Project scope and plan

Project name	**QUEST: Quantifying Uncertainties over Europe in climate models, Scenarios and Tunings**
Research field	Climate modelling, climate dynamics

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1. Key scientific/societal/technological contribution of the proposal

Climate change is a central problem for humanity with important ramifications in policy and decision making. Robust and cost-efficient policies on mitigation and adaptation require assessments of current and future risks for natural and human systems. The major goal of the present project is to quantify uncertainties of future climate change over Europe and west Africa. The work will concentrate on understanding the changes in climate at +2°C and +4°C global-mean temperature change. The first target corresponds to the one of the Paris Agreement, the second one to the warming level in 2100 according to the current global emission trajectory. Nevertheless, our knowledge of climatic change for such targets is hampered by very large uncertainties from various sources. They arise from internal climate variability, representation by climate models of the present climatic state, unresolved processes and numerical choices in the design of these models. The present project proposes an ambitious plan to assess these sources of uncertainties using the recently developed IPSL climate model in an unprecedented coordinated framework. Ensembles of hundreds of simulations to be run in parallel will explore internal, numerical and structural uncertainty in future climate change projections and near-term decadal predictions.

2. Detailed proposal information

2.1. Justification for the importance of the scientific problem and the requested resources

The IPCC special report on global warming at 1.5°C agreed on October 8th 2018 makes clear statements on the ongoing climate change and the necessity for urgent political and socio-economical action. Climate change is no longer a possible future, it has become a reality : we are now already close to 1°C of increase in global temperature since the pre-industrial era. Yet, robust and cost-efficient mitigation and adaptation policies require assessments of current and future risks for natural and human systems. This risk assessment relies on projections of the future climate relying on physically-based numerical simulations of the global climate that couple oceanic circulation, atmospheric dynamics, convection and clouds, together with continental hydrology, the carbon cycle and its interaction with the biogeochemistry *etc*. Because of the global nature and complexity of the climate system, and because of the length of the simulations required, the approximations made in such models are numerous. Improving those simulations and quantifying the associated uncertainties are of prime importance for society.

The present QUEST project targets the quantification and understanding of uncertainties in climate change projections for the next decades using the brand new version of the IPSL coupled atmosphere-ocean model, IPSL-CM6, which has been developed for the 6th version of the international Coupled Model Intercomparison Project (CMIP6). The development of this new version of the model is the result of an unprecedented coordinated effort at IPSL and has resulted in remarkable improvements in the representation of the present-day climate in comparison with previous versions. The PRACE resources will allow for the first time to explore the main sources of uncertainties in climate projections in a fully integrated way: [i] **uncertainties associated with the internal variability (found to be large in the latest version of our model) require large**

ensembles of simulations unaffordable with currently available national resources, [ii] **structural uncertainties,** and in particular those associated **with a significant increase of the grid resolution** allowed by the PRACE resources, and finally [iii] parametric uncertainties associated with the **choice of the model free parameters**, for which the PRACE resources will allow to **run ensembles of hundreds of simulations in parallel.** The latter will sample the space of free parameters by applying for the first time in climate change projections the state-of-the art approaches developed by the Uncertainty Quantification community. IPSL (LMD) is already involved in the use of such new approaches in the framework of the ANR HighTune project coordinated by Météo-France CNRM.

Addressing these three sources of uncertainty will drive the structure of the project in 3 specific yet coordinated work-packages, each being associated with a plan of simulations and subsequent analysis that will contribute answering topical questions regarding our current and future climate. The uncertainty associated with the internal variability of the climate system will be explored here by running ensembles of transient simulations of the changing climate starting from various observation-based initial states but also more original equilibrium long simulations at various constant forcing, required to estimate the impacts of various warming levels, in particular +2°C and +4°C. Analysis will be specifically focused on the climate over Europe and west Africa. The level of +2°C corresponds to the target of the Paris Agreement, adopted in December 2015 by 195 countries. The +4°C of global temperature increase corresponds to the warming expected in 2100 given the global emission trajectory as expressed in national pledges. To address the uncertainties associated with current trade-offs on the model grid resolution, we will run, in parallel of IPSL-CM6 reference configuration, simulations at increased resolution, in particular in the ocean. Indeed, a significant increase of the oceanic resolution is expected to substantially improve the representation of the mean oceanic circulation at the global scale and particularly in the North Atlantic. What is the impact of such improvement on the representation of oceanic and hence climatic modes of variability, on interannual to multi-decadal timescales ? The project QUEST should allow to provide first responses to this critical question. Concerning the sensitivity to free parameters, we will tackle another very important and unaddressed question so far: what are the smallest and largest climate sensitivities that could come from possible alternative choices of cloud and convective parameters, under crucial energetic constraints that are imposed in the tuning of the standard configurations of our coupled model? We will consider as well the uncertainties associated with the representation of freshwater transfers from the cryosphere (Greenland ice sheet, sea ice, polar glaciers) to the North Atlantic, the representation of the vertical mixing in the ocean and ice and snow properties.

This set of scientific questions requires a global approach from the climate community and a heavy set of coordinated experiments. The project is estimated to require 72,685,000 hours of CPU, among which 17,040,000 will be devoted to ensemble and equilibrium experiments with the IPSL-CM6A-LR standard configuration, 40,470,000 to the exploration of higher resolutions and 15,175,000 to the realisation of parametric ensemble and tuning issues with the atmosphere alone configuration. We aim to use the requested computing resources as uniformly as possible throughout the project duration (see section 3.1). We emphasize furthermore that the project needs a full access to the ensemble of tools and software developed at the IPSL around the climate model, which is only available in the container cont003 on the Joliot Curie - SKL supercomputer. Hence the present project will require an access to this container, and will not be achievable without such access.

2.2. Overview of the project

In order to address the question of uncertainty quantification and understanding in future climate projections, the project will use the latest version of the IPSL coupled model IPSL-CM6A. The climatology of the model has been greatly improved compared to the previous IPSL-CM5A version concerning the representation of clouds, a significant reduction of systematic biases in sea surface temperature, a better representation of monsoons and life cycle of rainy convection over lands and in particular over West Africa. An important effort has been done as well to adjust the parameterizations of the atmosphere and ocean to obtain a strong enough formation of North Atlantic deep water (NADW) and associated meridional heat transport, and better representation of the Arctic sea ice. This version of the model is characterised by large centennial variability in the Atlantic circulation, inducing a large internal climate variability, even at the global scale. Although climate change is global in nature, we propose here to focus our uncertainty quantification on the near future evolution of the climate over Europe and West Africa and their relationship with the variability of the Atlantic Ocean. This variability is associated with the dense water formation in the North Atlantic and Weddell Sea, which shows a much larger variability in IPSL-CM6A than IPSL-CM5A, and could be strongly affected in the future, notably by the evolution of the Arctic sea ice.

In order to reach its main objectives, the QUEST project will tackle important technical and methodological issues. It will first promote the use of equilibrium coupled simulations with constant forcing as an alternative to ensemble of transient experiments. The idea is to separate the "equilibrium climate sensitivity" from the internal variability when looking at the structural or parametric uncertainties (WP 2 and 3), in order to avoid rerunning large ensembles for each question, as is usually done. The current or future climates are indeed not in equilibrium, producing a delay in the global warming (for a constant forcing). This is due to the large thermal inertia of the ocean and of its slow heat uptake, which should in principle prevent investigating the future climate with equilibrium simulations. It has been shown during the preparation of the IPSL-CM6A model for CMIP6, that it is possible to target the correct present-day conditions in transient historical simulations by first adjusting a present-day equilibrium simulation, with a slightly increased ocean surface albedo in order to account for the effect of the oceanic heat uptake. The CMIP6 historical simulations are then initialized with the true albedo and pre-industrial forcing. One aspect of the proposal will be to validate and use this methodology (by comparison with ensemble of transient simulations in WP1) for future climate projections.

The second aspect concerns the increase in grid resolution, especially for the ocean for which we will switch from 1° to 0.25° global resolution. Although that target resolution remains too coarse to represent explicitly the predominant fine scale structures in the ocean, it allows a far better representation of the mean barotropic currents and general thermodynamic structure of the ocean interior, by notably better representing topography and its effect on oceanic currents. This is expected to improve horizontal and vertical mixing within the ocean, a key process for taking up heat from the warming atmosphere.

Furthermore, it will allow to use state-of-the-art oceanic reanalysis using the same ocean model, which are performed at this resolution (e.g. Mercator-Ocean GLORYS2v1), which could be then used as initial conditions for the hindcast and forecast simulations. The effect of fine scale processes, not resolved explicitly at mid and high latitudes, on horizontal heat and salt fluxes, is represented through parameterizations which have been extensively tuned at IPSL for this purpose. An important argument in favor of not increasing the resolution higher in the ocean, is to allow running several centennial scale climatic simulations, to explore variability up to multi-decadal scale and quantify uncertainties associated with the tuning of these configurations (see below).

The last and most original methodological aspect of the project will be the use of objective methods developed by the Uncertainty Quantification (UQ) community to explore the uncertainties associated with the "tuning" of free parameters, a question which has been given more importance recently in the literature (Hourdin et al, BAMS, 2017; Schmidt et al. 2018). In those approaches, the N dimensional space, N being the number of parameters to be adjusted (typically of the order of 20), is explored with only a few hundreds of simulations. Metrics computed on these simulations are then extended to the full N dimensional space (in fact a hyper-cube defined by the [min,max] interval attributed a priori to each parameter) using emulators or meta-models. This approach will be used both in WP2 for tuning the new configurations with a history matching approach (Williamson et al. 2013) and in WP3 to determine the range of possible climate sensitivities than can be reached by changing atmospheric parameters.

The project is divided in 3 work packages that correspond to three types of uncertainties, associated with internal variability of the climate system (WP1), model grid configuration (WP2) and choice of free parameters and most uncertain aspects of the physics content (WP3). Although all simulations will be analyzed systematically on a global scale (see section 2.3.1), detailed analysis will focus on essential climate variables for Europe and Africa, as this is where lies most expertise of the proposing team and so as to meet deliverables of the scientific projects associated to QUEST proposal.

<u>WP1: Uncertainties related to internal variability and initial state</u>.

The first type of uncertainty is intrinsically probabilistic. Internal variability partly masks out the response to climate change and only large ensembles can help to derive robust estimates of the externally-forced climate response (Kay et al. 2015). Preliminary analysis of the IPSL-CM6A-LR configuration suggests that this internal variability is very large. Given the influence of oceanic decadal modes of variability over the surrounding continents hence Europe and Africa, investigating the climate response over these regions therefore requires a large ensemble to average this variability out and isolate the potential signals due to external forcing and initial conditions of the ocean. Both can provide useful sources of climate predictability at the decadal time scale.

The large ensembles are also required because in principle, the probability associated to internal variability is ergodic, meaning that time statistics (the usual approach for describing internal variability) are not a proper substitute for ensemble statistics. While the first approach is more accurate statistically, as explained above, it is very expensive computationally. On the contrary, the second one only requires one simulation, long enough to estimate the variability of the internal modes, but much cheaper than the large ensemble described above. It may however miss important aspect of the climate variability. In a second step, we will thus compare large ensembles of transient runs to stabilized runs around a global temperature target. The comparison of the two approaches will validate this simplified protocol of target warming levels simulations, which is aimed to be used for subsequent more expensive model configurations (see WP2). It will also allow a first estimation of the global climate sensitivity to greenhouse gases further used in WP3. Investigating climte impacts around stabilized target warming levels corresponds to the new IPCC spirit that focuses on target levels of warming, but for which large uncertainties and methodological issues remain. They will be thus correctly tackled and assessed in this project.

Finally, we will explicitly estimate the influence of uncertainty of the climatic initial conditions by performing initialized predictions of the past and future climate. Indeed, the climate of the next decade can in general be attributed to a combination of internal and externally forced variability. At the scale of a country, it has been shown that internal variability can account for more than half of the uncertainty in the projections over a few decades. In this respect, predictions initialized using observations can be very useful to reduce this source of uncertainty. Hindcast simulations starting from observed past climate states should allow evaluating their ability to reduce the uncertainty from internal variability. For this purpose, the hindcasts simulations can be compared with uninitialized historical simulations in which the same external forcings are applied, allowing to evaluate the ability of the two kind of simulations to reproduce past climate evolutions. Initialization could indeed potentially allow to better sample the ongoing internal variability of the ocean and therefore reduce uncertainty in near-term (decades) climate forecasts. Such hindcast simulations also necessitate large ensemble to correctly isolate the forced signal that is coming from the initial conditions (e.g. Yeager et al. 2018). Indeed, this forced signal appears to be key for the forecast quality, although it is not always large enough in present-day climate model, as highlighted recently by Scaife et al. (2018) in their so-called signal to noise paradox. They suggested that climate models are better at predicting the real world than themselves, indicating that the signal induced by initial conditions is possibly larger in observations than in the models. The improvements of the climate model resolution could possibly reduce this aspect, although further research is needed at this stage to fully validate this hypothesis.

To summarise, WP1 will comprise 6 millions of CPU hours to perform the large ensemble of transient scenarios experiments, 1.2 millions of CPU hours for the equilibrated warm climates, and 9.7 millions of CPU hours for the initialised hindcasts. All of these simulations can be started from the first day of the project and most of them will run throughout the whole course of the project.

WP2: Uncertainties related to the grid configuration

This second source of uncertainty will be explored by varying the grid configuration of the IPSL coupled model, upgrading the nominal eORCA 1° resolution eORCA1 grid configuration to the 0.25° resolution eORCA025 and increasing the atmospheric number of points in longitude x latitude from 144x142 (Low Resolution, LR) to 256x256 (Medium Resolution, MR). The coupled model configuration will be denoted by the atmospheric grid acronym followed by the ocean Orca resolution in degree : configurations LR (CMIP6 standard), MR1 and MR025. The simulations will be performed with an updated version of the source files, with slight improvements in the physical content, and corrections of inconsistencies and bug fixes, with respect to the standard versions of the configuration frozen in March 2018. As for LR configuration, MR1 configuration has already been used in long coupled experiments, which produced climatic modes of variability very similar to those obtained in configuration LR. We still plan to maintain a substantial amount of simulations with IPSL-CM6A-MR1 as it will allow to disentangle the role of atmospheric vs oceanic increase in resolution. The upgraded version of MR1 will be ready to use at the beginning of the project. The configuration eORCA025 has been used, adjusted and evaluated extensively in forced mode. The coupled configuration MR025 will be ready at the beginning of the project but the final tuning of this version will be part of the PRACE project.

Tuning of free parameters is a key and intrinsic aspect of the derivation of a new model configuration. The tuning of the IPSL-CM5A-LR version was done by targeting radiative metrics (top-of-atmosphere radiation and its decomposition into Long-Wave and Short-Wave, clear sky and Cloud Effect, etc.), from tests in stand-alone atmospheric simulations (Hourdin et al 2015). This tuning was done “traditionally” by selecting a subset of ~10 parameters, running independent sensitivity experiments, computing the selected metrics and trying to find iteratively a pathway toward a better solution. The project will start by a retuning of the LR configuration using the more objective and automatic uncertainty quantification (UQ) approaches mentioned above, targeting the same metrics. A larger set of parameters will be explored at once by running about 200 5-year long atmospheric simulations randomly within the 20-dimension hypercube, from which the series of target metrics will be computed. The history matching approach will be used to reduce iteratively the range of acceptable parameters (Williamson et al. 2017). Three iterations of 200 simulations will be required. Although preliminary tests are underway, it will be a proof of concept of a very promising tool for the modeling community. For the project, the backup will be the well oiled traditional way of tuning, particularly easy here in view of the weak evolution of the atmospheric physics package.

A long present-day coupled MR025 simulation will then be started with this atmospheric tuning to further adjust the global mean temperature, sea-ice cover or NADW intensity, sightly retuning some atmospheric parameters and adjusting key oceanic parameters identified for the tuning of the IPSL-CM5A-LR version. From the final tuning of the MR025 configuration, two different tunings of the energetic balance will be considered for configurations LR and MR1, either exactly the same one as for the MR025 version, or targeting a slight traditional retuning of the same global temperature (as usually done). This makes at the end 5 configurations of the model for which 200-year long equilibrium experiments will be run for present condition and with the forcing of the +2° and +4° targets in order to assess in a very proper way the uncertainty in climate change projections associated with these changes in grid configuration.

WP2 will thus comprise 1.8 millions of CPU hours for the LR minor retuning, 8.4 millions of CPU hours for stabilized present-day and warm simulations with the MR1, 20.2 millions of CPU hours with the MR025 (present-day and warm simulations) and 6 millions of CPU hours in atmosphere only configuration.

<u>WP3: Uncertainties related to parameters choices and most uncertain process</u>

The history matching approach was used in WP2 to tune a single reference version for each grid configurations. The same approach will be used here to determine with present-day SSTs the subspace in the parameter domain which is compatible with the same tuning metrics, given the various sources of uncertainties. The global sensitivity to greenhouse gases (Equilibrium Climate Sensitivity, or ECS) will then be computed for all the simulations of the ensemble as the difference of the top energy balance between a control simulation and one with SST increased by 4°C (following Ringer et al., 2014). Building an emulator of the ECS for the ensemble will allow identify parameter sets with very large or small climate sensitivities which will then be used in coupled equilibrium simulations with IPSL-CM6A-LR to confirm the ECS obtained in coupled mode, and characterize the differences in climate change of those extreme configurations. Another proof of concept will be done in this work package too. Experience of model tuning clearly shows that a large part of the tuning can be done at a coarser horizontal resolution than the targeted grid, and that SST biases in coupled experiments can be targeted from flux biases in atmosphere alone simulations (Hourdin et al., 2015). Building emulators that combine large ensembles of a cheap configuration with a subset of simulation with a more expensive configuration is a promising approach, already tested for oceanic grid configurations in stand alone simulations (SackWilliamson et al. 2017). We will investigate this transfer between forced and coupled configurations or across grid resolutions by using the emulator derived above for the energetic metrics with the LR atmospheric model (3 iterations of 200 simulations) and emulating energetic metrics (atmosphere alone) or SSTs (coupled mode) for subsets of 50 5-year MR atmospheric simulation and 20-year long initialized coupled simulations.

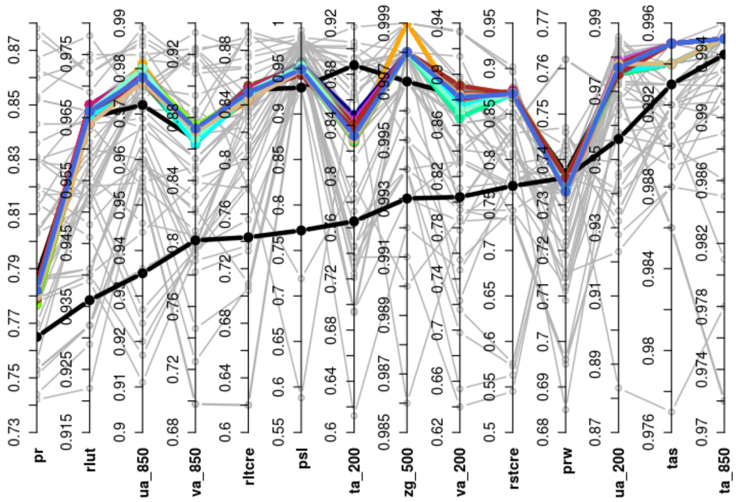
The same protocol of equilibrium sensitivity experiments with IPSL-CM6A-LR will be used to estimate uncertainties associated with model parametrization choices which are particularly weakly constrained by observations or difficult to represent. Several key parameters have been identified during the tuning of IPSL-CM6A-LR as crucial for the evolution of the ocean mean state as well as the manifestation of decadal variability in the North Atlantic region - a region of particular interest in terms of climate impacts over Europe and Africa. In the ocean, specific examples of parameters that will be tested include coefficients of background mixing (and their spatial design) and aspects of the turbulent kinetic energy (TKE) scheme including its profile below the mixed layer. Within the sea ice module, the sea ice and snow albedo and the sea ice thermal conductivity are parameters typically used to tune the mean state of the coupled models. Their impacts on the mean climate are currently debated, as the sea ice cover also influences the other climate components (atmosphere and ocean) through a fast (monthly time scale) and a transient (decadal to centennial time scale) response. These responses, in particular concerning the global ocean overturning and the atmosphere large scale circulation, will be evaluated and compared to that obtained in the CMIP6-PAMIP simulations (dedicated to study the influence of sea ice on climate and performed within CMIP6) and in the coupled experiments stabilized at +2°C. The impact of on-going ice sheet and Arctic glaciers melting is mainly neglected in present-day climate projections and near-term forecasts, although it may also influence the fate of ocean circulation in the Atlantic, with substantial impact on the climate of Europe and West Africa. Ensemble (>5) of simulations using recent estimates of the source of freshwater in North Atlantic and Arctic imposed in IPSL-CM6A-LR, as well as ensembles of hindcast and forecast simulations starting from reconstructions of the initial state for the ocean will be performed to gain insights on this question. The formulation of ice/snow optics and resulting primary production is another source of uncertainty in the model that significantly impacts primary production in the Arctic / Antarctic sea ice zones. In addition, there are unresolved questions on what drives changes in the seasonality of sea ice that require to separate thermodynamic / dynamic contributions. To also gain insights on these questions, ensemble (5) simulations with improved representation of ice optics and primary production under ice will be run with and without ice dynamics activated. Finally, the land-surface evaporation capability will be tested through simple sensitivity experiments to the strength of the bare soil resistance to the evaporation in order to explore the sensitivity of the climate model convection and precipitation to the land-surface evaporation capability.

WP3 will thus include 3.8 millions of CPU hours dedicated to the configuration emulators testing atmospheric tunings and 11.3 millions of CPU hours for testing the other individual parameters.

2.3. Validation, verification, state of the art

2.3.1. Validation

Figure 1 : correlation between model and observation of the monthly mean climatology for some classical meteorological variables. The lowest black curves shows the results of IPSL-CM5A-LR. The grey curves represent the performance of all the models involved in CMIP5. The colored curves correspond to 30 realisations of historical runs with IPSL-CM6A-LR.



A large part of the project will rely on the standard IPSL-CM6A-LR of the model which has been demonstrated to show a number of improvements with respect to the IPSL-CM5A-MR version. From Fig. 1, it is clear that the 6A version is significantly improved for all the variables except for precipitable water (prw) compared to 5A and that it is much closer to the best models involved in CMIP5.
This figure has been produced by the Climate model Evaluation Platform tool (C-ESM-EP) developed jointly by IPSL and the Centre National de Recherches Météorologiques of Météo-France. This platform enables the systematic production of diagnostics of all the model components, including differences to the state-of-the-art available observations and differences among different simulations. It has been used extensively during the production of IPSL-CM6A-LR simulations on Joliot Curie - SKL machine in 2018 and we plan to continue using it during QUEST project as a rapid and synthetic evaluation of the simulations during production, as well as during the in depth analysis of simulations after production.
The project also largely relies on our ability to run the model around targeted stabilized warming levels. The tuning protocol performed over the last couple of years for IPSL-

CM6A-LR has proven its efficiency, as illustrated on Fig. 2. The final point of the historical transient curves matches very well with the temperature of the present-day simulation, demonstrating the relevance of the proposed protocol. It works also for the North Atlantic sea ice coverage and other variables. Note that without the delta on the albedo the present-day stabilized simulation would be typically 0.5K warmer.

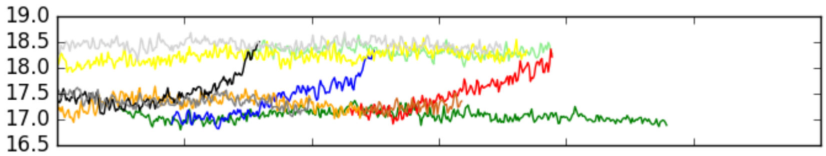


Figure 2 : Global mean sea surface temperature in degrees as a function of years of simulation (fictive years, the spacing between ticks represents 100 years). The grey and light green curves show stabilized present-day control simulations at the level of the transient present day climate, in which the mean oceanic heat uptake is replaced by a delta on the oceanic surface albedo. The orange and dark green curves show stabilized simulations performed with exactly the same model and the same set of parameter values but with pre-industrial forcings (greenhouse gases, aerosols, ozone, land use) and the true oceanic surface albedo (no heat uptake).The black, blue and red curves finally show the transient historical curves which indeed warm from pre-industrial to present day climate levels.

2.3.2. Verification

The long experience of the proposing team in terms of preparing configurations for "Coupled Model Intercomparison Programs" has been strongly improved for the last CMIP6 exercise. It includes the systematic verification of conservation of some quantities like total water or energy conservation at the Atmosphere/Ocean interface, although energy is not fully conserved by phase changes within the atmospheric component as it is the case of many climate models. In terms of code verification, several automatic procedures have been deployed, both at the scale of the components and for the full coupled system. In particular, systematic automatic check of bit-to-bit convergence with previous versions of the model when the code modifications should not change the results has been developed. Compilation checks are also performed with three level of compilation.
A particular effort has been done recently in checking the reproducibility of the fully coupled simulations. At the beginning of the production of the CMIP6 exercise, in spring 2018, there were still spurious numerical violation of it: typically every 100 years, one operation in the system was creating a bifurcation of the model trajectory. This issue has been solved since.

2.3.3. Sensitivity analysis and uncertainty quantification

Sensitivity analysis and uncertainty quantification is at center of this proposal, targeting the uncertainty coming from initial state (WP1), structural uncertainty (WP2 and WP3) and uncertainty associated with free parameters (WP3). As explained in the main text, we will use state-of-the art approaches coming from the Uncertainty Quantification community: automatic generation of sampling of the N-dimensional latin hypercube made of the N segments corresponding to the the [min,max] interval of each of the N-parameters involved in the sensitivity analysis; use of emulators and history matching approaches. Daniel

Williamson, who is a leading scientist in the use of these approaches for climate modeling, is a member of the proposing team.

2.3.4. Comparison with state of the art

The present protocol is unique in several respects. First it is based on a new and most up-to-date climate model, namely the IPSL-CM6 model, which offers largely improved performance in reproducing the present-day mean state, as described above. HPC performance of IPSL-CM6 also improved substantially as preparing for CMIP6 production on Curie machine (predecessor of Joliot Curie - SKL machine), and that is currently being benchmarked on Joliot Curie - SKL machine.
Furthermore, the unique and consistent framework that we propose in QUEST will allow us to answer scientific questions around and beyond the CMIP6 exercice, that cannot be addressed by looking at CMIP6 simulations alone, namely quantifying the various sources of uncertainties rising from the different components of the climate model. Although this is a highly topical idea, producing large ensembles of projections and investigating the dependency of climate sensitivity to resolution and other parameters of the climate system, is not included in the current CMIP6 protocols. It is indeed in general far too demanding in terms of computing power. Yet analyzing these simulations alongside those produced for CMIP6 will be extremely instrumental as it will provide the unique opportunity to quantify the uncertainty of our CMIP6 simulations. Up to now, one research institute in climate has tackled the question of the necessity of large ensemble, namely the NCAR in Boulder (USA). Their first results clearly highlight 1) the large uncertainty arising from internal variability at the regional scale in projections and 2) the added value of large ensemble (40 members) in term of decadal prediction skill. The QUEST project will therefore help a European climate prediction system to reach this new high standard in climate projections and forecasts that has not been reproduced up to now.
The new tuning techniques described before will be entirely unique for climate model development and should therefore allow to make a step change in the way we improve climate models, and hopefully and the precision of climate models in their estimation of future climate trajectories both at the global (e.g. better climate sensitivity estimation) and local (e.g. better constrain on internal variability) scales.
Thus, QUEST proposal will build a unique expertise at IPSL Climate Modelling center (IPSL-CMC) in quantification of diverse sources of key climate model uncertainties. We plan to share that expertise with other climate modelling centers by making use of pre-existing strong collaborations (for example with CNRM and UKESM). As a result, it is foreseen that the new knowledge on climate model uncertainties and tuning procedures obtained thanks to PRACE allocation ultimately benefits other climate models beyond IPSL-CM6 and will provide a new benchmark for preparing next generation climate models.

2.4. Software and Attributes

2.4.1. Software

IPSL-CM6 is a state-of-the art Earth System Model, and QUEST simulations will include full interactive carbon cycle. IPSL couples several sub-models, representing the physical processes and the biogeochemical cycles, as described below. All these sub-models have

been extensively developed, assessed and benchmarked for IPSL-CM6, independently of each other as well as in coupled mode, so that the current code of IPSL-CM6 is robust and reliable for massive data production.
LMDZ (http://lmdz.lmd.jussieu.fr) is an atmospheric general circulation model.
ORCHIDEE (http://orchidee.ipsl.jussieu.fr) is a continental surface model, with three components. SECHIBA handles the energy and water transfer between soils, vegetation and atmosphere. STOMATE handles the carbon cycle in soil and vegetation. LPJ is a dynamic vegetation model, which will be not activated in this study. Actually ORCHIDEE is a software library linked to LMDZ.
NEMO (http://www.nemo-ocean.eu) is a state-of-the-art modelling framework for oceanographic research, operational oceanography seasonal forecast and climate studies. It is used by a large community: at present around 240 projects in 27 countries (14 European countries). NEMO includes OPA (ocean dynamics), LIM (sea ice rheology, dynamics and thermodynamics) and PISCES (biogeochemical cycles). The parallel coupler OASIS-3 MCT (https://verc.enes.org/models/software-tools/oasis) handles parallel communications (through MPI) and parallels interpolation between NEMO and LMDZ. It is instrumented to monitor the load balance of the different components.
XIOS is an I/O client/server system for fast parallel outputs (https://forge.ipsl.jussieu.fr/ioserver). Specific developments were realized for IPSL-CM6, so as to optimize the production of standardized variables in particular (following guidelines of CMIP6 Data Request).
There is no possible alternatives to the use of these softwares, that constitute the fundamental core of IPSL-CM6 hence all simulations to be produced within QUEST Project. To make use of these and the environment prepared by IPSL-CMC for the production of simulations, as well as to get access to input files, it is compulsory that we have access, within the PRACE allocation, to the container cont003 of Joliot Curie - SKL machine.
This project is primarily based on the IPSL-CM6A-LR configuration, which is the currently standard configuration of the IPSL climate model and which is used extensively for the recent CMIP6 exercise. Additional experiments will be performed on two extra configurations, namely IPSL-CM6-MR1 and IPSL-CM6-MR025. In these two configurations, the atmospheric number of points in longitude x latitude is increased from 144x142 (Low Resolution, LR) to 256x256 (Medium Resolution, MR) while the nominal eORCA 1° resolution is kept unchanged in IPSL-CM6-MR1 and increased to the 0.25° resolution in IPSL-CM6-MR025.

2.4.2. Particular libraries

All components of the IPSL-CM6 climate model are written in Fortran 90 and the I/O library, while XIOS is in C++. We need access to IPSL svn repository to get the code sources. They also require NetCDF library to compile.
To execute IPSL-CM6 software on Joliot Curie - SKL machine, we use ccc_mprun command. However for the post-processing of the model outputs, the following libraries and softwares are required: evince ; cdo ; netCDF ; ferret ; firefox ; ghostscript ; imagemagick ; nco ; netpbm ; python 2.6.2 with NetCDF4 and numpy ; subversion ; tetex-latex.
During the run and once it finished, the job is set to send an email to the user to inform on the simulation status and relaunch a new job so as to continue the simulation.

2.4.3. Parallel programming

IPSL-CM6 software requires multiple programs, multiple data launch mode. Each sub-model is parallelized following a specific strategy.
LMDZ is parallelized with MPI, using three domain decompositions. For dynamics (Navier-Stoke equation with ad-hoc hypotheses), the domain is decomposed in latitude, with less latitude bands in the regions (near the poles) where the longitudinal filter add computation. Tracer advection is parallelized in latitude with a different load balancing. For these two decompositions, OpenMP is used to decompose the vertical dimension. For the physics (water in three phases, subgrid scale physics, etc ...), there is no communication. Hence all horizontal grid points are distributed as a one-dimensional vector, and the domain is decomposed horizontally using both MPI and OpenMP. During the first iterations, the model decompositions are adjusted to reach the optimal load balance.
NEMO is parallelized using a 2D (horizontal) MPI decomposition.
XIOS library reads and writes in parallel mode using MPI.

2.4.4. I/O requirements

As mentioned before, this project is linked to many other projects pre-existing on Joliot Curie - SKL machine (mainly gencmip6, gen2212, gen7403 and gen7451) that we need to have access to, as they will provide input forcings and parameterizations. Therefore our PRACE allocation has to be given on Joliot-Curie SKL machine and in the same container (ie cont003) as those projects. Indeed we estimate that adapting IPSL-CM6 to another environment (ie another container and/or machine) would require around 2 years of testings. Hence all I/O requirements and further technical specificities are given hereinafter for this machine exclusively, based on our experience of production on this machine.
During the production of IPSL-CM6A-LR simulations (which will constitute the majority of our CPU consumption), input files are read every year in the model time (ie every 30 min in real time), hence nearly continuously throughout the course of the simulation. Similarly, output files are written nearly continuously throughout the course of the simulation, and on average 15Mo every 2s, on CCCWORKDIR and CCCSTOREDIR. As a reference, during a simulation of 150 years, a total of 3.4 TB (844 inodes) will be written on CCCSTOREDIR for restart files, debug files and selected outputs, 5.7 GB (12 448 inodes) will be written on CCCWORKDIR for on the fly validation of the simulation, and 13 TB (1 725 inodes) will be written on CCCWORKDIR for the bulk of output variables. CCCSCRATCHDIR is used to keep temporary files during a couple of months. This represent approx. 500 TB for one month of production of this project. For the IPSL-CM6-MR1 and IPSL-CM6-MR025 configurations, the number of files (inodes) is identical. The volume of data is nevertheless increased by a factor of 2 for IPSL-CM6-MR1 and a factor of 7 for IPSL-CM6-MR025.

2.5. Data: Management Plan, Storage, Analysis and Visualization

2.5.1. Data Management Plan covering

Different type of data are produced during the climate simulations. For 150 years of simulation with IPSL-CM6A-LR,
- the sources amount to 1.3GB and should be kept for 10 years ;

- about 6Gb of data are used for online verification tools (atlas and monitoring) and should thus be kept only 6 months ;
- the restart and debug files written on the CCCSTOREDIR amount to 1.2TB and are stored for 2 years ;
- 2TB of the outputs, used for the online verification as well, are to be kept for 5 years ;
- the 13TB of data in final format should be stored for 10 years, on CCCWORKDIR. These will be distributed on the IPSL data node ;
- Temporary files written on CCCSCRATCHDIR represent a total of 20 TB.

Because QUEST simulations will be analyzed identically to IPSL-CM6 CMIP6 simulations, we plan to archive the exact same variables from all components of the climate system. This represents a substantial amount of storage, but it ensures an efficient use of QUEST simulations as most programs for analysis are already available. For this reason, we envision very prompt publication of QUEST simulations, in nearly all publications about IPSL-CM6 CMIP6 simulations.

Extrapolating the estimates above for MR1 and MR025 configurations (which cannot produce the full CMIP6-complient variables yet), we assume that QUEST data will occupy roughly 6PB of CCCSTOREDIR for 10 years. Note that there is space within the IPSL-CMC storage allocation on CCCSTOREDIR for these data (allocation of 14PB, which only 7PB are currently occupied).

We insist once more here that the model workflow requires an access to **input files** which are centralized for the whole IPSL climate modelling community on the cont003. This corresponds to about 20TB of data that need to be stored for 10 years.

2.5.2. Project workflow

At the project level, some simulations sets are dependent from each other, but only 40% of them. Besides, 38% of the planned simulations could be started on Joliot Curie - SKL machine at the time we write the proposal. We plan to use this flexibility to ensure a regular and uniform use of 12,000 cores for the whole duration of the project. Note that to achieve this, we schedule using up to 17,000 cores for the first 9 months of the project, and then 7,000 core, as we wish to provision computing resources for the simulations that would be delayed. For example, the decadal hindcasts of WP1 represent a set of numerous short experiments, ready to be launched, independent of all other simulations, that we will use to maintain the adequate workload on the machine.

Regarding the analysis of QUEST simulations, first step will be using C-ESM-EP (see section 2.3.1) to evaluate efficiently and rapidly the most important variables of all components of the climate system. These can be produced directly on Joliot Curie - SKL machine, as well as from IPSL mesoscale computer ESPRI with no data transfer requirements. Such analysis will be undertaken on a weekly basis, and the information provided will be discussed during our weekly meetings to manage computing resources.

Further detailed analysis will be undertaken either directly on the production machine, either on IPSL mesoscale computer ESPRI once a selection of the essential variables has been transferred. This second step analysis will be undertaken on a monthly to yearly timeframe, subsequent to the production of QUEST simulations, within the scope of the many scientific projects that will make use of QUEST simulations to produce their scientific deliverables : ANR EUCLIP, ANR ARCHANGE, ANR HRMES, EU-Marie Curie EPICE, EU FP7 IS-

ENES3, EU-H2020 EASIWACE2, EU-H2020 Blue Action, EU-H2020 EUCP, EU-H2020 C3, EU-CONSTRAIN. The coordination of these projects together with QUEST proposal, ensures that the requested manpower and expertise will be available to make the most of the simulations produced with the PRACE allocation.

2.5.3. Software workflow solution

Generally input file are ready to read by the model. A pre-processing could be done via libIGCM (the set of script that drive the coupled model) to create an ensemble set of simulations from a general configuration file (prepare all directories, select and modify restart files, create scripts to launch and clean simulations).
For each individual IPSL-CM6 simulation, the main job starts by creating temporary and permanent output directories and checking the environment. Initialisation and external boundary inputs are read from cont003 files. The model writes temporary (for 48h maximum) files on CCCSCRATCHDIR before the post-processing phase when files are packed and stored into CCCWORKDIR or CCCSTOREDIR filesystems, where they stay for 2 to 10 years. Final restart files remain in CCCSCRATCHDIR to enable (automatic) continuation of the simulation. There is a single job file that runs a simulation chunk and launches the following job, to ensure continuation of the simulation, before ending after 24h maximum. It is possible to redo all the steps in case of an interruption of the job (due to issues in the simulation or in the machine production).
For post-processing, most of the work is done by XIOS which writes output files in parallel and manages several output frequencies (instantaneous, daily/monthly/yearly averages/min/max) in netCDF4 compressed files. The configuration is driven by XML files.
This workflow was designed for the CMIP6 exercise and has actually been used for production, in a very robust and efficient way. For example, the production of CMIP6 simulations with IPSL-CM6 generated 622 To from June 15th 2018 to October 15th 2018. The different types of simulations are launched by different contributors of the project. Coordination is ensured by shared online tools and weekly meetings. The capability of the IPSL Climate Modelling Center to efficiently exploit HPC for a massive production of climate simulations was demonstrated recently when the curie machine (the predecessor of Joliot Curie - SKL at TGCC) was phased out: the group had the opportunity and was able to use efficiently the whole curie machine (80 000 cores) continuously for 10 days before its final shutdown with only a 3 day notice.

2.5.4. I/O requirements

Outputs are produced thanks to XIOS library as compressed NetCDF files, first on CCCSCRATCHDIR during the run and moved to CCCSTOREDIR after each pack-period is completed. Output analysis will be performed on the IPSL mesoscale supercomputer ESPRI. Data will thus be transferred to the DMNFS thredds mounting point between Joliot Curie - SKL machine and the IPSL mesoscale computer ESPRI (ie in WORK and STORE of the thredds directory in container 003). The transfers between Joliot Curie - SKL machine and the IPSL center are currently being optimized for a bandwidth of 10 Gb/s thanks to coordinated efforts from TGCC support team and IPSL engineers. Some of these files are used to monitor the simulation and check the performances online. At the end of the simulation, the job also needs to send a mail to inform the user that the simulation has ended correctly or not.

2.6. Performance of Software

2.6.1. Testing of your code on the requested machine

We have just obtained a preparatory access (n°PA4586) to prepare for this PRACE regulatory access project on Joliot Curie - SKL machine. In the meantime, we execute IPSL-CM6 software on Joliot Curie - SKL machine (within allocations gencmip6, gen2212, gen7403 and gen7451) and we interact very regularly with TGCC support team in order to improve the performance of the software on this machine. We are also finalizing the development of configurations IPSL-CM6-MR1 and IPSL-CM6-MR025, on the same machine, so as to be able to launch production of simulations from all three configurations, in the most possible efficient way, as soon as PRACE regulatory access is provided.
Once the preparatory access is granted, we will verify that the production of simulations is still operational within PRACE context. As mentioned above, this should be straightforward if we are granted full access to container cont003, and nearly impossible otherwise. We will also test availability of requested libraries, in particular svn access to install the software.
On October, 10th 2018, the performances on Joliot Curie - SKL machine were the following
- IPSL-CM6A-LR : 4 500s/year with 960 cores (71 MPI * 8 OpenMP for LMDZ, 360 for NEMO + 1 XIOS), 20 nodes. 12 000 hCPU for 10 years (19,2 years/day in average).
- IPSL-CM6-MR1 : 9 200s/year with 1 200 cores (128 MPI * 8 OpenMP for LMDZ, 171 MPI for NEMO + 1 XIOS), 25 nodes. 31 000 hCPU for 10 years (9,4 years/day in average).
- IPSL-CM6-MR025 configuration is still under development, but we estimate its performance, based on forced simulations of individual components, as 18 000s/year with 1800 cores (500 cores for LMDZ, 1295 MPI for NEMO + 5 XIOS), hence 90 000 hCPU for 10 years (4,8 years/day in average).
The requirement in CPU hours for QUEST project has been estimated from the plan of simulations mentioned in section 2.2 and the performances above. Note that the IPSL CMC technical team is currently interacting with the TGCC support team for possible further improvements.

2.6.2. Quantify the HPC performance of your project

2.6.2.1. Strong and weak scalability

All our models have a set size for their respective domains, hence we only test the strong scalability of the software. To evaluate separately the strong scalability of every component of our coupled system (mainly LMDZ and NEMO, which are running concurrently), we use the LUCIA tool [Maisonnave et Caubel, 2014] included in OASIS3-MCT which allows to produce, for example, Fig. 3.
For IPSL-CM6A-LR, we have tried 8 configurations corresponding to different splitting of MPI and OpenMP in the component (from around 600 to 1400 cores) to evaluate the computing cost compared to the time elapse per simulated years shown in Fig. 3, the cheapest configuration but with a poor workload equilibrium (ie the time of waiting between atmosphere and ocean components is not zero, orange and yellow plots in Fig. 3) is the

one highlighted with the green circles ; the fastest configuration, with twice more cores and a speed-up around 1.35 is shown in red circles - it shows little latency between atmosphere and ocean part. “The best compromise” with 1.4 times more cores with a speed-up around 1.2 and a good latency between atmosphere and ocean part corresponds to the dark blue circles. By default, we will thus use this last solution for IPSL-CM6A-LR : 960 cores (71 MPI * 8 OpenMP for LMDZ, 360 for NEMO + 1 XIOS), 20 nodes. The first configuration mentioned above could be used for specific simulations.

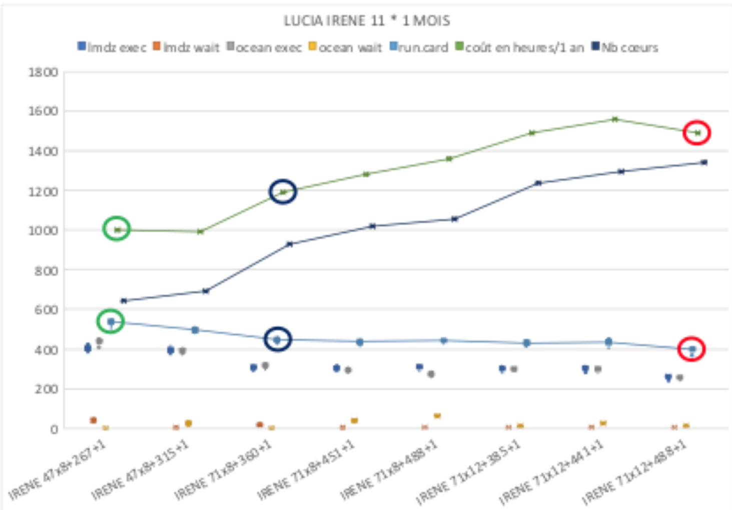


Figure 3 : CPU time in hours for 1 simulated year of IPSL-CM6A-LR coupled model on Joliot Curie - SKL machine (green curve), as a function of the choice of splitting of MPI and OpenMP in the different components. The light blue curve shows the elapse computing time and the dark blue curve the number of cores needed. Time spent waiting coupling fields from the other model is given by orange and yellow dots. Time spent for calculations is plotted with blue and grey dots.

We plan to make use of our preparatory access to Joliot Curie - SKL machine within PRACE context (see section 2.6.1), to perform the same analysis for configurations IPSL-CM6-MR1 and IPSL-CM6-MR025.

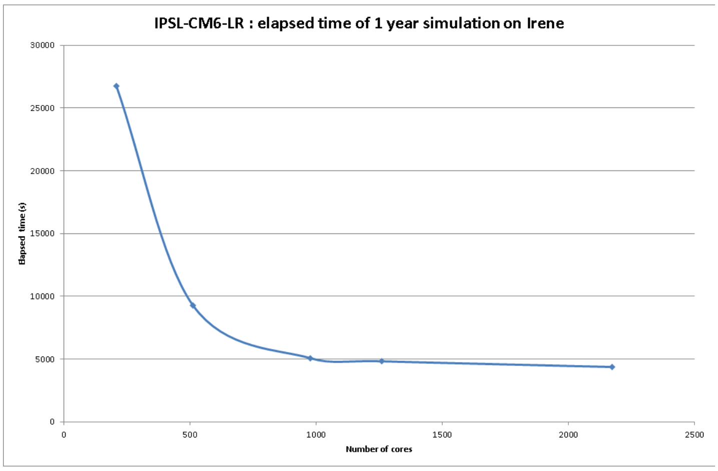
2.6.2.2. Precision reported

All codes entering the production of IPSL-CM6 simulations use double precision.

2.6.2.3. Time-to-solution

As discussed in section 2.6.2.1, we could choose between 3 configurations of our software: the “less costly”, the “fastest time-to-solution” and the “best compromise”. Orange and yellow dots in Fig.3, resulting from a “LUCIA” load imbalance analysis, show how long the ocean and atmosphere components are waiting for each other. For the cheapest configuration, this time is not zero. This motivates our choice to use 960 cores (71 MPI * 8 OpenMP for LMDZ, 360 for NEMO + 1 XIOS), 20 nodes. For this configuration, the time-to-solution to produce 1 model year is 4,500 s real time so 1,200 hCPU. Yet, due to the complexity of our software workflow solution, the time it takes to complete a simulation is highly dependent on the status of the machine, and can be substantially increased due to shutdowns or maintenance operations. As a result, we have designed our production plan assuming that Joliot Curie - SKL machine will be fully operational during 20 days/month on average over the year of our PRACE allocation.
For the large ensembles of simulations, a cheap configuration IPSL-CM6A-LR could be employed, using 644 cores (green circles in Fig. 3).

2.6.2.4. System scale



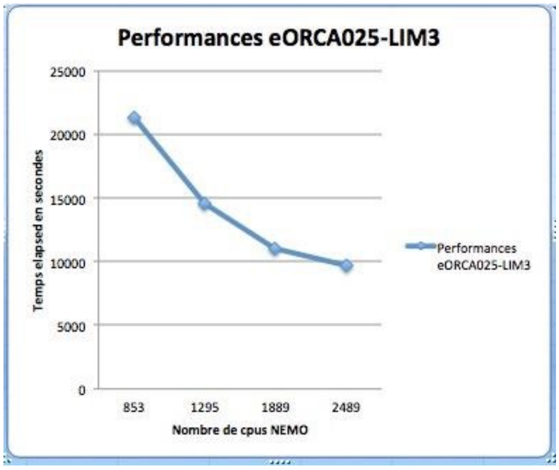


Figure 4 (left) : Scalability plot (estimated as elapsed time to perform one year of simulation) on Joliot Curie - SKL supercomputer for IPSL-CM6A-LR model with all the CMIP6 compliant workflow. This last point is what differs from the plot shown in Fig. 3.

Figure 5 (right): Scalability plot (estimate as elapsed time to perform one year of simulation) on Joliot Curie - SKL supercomputer for eORCA025 NEMO configuration, that will be part of IPSL-CM6-MR025 configuration.

Following the scalability of IPSL-CM6A-LR on Joliot Curie - SKL machine (provided in Fig. 4), we plan to produce most simulations using 1000 cores, which corresponds to the best compromise option mentioned in section 2.6.2.1 (highlighted in blue in Fig. 3). The elapse time for IPSL-CM6-MR1 with a similar number of cores is provided in section 2.6.1.
Scalability of IPSL-CM6-MR025 cannot be estimated yet because the coupling of LMDZ and NEMO respective configurations is still ongoing. Yet, we provide scalability of the NEMO configuration eORCA025 that will be part of IPSL-CM6-MR025, as it is likely to constrain the final choices for the coupled configuration (Fig. 5). Our estimate of computing hours needed for IPSL-CM6-MR025 configurations, is based on the use of 1800 cores for NEMO.

2.6.2.5. Measurement mechanism

The performance of IPSL-CM6 configurations is measured according to the number of simulated years per effective day. To do so, our software provides the real time spent for each model year and an estimation of the total time during which the simulation will run. These informations allow us to check regularly the performance of the model and detect suspicious latency.

2.6.2.6. Memory usage

In terms of RAM memory, IPSL-CM6A-LR requires a maximum of 3Gb/core (2Gb for LMDZ and 1Gb for NEMO). The IPSL-CM6-MR1 and IPSL-CM6-MR025 configurations aim at using the same amount of RAM though more cores.

2.6.2.7. OPTIONAL: Percentage of available peak performance

This aspect will be dealt with during the preparatory access n°PA4586 so as to optimise at best the performance of the three configurations before the effective start of the project.

3. Milestones

3.1. Gantt Chart

	1st term	2nd term	3rd term	4th term
WP1	6 000 cores	5 000 cores	5 000 cores	1 000 cores
WP2 (LR+MR1)	3 000 cores	3 000 cores	3 000 cores	
WP2 (MR025)	4 000 cores	6 000 cores	4 000 cores	4 000 cores
WP3	4 000 cores	3 000 cores	3 000 cores	2 000 cores

Table 1 : Gantt diagram illustrating the simulation plan on a quarterly basis. In order to account for machine maintenance operations and interruptions that are expected to affect the time-to-solution of our software, we assume that Joliot Curie - SKL machine is only fully operational 20 days/months.

The plan of simulations (Table 1) has been prepared so as to start the project with a relatively heavy workload (17,000 cores). Actually, 38% of all resources requested could be launched already, as this proposal is being written. The workload is planned to decrease progressively down to 15,000 cores after 6 months and then finally 7,000 cores in order to integrate the possible delays in the production of simulations. Note that this plan is designed to ensure that we use constantly at least 7,000 cores over the whole year of the allocation (365 days), and on average 12,000 cores throughout the effective time when the machine will be fully operational (which we roughly estimate as 20 days / month), which corresponds to the overall resources requested (72,685,000 hCPU).

Notwithstanding, our simulation strategy is partly flexible for two reasons: WP1 includes a large amount of short ensemble simulations which can be run successively or simultaneously to adjust the computing charge. Furthermore, several simulation sets (40% of all resources requested) do not depend on each other and can thus be started flexibly. As a result, our production plan will be evaluated and revised on a weekly basis, as soon as our allocation is granted, consistently with on-the-fly evaluation of the time-to-solution of each simulation.

3.2. Communication plan

[March 2019] *Ateliers de Modélisation de l'Atmosphère (Toulouse, France)* dedicated to uncertainty quantification, co-organized by a PI of QUEST project, will ensure that we communicate nationally about QUEST proposal and the associated methodology.

[December 2019] IPSL-CM6A-LR large ensembles scenarios will be made available to the international community through the IPSL data node and a publication on the forced climate response will be submitted, to be taken into account by the 6th IPCC assessment report .

[April-May 2020] The three co-PIs will submit a proposition for a special session on uncertainty quantification in climate models at the *General assembly of the European Geophysical Union*, which gathers a large portion of the community, so as to foster attention around uncertainty quantification in climate models and highlight achievements made possible thanks to PRACE allocation.

This communication plan will be complemented by the usual strategy of scientific publications and presentations to various conferences and general assemblies of national and EU Projects. As the simulations realized within PRACE allocation will be evaluated alongside simulations produced for CMIP6, so as to quantify uncertainty of those, we expect a substantial number of publications acknowledging PRACE support (at least 15 publications in peer-review “A” journals). Results are planned to be used and valorized for at least 3 years after the end of the project.

4. Personnel and Management Plan

The PI and two co-PIs of the project are strongly involved in the development and evaluation of the IPSL climate model. Dr J. Deshayes and Dr J. Mignot are both physical oceanographers, working at the LOCEAN laboratory. For QUEST project, Dr J. Deshayes is specifically involved in the design and evaluation of the oceanic component of the climate model, while Dr J. Mignot is coordinating the design and evaluation of the simulations investigating the future climate. Dr F. Hourdin is an atmosphere scientist working at the LMD laboratory in charge of the development and implementation of the atmospheric component in the IPSL climate model. The three co-PIs are permanent researchers at the IPSL federation, and have been very active in the IPSL-CMC group for the last 4 years. In order to realize QUEST project, they will benefit from contributions from IPSL-CMC group, namely 23 engineers and research scientists affiliated to LOCEAN, LMD and/or IPSL. Among those, only 3 members are non permanent as they are contracted post-doctorates. Yet their contracts last until September 30th 2020 or later, that is after the end of QUEST project. Thus the scientific and technical team that will effectively carry on QUEST project, realizing simulations and analyzing outputs, is particularly stable.
The fact that all QUEST collaborators are formally affiliated to different organizations should not be seen as an issue, as they are all members of IPSL-CMC group which constitutes a well identified community, already structured by regular meetings (weekly to quarterly), efficient at communicating internally (through mailing lists and wiki pages) and externally (thanks to the IPSL communication service), and empowered with common repositories (within cont003 of Joliot Curie - SKL machine in particular).
In addition, QUEST project will benefit from collaboration with Dr Daniel Williamson from Exeter University, specialist of UQ approaches applied to climate modeling, who has a history of collaboration with IPSL-CMC through ANR HighTune project. Dr Williamson will lead the design of parameter sampling, emulator building and history matching.
QUEST proposal is associated to several scientific projects, which have already or will implement their own management plan and this will ultimately benefit to QUEST. The three PIs of QUEST will organize weekly meetings to supervise production of simulations within PRACE allocation, in addition to quarterly meetings to foster analysis of simulations and interpretation of the results. Minutes of all meetings will be shared widely and promptly with the whole group of QUEST collaborators so as to maximize technical and scientific coordination of all efforts.

5. Previous Allocations and Results

The PIs trio has never been awarded directly any PRACE allocation. Yet, at least one major project based on the IPSL climate model has (THROLL 2015-2016). Another PRACE project (PULSATION, Nov 2011 - Aug 2015) has been conducted by collaborators of LOCEAN, using a high resolution version of NEMO very close to the one that will be used within QUEST. The expertise gained by collaborators of these two projects have already been used to prepare QUEST proposal. We are convinced that this context will again benefit to QUEST and prevent us from falling into usual hazards of massive simulation production.

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Appendix 1: Track Record of the PI

Curriculum vitae of the Principal Investigator

Dr Julie Deshayes

ocean modeller, 37-years-old, h-index 13, RG Score 26.36

Responsabilities

since 2016	Member of the Advisory Board of UKESM-LTSM project (https://ukesm.ac.uk/).
since 2015	**Manager of NEMO R&D team of LOCEAN** which comprises 5 research scientists, 5 research engineers and the project manager of NEMO (http://www.nemo-ocean.eu).
since2015	PI of the preparation, tuning and validation of the ocean component of IPSL-CM6 (configurations eORCA1 and eORCA025 using NEMO v3_6_STABLE).
since 2015	Nominated member of CSS5 of IRD for evaluation and recruitment of research scientists on Data and Model sciences.
since 2009	co-PI of the DRAKKAR consortium (http://www.drakkar-ocean.eu).
since 2009	PI of GENCI projects (see page 6).

Appointments

since 2015	**CNRS Research Scientist** at Laboratoire d'Océanographie et du Climat : expérimentations et Approches Numériques (LOCEAN, UMR 7159 UPMC-CNRS-IRD-MNHN, France).
2015-2017	**Honorary Research Associate**, Department of Oceanography, **University of Cape Town** (UCT, South Africa)
2013 - 2014	CNRS Research Scientist at Laboratoire de Physique des Océans (UMR 6523 CNRS-IFREMER-IRD-UBO, France), funded by IRD to join LMI ICEMASA at University of Cape Town (South Africa).
2009 - 2012	CNRS Research Scientist at Laboratoire de Physique des Océans (UMR 6523 CNRS-IFREMER-IRD-UBO).
since 2009	Guest Investigator, Woods Hole Oceanographic Institution (WHOI, USA)
2006 - 2008	**Postdoctoral Scholar at Woods Hole Oceanographic Institution** (Woods Hole, USA), with F. Straneo and M. Spall (personal research project): analytical and numerical development of a conceptual model reproducing interannual to decadal variability in the Labrador Sea, development and analysis of numerical simulations (using MITgcm) in an idealized convective basin.
2003 - 2006	**Research assistant at LOCEAN**, Paris (France), with Pr. C. Frankignoul : statistical analysis of interannual to decadal variability in dense water formation and circulation in the North Atlantic from 1953 to 2003, in a realistic hindcast simulation (using MICOM), analytical development of a simplified theoretical model of the meridional overturning circulation .
2004 (1 month)	**Research assistant at NERSC** (Bergen, Norway) with Pr. H. Drange.
2002 (6 months)	**Research assistant at University of Hawaii** (USA), with Pr. Flament, for a project consisting in the deployment of HF radars for a measurement of the coastal surface currents: technical responsibilities, organization and coordination of the team work.

Projects, fellowships and awards

2015	**Co-PI of WP2 of FP7 EMBRACE project (#282672).**
2014	**Organiser of the international ICEMASA-NTC-UCT/MaRe workshop** (8-10 April 2014 at Cape Town) funded by NRF, ICEMASA, NTC and UCT/MaRe (80 participants).
2009	Organiser of the international workshop DRAKKAR AGRIF (July, 6-7, 2009 at Plouzané, France) funded by UBO, La Région Bretagne and Ifremer, (30 participants).
2008-2011	**co-PI of NSF projet: "Freshwater content and circulation in the North Atlantic: are they related ?"** with R. Curry (WHOI).
2007	Fellowship "Initiative Post-doc", from French Ministry of Research.
2006	Postdoctoral scholarship from the Woods Hole Oceanographic Institution (WHOI).
2006	Postdoctoral scholarship from NOAA Climate and Global Change, Visiting Scientist Program.
2003	PhD scholarship from the French Ministry of Research.

Teaching and advising activities

2015, 2017	Course on **Numerical Approaches for modelling geophysical fluid dynamics, Master 1**, ENS (9h lectures, 12h practical sessions).
2015-2018	Co-advisor of Sarah Asdar, PhD, cobadging UCT-UBO.
2017	Co-advisor of Clément Weber, L3, Université Paris Diderot.
2015	Co-advisor of Jeanne Barreyre, L3, Université Paris Diderot.
2014	Co-advisor of Lisa Holton, Taught Master, UCT (6 months), who graduated with honors. Publication [A-20].
2014	Co-advisor of Marion Bezaud, Master 2 UBO and 3-yr student at ENSTA-Bretagne (5 months).
2014	**Course on Western Boundary Currents, Master**, UCT (10h lectures, 15h practical sessions).
2013-2014	Co-advisor of Kyle Cooper, Master by dissertation, UCT (2 yr).
2015, 2014 & 2013	Lecture on the use of climate simulations for biogeochemical applications, Master level, Winter School E2E, UCT (1h).
2015, 2014 & 2013	Course on the analysis of numerical simulations, Master level, Winter School E2E, UCT (6h lectures and practical sessions).
2014 & 2013	**Course on statistical methods for climatological applications, Master 2,** UCT (10h lectures, 15h practical sessions).
2013	Co-advisor of Sarah Asdar, Master 2 UBO and UCT (5 months), funded by IRD.
2012	Co-advisor of Natalia Signorelli, Master (6 months), Universidade de Sao Paolo.
2010-2015	Co-advisor of Claude Talandier, PhD, graduated on 31/03/2015. Publication [A-15].
2010-2013	Co-advisor of Nicolas Barrier, PhD, graduated on 25/11/2013. Publications [A-9], [A-17], [A-19], [AB-1].
2012	Advisor of Charlene Feucher, Master 1 (4 months), funded by Ifremer and IUEM .
2010-2011	Advisor of Alexandros Chronis, Undergraduate (6 months), funded by Ifremer.
2010	Advisor of Lukas Vollmer, Undergraduate (3 months), funded by Ifremer.

Outreach

2017 Scientific experiments around climate change, in a class of 6 to 7 year old children, 4 hours, Paris.

2014 Invited panelist at the workshop **Climate Change in Africa: perspectives on scientific evidence, public policies and leading initiatives**, Johannesburg (South Africa), 3-4/11/2014.

2013 *La circulation méridienne océanique est-elle aussi stable qu'on le pensait ?* **Actualité Environnement de l'INSU**, http://www.insu.cnrs.fr/node/4535.

2013 *La grande circulation méridionale de l'Atlantique: stable ou bistable ?* **L'Actu des publis de l'Institut Universitaire Européen de la Mer**, http://www-iuem.univ-brest.fr/science-et-societe/sciences-pour-tous/actu-des-publis/Aout2013.

2012 *Prévoir l'état de l'Océan*, Scientific report GENCI 2012, p. 24-25, http://www.genci.fr.

08/2012 Organization and animation of a stall about ocean and climate modelling at Village des Sciences de la Mer, during Tonnerres de Brest (France)

05/2009 Realizing a video showing the Gulf Stream as simulated at very high resolution, in collaboration with G. Roullet (LPO), for the non-scientific public. This video was broadcasted in the French program “E=M6” on May, 31st, 2009.

02/2009 Member of the jury Experts Océans, Ouest France..

Educational degrees

2006 **PhD in physical oceanography** at Université Paris VI.

2003 **Master Degree in oceanography, meteorology and environmental sciences** at Université Paris VI, with honors.

2003 **Physical Engineer in fluid mechanics and oceanography**, graduated from ENSTA (national institute for advanced technologies), Paris (France), one of the top 10 engineering institutions; studying mathematics, physics (solid and fluid mechanics) and computer sciences.

Contributions to the community

Development of a package of programs (for Matlab and python) to analyze realistic simulations using ocean general circulation models (NEMO, POP, MOM, MPIOM, HYCOM, ROMS, MICOM, OFAM), in order to perform inter-comparison of model outputs and observations (http://www.whoi.edu/science/PO/pago).

Reviewer for Journal of Physical Oceanography, Journal of Climate, Deep Sea Research 1, Ocean Modelling and scientific projects submitted to NSF, NOAA, ANR and NRF.

Skills and expertise

Physical Oceanography: analytical development of theoretical and conceptual ocean models; numerical analysis of simulations using oceanic general circulation models; development and running of configurations (with single and multi-processors) using MITgcm and NEMO (stand-alone and coupled in IPSL-CM6).

Statistics: mono- and multi-variate analysis, linear and non-linear.

Computer sciences: programming languages (Html, C, java, Fortran 90), Matlab, python, Mac OS, Linux.

Languages: French (mother tongue), English (bilingual), Chinese (mandarin), Spanish.

Other professional activities

Statistical analysis of a database of young children cephalometric measurements to understand the process of cranio-facial growth and its impacts on dento-facial disharmonies, for TéléCrane Innovation (TCI).

Contributions to the Skull-Speech Project (2010-2012), funded by French ANR (ANR-08-BLAN-0272), in collaboration with TCI, MNHN, GIPSA (French UMR 5216).

Deshayes M.-J. et **J. Deshayes** (2013) : Etude des relations entre la morphologie cranio-faciale et l'occlusion en denture temporaire : remodelages occipitaux et singularités basicraniennes déterminantes pour l'occlusion, L'Orthodontie Française, vol. 84, 97-112.

Mother of Céleste Pous, born on May, 15, 2010 and Anita Pous, born on June, 20, 2016.

List of publications of the Principal Investigator

peer-reviewed "A" publications

[A-23] McInnes M. A., P. G. Ryan, M. Lacerda, **J. Deshayes**, W. S. Goschen, L. Pichegru 2017: Small pelagic fish responses to fine-scale oceanographic conditions: implications for the endangered African penguin, Marine Ecology Progress Series, 569, 187–203, doi:10.3354/meps12089.

[A-22] Treguier A.-M., C. Lique, **J. Deshayes**, J.-M. Molines 2017: The North Atlantic eddy heat transport and its relation with the vertical tilting of the Gulf Stream axis, Journal of Physical Oceanography, 47, 1281–1289.

[A-21] Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., **Deshayes, J.**, Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Heimbach, P., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclaus, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso, M., Wang, Q., Winton, M., and Yeager, S. G. 2016: OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project, Geosci. Model Dev., 9, 3231-3296, doi:10.5194/gmd-9-3231-2016.

[A-20] Holton, L., **J. Deshayes**, B.C. Backeberg, B.R. Loveday, J.C. Hermes and C.J.C. Reason 2016: Spatio-temporal characteristics of Agulhas leakage: a model inter-comparison study. Climate Dynamics, doi: 10.1007/s00382-016-3193-5.

[A-19] Barrier N., **J. Deshayes**, A.-M. Treguier et C. Cassou 2015 : Heat budget in the North Atlantic subpolar gyre : Impacts of atmospheric weather regimes on the 1995 warming events, Progress in Oceanography, 130 75–90, doi:10.1016/j.pocean.2014.10.001

[A-18] Thomas M., A-M. Treguier, B. Blanke, **J. Deshayes** et A. Voldoire 2015 : Isolating the impacts of mixed layer subduction on the meridional overturning circulation in a numerical model, Journal of Climate, 28, 7503-7517.

[A-17] Barrier N., C. Cassou, **J. Deshayes** et A.-M. Treguier 2014 : Response of North Atlantic ocean circulation to atmospheric weather regimes, Journal of Physical Oceanography, 44, 179- 201, doi:10.1175/JPO-D-12-0217.1

[A-16] **Deshayes J.**, R. Curry et R. Msadek 2014 : CMIP-5 model intercomparison of freshwater budget and circulation changes in the North Atlantic, Journal of Climate, 27 (9), 3298-3317

[A-15] Talandier C., **J. Deshayes**, A.-M. Treguier, X. Capet, R. Benshila, L. Debreu, R. Dussin, J.-M. Molines et G. Madec 2014 : Improvements of simulated Western North Atlantic current system and impacts on AMOC, Ocean Modelling, 76, 1-19, doi:10.1016/j.ocemod.2013.12.007

[A-14] Tréguier A.-M., **J. Deshayes**, J. Le Sommer, C. Lique, T. Penduff, J.-M. Molines, G. Madec, C. Talandier et R. Bourdalle-Badie 2014 : Meridional transport of salt in the global ocean from an eddyresolving model, Ocean Science, doi:10.5194/os-10-243-2014

[A-13] **Deshayes J.**, A.-M. Tréguier, B. Barnier, A. Lecointre, J. Le Sommer, J.-M. Molines, T. Penduff, R.Bourdalle-Badie, Y. Drillet, G. Garric, R. Benshila, G. Madec, A. Biastoch, C. Boning, M. Scheinert, A. C. Coward, J. J.-M. Hirschi 2013: Oceanic hindcast simulations at high resolution suggest that the Atlantic MOC is bistable, Geophysical Research Letters, 40, 3069-3073, doi:10.1002/grl.50534

[A-12] Maze G., **J. Deshayes**, J. Marshall, A.-M. Tréguier, L. Vollmer et A. Chronis 2013 : Surface vertical PV fluxes and subtropical mode water formation in an eddy-resolving numerical simulation, Deep Sea Research 2, 91, 128-138, doi:10.1016/j.dsr2.2013.02.026

[A-11] Mignot J., D. Swingedouw, **J. Deshayes**, O. Marti, C. Talandier, R. Seferian, M. Lengaigne et G. Madec 2013 : On the evolution of the oceanic component of the IPSL climate models: from CMIP3 to CMIP5, Ocean Modelling, 72, 167-184, doi:10.1016/j.ocemod/2013/09/001

[A-10] A. Voldoire, E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, **J. Deshayes**, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart et F. Chauvin, 2013 : The CNRM-CM5.1 global climate model: Description and basic evaluation, Climate Dynamics, 40, 2091-2121,doi:10.1007/s00382-011-1259-y

[A-9] Barrier N., C. Cassou, A.-M. Treguier, **J. Deshayes** 2012 : Impact of the winter North-Atlantic Weather Regimes on subtropical Sea-Surface Height variability, Climate Dynamics, doi:10.1007/s00382-012-1578-7

[A-8] Treguier A. M., **J. Deshayes**, C. Lique, R. Dussin et J.M. Molines, 2012 : Eddy contributions to the meridional transport of salt in the North Atlantic, Journal of Geophysical Research, 117, doi: 10.1029/2012JC007927

[A-7] **Deshayes J.**, F. Straneo, et M. Spall, 2009 : Mechanisms of variability in a convective basin, Journal of Marine Research , 67, 273-303, doi:10.1357/002224009789954757

[A-6] Frankignoul C., **J. Deshayes** et R. Curry, 2009 : The role of salinity in the decadal variability of the North Atlantic meridional overturning circulation, Climate Dynamics, 33, 777-793, doi:10.1007/s00382-008-0523-2

[A-5] **Deshayes J.**, C. Frankignoul, 2008 : Simulated variability of the circulation in the North Atlantic from 1953 to 2003, Journal of Climate, 21, 4919-4933, doi: 10.1175/2008JCLI1882.1

[A-4] **Deshayes, J.**, C. Frankignoul, et H. Drange, 2007 : Formation and export of deep water in the Labrador and Irminger Seas in an ocean model, Deep-Sea Research 1, 54, 510-532, doi:10.1016/j.dsr.2006.12.014

[A-3] Sirven, J., C. Herbaut, **J. Deshayes** et C. Frankignoul, 2007 : Origin of the peaks of variability in the response of a 1.5 layer ocean model to stochastic forcing, Journal of Physical Oceanography, 37, 2146-2157, doi:10.1175/JPO3095.1

[A-2] Herbaut, C., J. Sirven et **J. Deshayes**, 2006 : Sensitivity of the meridional transport in a 1.5 layer ocean model to localized mass sources, Journal of Marine Research, 64, 819-833, doi: 10.1357/002224006779698404

[A-1] **Deshayes, J.** and C. Frankignoul, 2005 : Spectral characteristics of the response of the meridional overturning circulation to deep water formation, Journal of Physical Oceanography, 35 (10), 1813-1825, doi: 10.1175/JPO2793.1

peer-reviewed "B" publications

[AB-1] Barrier N., A.-M. Treguier, C. Cassou, **J. Deshayes** 2014 : Influence des régimes de temps atmosphériques sur la circulation océanique de l'Atlantique Nord, La Météorologie, Série 8, N° 87 ; p. 38-44, doi : 10.4267/2042/54335

Book chapters
[B-1] **Deshayes J.** et O. Aumont, 2017: La modélisation numérique de l'océan, in A. Euzen, F. Gaill, D.Lacroix and P. Cury, L'océan à découvert, Paris : CNRS editions, 978-2-271-11652-9, 321 pp.

Softwares
[S-1] Physical Analysis for a Gridded Ocean (http://www.whoi.edu/science/PO/pago)

Granted patents and other measures for the relevance of the work

not relevant.

Prior allocation history in PRACE, national calls, as well as international programs such as INCITE of the US DoE

Dr J. Deshayes has been the PI of several GENCI projects (French national calls) since she was appointed as research scientist by CNRS:

year	project number	project title	machine	allocated hCPU
2010	i2010012202	subpolar Atlantic configuration to investigate air-sea interactions	IDRIS IBM SP Vargas	120,000
2011	i2011012202	*Role des fines echelles dans la circulation et la structure thermohaline de l'Ocean Atlantique*		200,000
2012	i2012012202			500,000
2015	x2015017451	NEMO R&D	IDRIS IBM SP Ada	841,955
2016	x2016017451			850,000
2017	A0020107451			1,250,000
2018	A0040107451			2,414,000
2018	A0040107451		Joliot Curie - SKL	2,200,000

Participation by team members in other European Commission (EC) actions, such as ERC or Marie Skłodowska-Curie EC grants, etc.

The QUEST proposal is scientifically motivated by several EU-H2020 collaborative projects, in which the PIs are directly involved, and which deliverables more or less depend on simulations to be produced within PRACE allocation (see list provided on online application form). For example, J.M. is a WP leader in the submitted C3 proposal which aims at reducing the uncertainty in Climate change projections over Europe ; PRACE allocation is currently the only opportunity to ensure the necessary computing resources to meet with deliverables of this project. Another example is EU-

Marie Curie grant EPICE (2018-2020) granted to Dr M. Menary, collaborator of QUEST, which will be supervised by Dr J. Deshayes and Dr J. Mignot. Dr M. Menary will be in charge of running simulations within WP3 of EPICE, which will be instrumental to accomplish deliverables of EPICE. As a result, the numerous projects in which the team members are involved, should be seen as multiple opportunities to disseminate results obtained thanks to PRACE allocation.

Previous presentations at PRACEdays

none.

Appendix 2: Resources from the European ICEI project (FENIX research infrastructure) – Pilot Phase

This 18th Call includes a pilot phase to incorporate a fraction of the resources from the Fenix Research Infrastructure, funded by the European ICEI project. Applicants interested in using the additional ICEI resources are requested to provide here the following information:

Amount of required ICEI resources

not relevant.

Description of the software and services that are planned to be executed within the ICEI infrastructure

not relevant.

Description of special needs, e.g. in terms of third-party software

not relevant.