for InterFrost participants providing the base to extend the results obtained with Cast3M (LSCE code) to several other codes possibly adopting other modeling strategies thus providing a range of uncertainties in terms of quantitative ToE results.

Sub-project 3: Impact of climate change on water quality and aquatic ecosystem services from land to coastal ocean: nutrient and carbon transfer

The project will extend the ongoing work of a L-IPSL project related to the impacts of modified hydrological regimes on the ecological functioning of aquatic ecosystems (Mélanie Raimonet, WP4 post-doc until September 2017), using a mechanistic biogeochemical model (pyNuts-Riverstrahler) at a pluri-regional scale. This modelling effort presently integrates a process-based understanding of fluvial nutrient and carbon exports from the upper watershed to the estuary. The development of this model and its test in one case study in the Seine River basin and estuary is presently finishing.

The present project aims at generalizing the hydro-biogeochemical modeling chain GR4J - pyNus-Riverstrahler – C-GEM over all the north-east European Atlantic rivers (from the Rhine to the Guadalquivir) with the introduction of carbon exchange fluxes between aquatic ecosystems and atmosphere; at assessing the response of the aquatic continuum to climate-induced changes for these rivers flowing into the Atlantic coast; at quantifying the time of emergence (ToE) of the impacts on these systems over the present variability; and at establishing high resolution budgets of GHG emissions from regional aquatic continuum especially CO_2 exchanges with the atmosphere, and contribute to the revision of their impact in global Earth System model estimates under changing climate condition.

Progress so far

Sub-project 1 which is the most mature has started in 2016.

SP1: Impact of climate change on water resources and agriculture in West Africa: a time-of-emergence approach (lead Benjamin Sultan – LOCEAN)

West African climate is dominated by the West African Monsoon (WAM) dynamics and associated summer precipitation. WAM precipitation variability at time scales from interannual to multidecadal is mainly driven by global ocean SST anomalies [Rodríguez-Fonseca et al., 2015], but also drivers at the regional scale are important, as the Saharan Heat Low (SHL) [Lavaysse et al., 2009], which is in turn modulated by the radiative forcing from CO_2 [Cook and Vizy, 2015], Saharan dust [Lavaysse et al., 2011], and water vapour [Evan et al., 2015]. Unfortunately state-of-the-art climate models are still deficient in reproducing the historical variability and agreeing on future projections (Biasutti et al. 2013). A particularly relevant issue is represented by the inconsistency between the recent precipitation recovery observed across the Sahelian belt (Fontaine et al. 2011) and the future scenarios projecting a zonal precipitation dipole with wet conditions in central-eastern Sahel and a drying in the west (Monerie et al. 2012). The uncertainties in the model representation of the historical and future West African climate may be attributed to the low skill in identifying and disentangling the numerous drivers of the variability, and the different sensitivity to global and regional drivers (Janicot et al. 2015; Gaetani et al. in review). Summarising, the open issues regarding the WAM dynamics and precipitation variability and change can be conveyed in two main issues: (1) the comprehension of the physical mechanisms; (2) the ability of the models in simulating the identified physical mechanisms and the sensitivity to different forcings.

Uncertainties affecting climate model simulations are reflected in impact studies, which are based on models outputs (Oettli et al. 2011). **The main objective of this study is the reduction of the uncertainties affecting the definition of the time of emergence of the climate change signal in impacts, through the understanding of the uncertainties in climate models. The definition of critical metrics to evaluate climate** models, based on the sensitivity to specific mechanisms and/or forcings, and the subsequent classification, appears crucial in this respect.

The project will be developed through the following actions:

- **Identification of key areas and indicators for impact assessment:** namely, agriculture (crop production), water resources (drought risk), human health (heat stress), energy (availability of renewable sources);
- **Analysis of climate models:** existing climate simulations, mainly from the CMIP5 archive, will be analyzed to build a classification process-oriented, i.e., based on the sensitivity to different forcings (SST, GHG and aerosol) and the model ability in reproducing the main physical mechanisms (global teleconnections, regional feedbacks);
- **Application of climate outputs to impact indicators:** simulated climate variables will be used to run crop models and compute impact indicators.
- **Process-oriented assessment of the impacts:** impacts will be assessed for each of the model family previously identified, to verify whether the model classification is suitable for building impact scenarios or a finer classification is requested.
- **A time of emergence analysis** will be performed on climate inputs and impacts outputs to determine when climate change impacts will emerge from present-day climate variability.

So far, Marco Gaetani has been hired as a postdoc in LOCEAN to work on the project on October 1st. He has started to read the papers and participated to a meeting with Mathieu Vrac (LSCE) and the team in LOCEAN (Serge Janicot, Benjamin Sultan, Moïse Famien, Dimitri Defrance) on methodological aspects (time of emergence studies, choice of runs) and future works.

Program until 2019

A series of workshop will be conducted with 2 workshops in 2017 and one per year in 2018 and 2019. The first two workshops will be dedicated to methodological issues of time of Emergence and regional climate uncertainties and projections, while the last two workshops will be dedicated to cross presentations of time of Emergence in different contexts related to the three subprojects.

Two subprojects will start in 2017 and will last until 2019:
- Impact of climate change on arctic and subarctic regions: the impacted water cycle from surface to groundwaters
- Impact of climate change on water quality and aquatic ecosystems services from land to coastal ocean: nutrients and carbon transfers

SP2. Impact of climate change on arctic and subarctic regions: the impacted water cycle from surface to groundwaters (lead C. Grenier-LSCE and F. Costard-GEOPS)

The project includes two main components. The first one concerns the development and evaluation of local process oriented Thermo-Hydraulical codes that can simulate the complex short and long time evolution of key landscape units under climate change. This is the overall aim of the InterFrost benchmark project in which the LSCE coupled TH LSCE Cast3M code is involved. The second concerns the studied system. A river-valley system was selected in the key region of Central Yakutia with a collaboration with the Melnikov Permafrost Institute (Yakutsk). A combined approach is considered to: i) complement and compile local Syrdakh river pilot site monitoring information, ii) simulate of the system with Cast3M over the monitoring period, iii) select and adapt (bias correction) past and future centennial climate evolution conditions based on climate simulation (CMIP5 and Arctic CORDEX) and local meteorological histories, and iv) based on these, study address the ToE issues, study the main system controlling parameters and provide a prospective of its future evolution. The unique Syrdakh database will be proposed to the InterFrost community. Due to the complexity of the natural system and code properties, simulation approaches among the presently 13 participating codes will necessary differ allowing inter-comparison of modeling approaches (from simple to complex) and of simulation results.

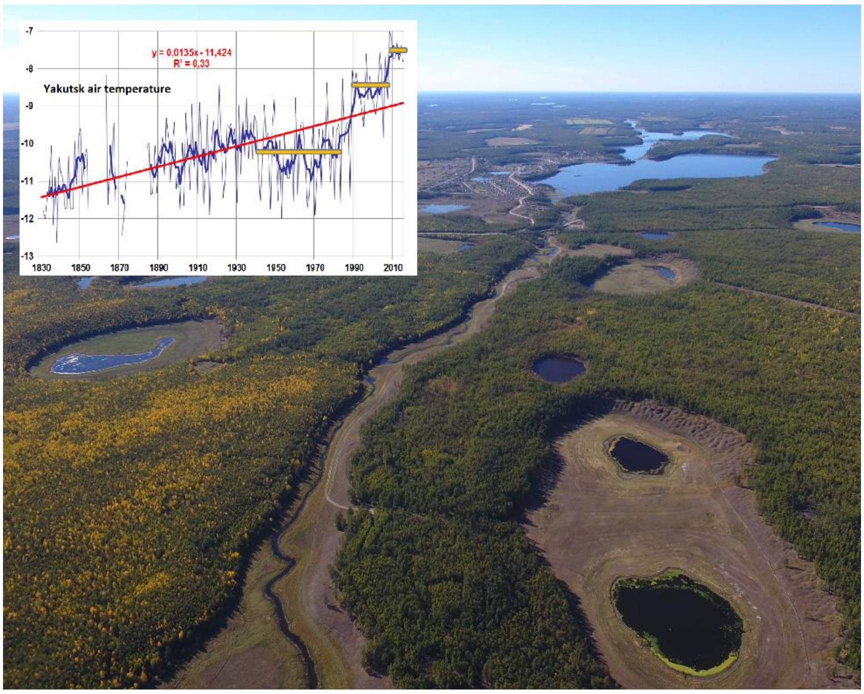


Figure: Drone view of Syrdakh region with the river valley with a thermokarst landscape, air temperature histories are provided from 1830 on.

The working program is structured as follows:

- **Task 1**: Global to regional climate simulations
    a. Review existing model results from CMIP5 and Arctic CORDEX for CY (Central Yakutia)
    b. Select a short list: reject models that are not adapted to permafrost conditions and/or unable to represent existing time series (e.g. T_{air}, Precip)
    c. Implement bias correction approaches and propose optimal time series for last and next centuries

- **Task 2**: Local impacts on the Syrdakh Pilot Site river-valley system (river, valley, meadow and pine forest covers)
    a. Complement ongoing field studies (e.g. implement some key measurements complementary to thermal monitoring like soil water content probes and/or geophysics like GPR or resistivity).
    b. Create a comprehensive and well-structured database for the Syrdakh site monitoring period (from 2012 on) to be published on the InterFrost web site.
    c. Simulate thermal state evolution during monitoring period with Cast3M (+ additionnal models from InterFrost project)
    d. Simulate past and future system evolution with ad hoc scenarios
    e. Sensitivity analyses to main parameters and extrapolate predictions to other typical CY river-valley systems

- Task 3: Time of emergence and controling parameters
  a. Atmosphere, ground & talik parameters from a combined analysis of observations and models
  b. Time to reach thresholds for start of ice wedge melting and through talik installation for typical CY systems

InterFrost aims are to propel the development and validation of efficient and realistic thermo-hydrological models to address the climate impact issues on small scale systems not represented in climate models. The dataset collected in Siberia will be proposed as InterFrost task once the dataset is gathered. The main tasks devoted to InterFrost are

- Publication of the first phase of the inter-comparison (13 codes on cases TH2 and TH3, refer to wiki.lsce.ipsl.fr/interfrost/), a preparatory step to the present project
- Organization of a workshop in late 2016 or beginning of 2017 to precise future tasks:
  a. Extension of the model development and evaluation issues to non-saturated flow conditions based on the most recent know-how. Review and reconsider existing laboratory cases to assess such issues and a future inter-comparison strategy. Climate simulation codes are already interested to join on this issue.
  b. Include realistic field cases for common simulation and inter-comparison, esp. the Syrdakh case.

A post-doc will be hired in 2017 to work on this program in close relation and making the link between simulation and field data participants, climate modeling and regional process oriented participants, prepare the Syrdakh dataset to communicate with the InterFrost participant community via web site publishing, publish the results in international journals.

SP3. Impact of climate change on water quality and aquatic ecosystems services from land to coastal ocean: nutrients and carbon transfers (lead V. Thieu-METIS and C. Rabouille-LSCE)

Global biogeochemical cycle's assessments have for long underestimated or oversimplified the transport of carbon and nutrient in watersheds, across the aquatic continuums. IPCC Assessments only recently accounted for the lateral flows of carbon, based on new research emphasizing its contribution to global and regional budgets (Battin et al. 2009, Bauer et al. 2013, Raymond et al. 2013, Reignier et al 2013). While research on nutrient cycling have rapidly integrated the filtering role of aquatic system (Meybeck and Vorosmarty 2005), biogeochemical models operating at large scales remain mainly (semi-)empirical (Global : NEW2 - Mayorga et al. 2010; European : GREEN - Grizzetti et al 2011; US : SPARROW - Alexander et al. 2001) and do not represent the physics and the variability of processes governing the functioning of aquatic ecosystems (Billen et al 2009; Garnier et al 2002). In addition, estuarine interfaces (involving multiple space and time scales dynamics) are often limited to well-constrained specific systems, and hardly ever consider in regional or global integrated land to sea assessment.

Global budgets thus required to be confronted with (and potentially enhanced by) regional models' assessments, as they are the only ones offering a comprehensive **biogeochemical accounting** of the transformation, elimination/immobilization of carbon and nutrients during their **transfer from small stream to larger river and finally to estuaries ad the coastal ocean**. These regional models are also prompted to help in **quantifying the cascade of climate-induced changes** along the aquatic continuum, which potentially includes both *direct* impacts on hydrological regimes and temperature, and *indirect* impacts on river ecosystem functioning, i.e. the biogeochemical response of the aquatic continuum to climate-induced changes in the hydrological cycle.

Subproject 3 (SP3) clearly identifies the need for a regional integrated process-based quantitative understanding of the aquatic continuum in response to climate changes.

A recent project was launched within the L-IPSL (WP4 project 15) to couple a semi-distributed hydrological model (GR4J-CEMANEIGE; Perrin et al., 2003, Valéry et al., 2014) to a mechanistic biogeochemical river model (pyNuts-Riverstrahler; Thieu et al 2015) and an estuarine 1-D biogeochemical model (C-GEM; Volta et al 2014). Developed in a view of a generic application at the continental scale, this modeling chain is currently tested on the Seine river basin (75,000 km², France) with regionalized projections of precipitation and temperature (BCCORDEX; Jacob et al., 2012) and using 4 GCM, a total of 5 RCM, and 2 prospective situations for the timeline 2100 (the most extreme IPCC scenario 8.5 and the stabilization RCP 4.5).

In SP3, the understanding of the carbon fate from land to ocean is of great importance and the modeling chain will directly benefit from the most recent progress on this research topic, in collaborations with scientists from the ITN C-Cascade (led by P. Regnier) which among other includes the improvement of the carbon dynamic within the pyNuts-Riverstrahler model (A. Marescaux, ongoing PhD). In addition, The UMR Metis has been collaborating since more than 25 yrs with several labs of the ULB and IFREMER, coupling our river basin model with their coastal zone models (EU-EROS, EU-Thresholds, EU-AWARE, and several projects of the Liteau program), while the LSCE group is actively involved in understanding river-sea connection in major regional rivers.

These recent or on-going researches will forms the basis of a dynamic modelling research framework, from which SP3 will take full benefits. SP3 research works will progress through the following achievements:

1. Generalizing the hydro-biogeochemical modeling chain GR4J - pyNuts-Riverstrahler – C-GEM over all the north-east European Atlantic (NEA) rivers (more than 350 000 km of drainage network from the Rhine to the Guadalquivir). Previous research has enabled to set up and validated the pyNuts-Riverstrahler for the recent period on the NEA domain (SEAS-ERA EMoSEM, Desmit et al. 2014) making the SP3 modeling exercise easier for the freshwater compartment. Most effort will be devoted to the generic application of estuarine C-GEM which reduces data-requirements by using an idealized representation of the estuarine geometry and allows quantitative prediction of hydrodynamics, salt transport and biogeochemistry at the appropriate spatial and temporal scales in alluvial estuaries. The scale of application (NEA domain) represents a main breakthrough for the river-estuary modeling chain.

2. Use the modeling chain to provide an integrated assessment of the aquatic continuum response to climate-induced changes for all western European rivers flowing into the Atlantic coast. Beyond the amount of carbon and nutrients exported to coastal area (where it might support harmful algal bloom), SP3 will grant a particular attention to the spatial and temporal assessment of aquatic ecosystems alterations along the gradient of climatic conditions offers by the NEA domain. Additionally, comparative analyses of individual NEA aquatic systems responses are expected (including hydrosystems morphology, climate conditions, estuarine geometry etc.). These outcomes should open promising discussions and collaborations with marine modelling teams (IPSL – LSCE – LOCEAN).

3. Main impacts brought out by the modelling chain in response to climate changes will be subject to concept of the time of emerge (ToE), in order to determine when climate change impacts will

emerge from present-day climate variability. Dedicated meeting will be held early in the project to define how to apply a common methodology and define metrics in the case of aquatic continuum.

4. Establish high resolution budgets of GHG emissions from regional (NEA) aquatic continuum especially CO_2 exchanges with the atmosphere, and contribute to the revision of their impact in global Earth System model estimates under changing climate condition. Beyond serving as regional benchmark for the global models, these regional emissions assessments should also provide useful quantitative information related to climate dynamic and feedbacks for Earth System models developed at IPSL.

We propose the following agenda for SP3:

	2016			2017				2018				2019	
	SP3 Impact of climate change on water quality												
	Generalizing the hydro-biogeochemical modeling to NEA												
	integrated assessment of response to CC												
	Times of Emergence												
	CO2 emissions from regional aquatic continuum												
	Datasets deliverable												
	Scientific paper achievement												

It appears important that SP3 starts in mid-2017 (ideally in June or July), to enable a joint time period where M. Raimonet (WP4 postdoc) could transfer the methodological developments produced in Labex project 15, in an efficient way to the SP3 postdoc candidate.

Deliverables for 2017-2019

Sub-project 1:

Deliverables	Type	Time of delivery
A comprehensive process-based classification of climate models	Paper	December 2016
Archive of multi-sectoral impacts indicators	Database	June 2017
Time of emergence of impacts on agriculture	Paper	December 2017
Time of emergence of multisectoral impacts	Paper	September 2018

Sub-project 2:

Deliverables	Type	Time of delivery
First phase of inter-comparison	Paper	February 2017
Interfrost workshop	Workshop	March 2017
Archive of CY meteorological and soil temperature Syrdakh field dataset	Database	End 2017, after compilation of September field survey
Simulation of talik evolution with Cast3M and comparison with Syrdakh field data	Paper	March 2018

Time of emergence of impacts and simulation of future impact of CC on river-valley system	Paper	Fall 2018

Sub-project 3:

Deliverables	Type	Time of delivery *
A new integrated quantitative assessment of nutrient and carbon transfer in western in western EU-rivers-estuaries	Paper	December 2018
Map of inland and estuarine aquatic ecosystem alterations under climate change (in river basins from the Rhine to the Guadalquivir)	Dataset	May 2018
Past and contemporary and future (climate-impacted) water, carbon and nutrient (N, P, Si) fluxes deliver to western EU coastal seas (southern bight of North sea, English channel, Gulf of Biscay, Iberian shelf)	Dataset	December 2018
Regional GHG estimate from regional aquatic system (rivers + estuaries) in western EU – contribution to global budget estimates	Paper	December 2018
Direction and magnitude of changes driven by climate, along the aquatic continuum of the North-East Atlantic domain (including time of emergence of impacts)	Paper	June 2019
CO_2 exchanges with the atmosphere,	Dataset	June 2019

4- Model development (TWP1)

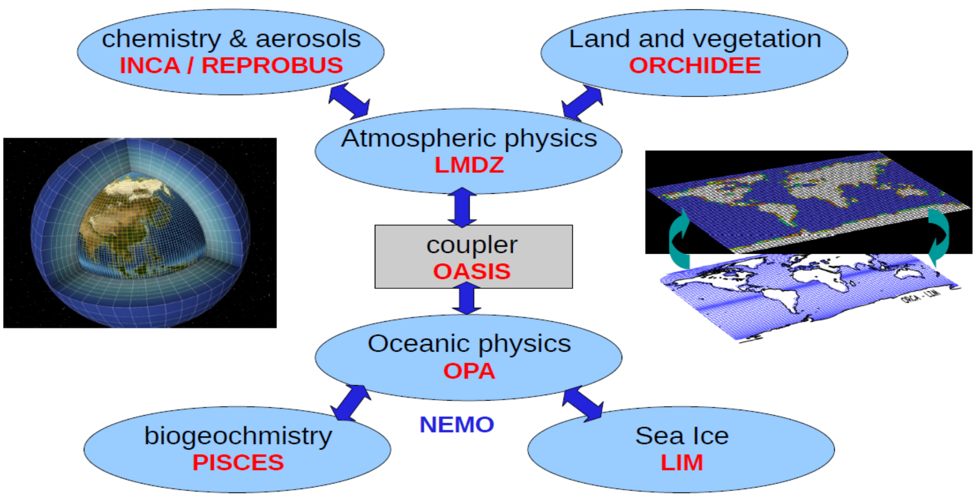
Project lead: Jean-Louis Dufresne, Olivier Boucher

Participants

Tasks	L-IPSL contributors	External collaborators
High resolution ocean modelling	Julie Deshaye (LOCEAN) Olivier Aumont (LOCEAN) Laurent Bopp (LSCE) Christian Ethé (IPSL)	
Running and checking a suite of CMIP6 simulations	Olivier Boucher (IPSL) Sébastien Denvil (IPSL) Marie-Alice Foujols (IPSL) and the ICMC steering committee	
Running and processing data for high resolution simulations	Olivier Boucher (IPSL) Sébastien Denvil (IPSL) Marie-Alice Foujols (IPSL) Thomas Dubos (LMD) and the ICMC steering committee	

Project summary

IPSL is continuously developing IPSL-CM, its Earth System Model, since about twenty years. This model is central to many research activities from theoretical studies to analysis of observations, from paleoclimate to future climate changes, from very specific studies to contribution to large coordinated experiments like CMIP. Currently, about 100 persons use and develop this model, and a much larger number of persons use the model results, within the IPSL community and beyond.



The IPSL-CM model is composed of physical, chemical and biochemical models of the various compartments (atmosphere, ocean, land, cryosphere) of the climate system. These models are all developed by IPSL generally in connection with other institutes. They are coupled with the OASIS coupler developed at Cerfacs as sketched in the figure above. Two new versions of this model, IPSLCM6.1 and IPSLCM6.2, are in development and will become operational in 2016 for the former and in late 2017 for the later. A next generation version that will use the new DYNAMICO dynamical core for the atmosphere is in development for a use in 2018. These developments are supported by different national or European projects, and the support of Labex L-IPSL can make the difference by supporting the following actions:

- *Development of a high resolution version of IPSL-CM.* High-resolution atmosphere models produce an improved precipitation distribution arising from higher-resolution orography and more realistic tropical cyclone frequency. Similarly, the sea surface temperature (SST) and ocean surface fields are better simulated by partly resolving oceanic eddies. It is therefore expected that higher-resolution coupled models will better represent some aspects of the climate at global and regional scales. Until now, IPSL-CM models have been mainly used for simulations over long periods (paleoclimate) or for process studies (cloud feedback, climate-carbon feedbacks, etc.) for which low or medium resolution models were more convenient. We will now also develop and use higher resolution version of our model to better address some topics such as climate change at regional scale. This requires some adjustments in current models as well as the use of the DYNAMICO dynamical core for the atmosphere.

- *Contribution to CMIP6.* The coupled model intercomparison project (CMIP) is central in climate and climate change studies. More than 25 projects have been endorsed for the sixth phase of the CMIP project, and each of them requires a significant number of experiments (typically 5 to 20). As a consequence of the broad range of scientific interest in the IPSL community and the added value of analysing an ensemble of experiments with the very same model, there is a strong interest in running a large ensemble of experiments with the IPSL-CM model. In addition to that, the CMIP results are used by a continuous growing community who request more model outputs and diagnostics. This leads to a complex management of model outputs, a production of a large number and volume of data and a difficult and demanding work to check and publish these data.

- *Development of specific and key aspects of models.* Models need to be continuously developed to improve their characteristics and to allow new possibilities. Many developments are supported by dedicated projects but some are not although they have large impact on model performance. We are in the final phase of gathering all these developments with IPSL-CM6, the new version of the IPSL earth system model. The completion of this work and the evaluation of the model performances will allow us to define in one year our priorities.

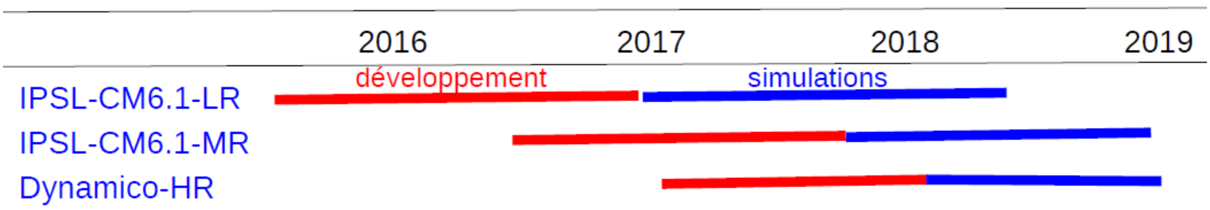
In the next two years, our work will be very much oriented by our contribution to the sixth phase of the CMIP project. We have obtained a large amount of computer time and storage volume during the period 2016-2018 that will allow us to have an ambition contribution to CMIP6. We plan to contribute to this project with the following model versions and resolutions:

1. two resolutions for the coupled model:

   - LR : Atm: 2.5x1.5° (144x144) L79, Oce: 1° L75
   - MR : Atm: 1.3x0.6° (280x280) L79 [TBC], Oce: 0.25° L75

2. a high resolution (0.5°) atmospheric model with the new dynamical core and the same physical package as IPSL-CM6. We plan to contribute to the prescribed SST experiments of the HighResMIP project with this model in late 2018.

The calendar of model development and simulations is the following:



The development of IPSL-CM6.1-LR is almost finished and this model version will be frozen beginning 2017. Test and improvements to prepare higher resolution version of the model has started and has benefit of some support to help the development of the high resolution version of the ocean model (task 1). IPSL will contribute to CMIP6 with a very large number of experiments and simulations, and support to help performing these runs is also asked (tasks 2 and 3).

Progress so far

Task 1: Development of a high resolution version of IPSL-CM

In order to take into account the effect of processes that are smaller than the model grid, atmospheric and oceanic models have parameterizations. When changing the grid resolution from a few hundreds to a few tens of km, most parametrizations can be kept unchanged but some have to be adapted. In the atmosphere, a classical problem when increasing the resolution is the tendency of model to develop so-called grid point storms, i.e. strong numerical convective rainfall associated with a strong vertical ascending motion in one particular column of the model. Developments to solve this problem are ongoing within an existing project (ANR Convergence). For the ocean, a high resolution NEMO 1/4° model (1442x1021x46 grid) will be used. A direct consequence of a better resolution is the improvement of the interactions between currents and topography. A better resolution allows an improvement of meso-scale processes provided that parameterizations are modified. Indeed, this spatial resolution is not sufficient to simulate the meso-scale processes in the low latitudes that cover more than 50% of the ocean. Without these improvements, the current simulations show very noisy vertical velocities, which is unsuitable for the biochemistry processes which variables are primarily driven by the vertical dynamical processes.

The developments made within the Drakkar collaboration that originally developed the high resolution NEMO 1/4 ° model, ORCA025, have been included in standard version of NEMO used by the IPSL climate model, eORCA025. Compared to ORCA025, the geographical imprint of eORCA025 has been extended to the south so as to represent better the coastline of Antarctica and the freshwater fluxes from the continental ice shelf toward the ocean. More precisely, these fluxes have been split in two components: freshwater fluxes along the coastline to mimic the dynamics of under-ice shelf seas (currently parameterized, but the configuration is ready to sustain an explicit representation of those dynamics) and freshwater fluxes associated to iceberg melting in the open ocean. The latter has been shown to reduce significantly an overestimated polynya in the Weddell Sea. Apart in the southernmost part of the configuration, the bathymetry of eORCA025 is identical from that of ORCA025 which has been carefully tuned so as to represent as well as possible current-topography interactions, in particular in small straights or deep ocean canyons (such as Faroe-Bank Channel).

At all latitudes, simulations with eORCA025 show intensified the eddy kinetic energy (EKE) at surface when compared to coarser resolution simulations, suggesting that they resolve more small scale processes, as expected. However, at this resolution, the mesoscale ocean processes are hardly resolved in the tropics only. Elsewhere, the model outputs are likely to reflect both numerical noise and realistic ocean processes. Gildas Mainsant delivered a substantial effort to reduce the numerical noise of eORCA025 simulations by adjusting the choices of model schemes and parameters. This task involved running multiple tests of sensitivity over interannual simulations and then intercomparing those, which is quite challenging at such high resolution on the global scale. It has led us to tune the horizontal viscosity, the conductivity of snow, the horizontal advection and convection schemes, the vertical mixing representation and the sub-meso-scale parameterisation, compared to the original ORCA025 configuration. Still ongoing is sensitivity experiments to mesoscale parameterisations which require ad-hoc tuning so as to preserve mesoscale processes where explicitly resolved by the model.

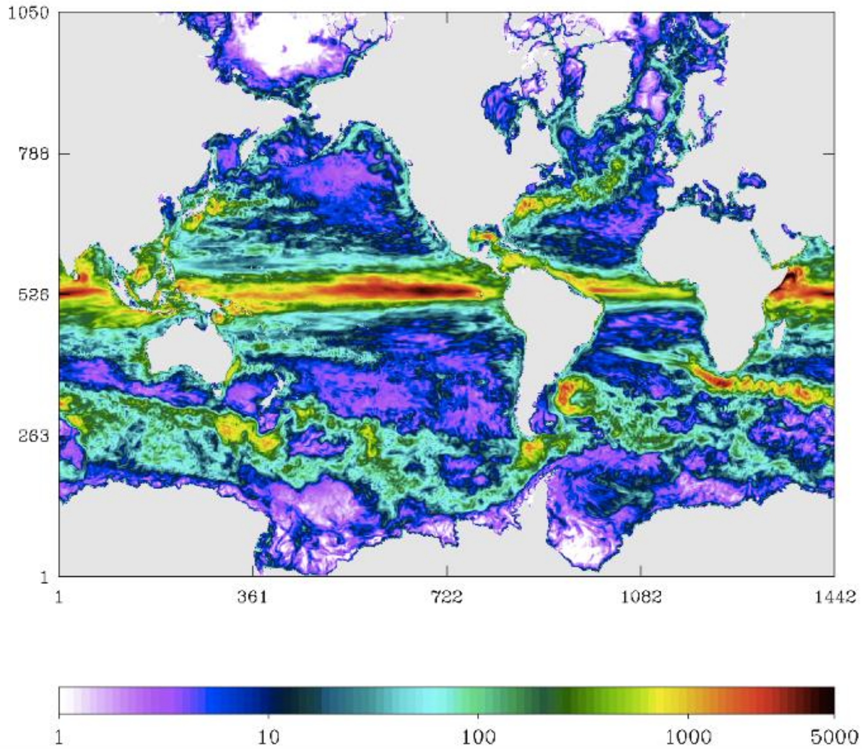


Figure : Eddy kinetic energy for year 1999 (run started in 1981 from climatology and rest, and uses CORE2 atmospheric forcings) in the model grid framework (colors follow log scale, unit is cm2/s2) for a simulation with the eORCA025 model.

Program until 2019

Task 2: Help to run and check a suite of CMIP6 simulations

The sixth phase of the CMIP project is very ambitious. The broad and diverse interests of IPSL scientists, the features of IPSL-CM6 and the computer resources we have obtained for the next years open the possibility of a major contribution of IPSL to CMIP6. IPSL scientists lead or are currently strongly involved in twenty MIPs endorsed by CMIP6. This will require to run a large ensemble of experiments and to publish the data produced. More precisely, this will require to drive the very large number of output variables (about one thousand), to specify the precise configuration of the model and the forcings, to check the proper execution of hundreds of runs, and to check the quality of the outputs and to publish them. We ask for a one year software engineer to help on these two latter tasks.

Task 3: Help to run the High resolution version of the IPSL-CM6 model

We plan to finish the developments on the high resolution of the IPSL climate model at the end of 2017 and the development of the high resolution atmospheric model with the new dynamical core by mid-2018. The runs and the processing of the data are very demanding and we ask for a one year software engineer to help doing these tasks.

Deliverables for 2016-2019

Task 1*:* A first version of the high resolution version of the ocean model, eORCA025

Task 2: A suite of CMIP6 runs are performed and their results are made available to the community through ESGF

Task 3: An ensemble of runs with the High resolution version of the IPSL model are performed and their results are made available to the community through ESGF