InfraStructure for the European Network for Earth System Modelling
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European Network for Earth System Modelling

Infrastructure Strategy
for the
European
Earth System Modelling
Community
2012-2022

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2012-2022

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Montvillargennes workshop participants, 2010

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Executive Summary

This document explores the infrastructure needed during the next decade to support European climate research for seasonal to centennial climate predictions. This research will be integral to providing the scientific basis for climate services. It is highly relevant to the objectives of the Joint Programming Initiative on Climate “Connecting Climate Knowledge for Europe”.

The scientific community working on climate modelling is organized within the European Network for Earth System modelling (ENES). It has outlined major scientific issues both related to the reliability of climate change predictions and to the scientific understanding of climate natural variability. The document presents a vision of what could be available in 10 years time. It is envisaged that by the end of the decade, convective scales will be fully featured in climate models. Initialization and ensemble techniques will be well developed. Uncertainty will be well characterised ensuring appropriate diversity in both regional predictions and longer paleoclimatic simulations. It will be possible to initialise models from real data using full data assimilation techniques. It will be easier to evaluate models and their shorter range projections using hindcasts applied to real data, and such evaluation will be harnessed in a cycle of continuous model improvement.

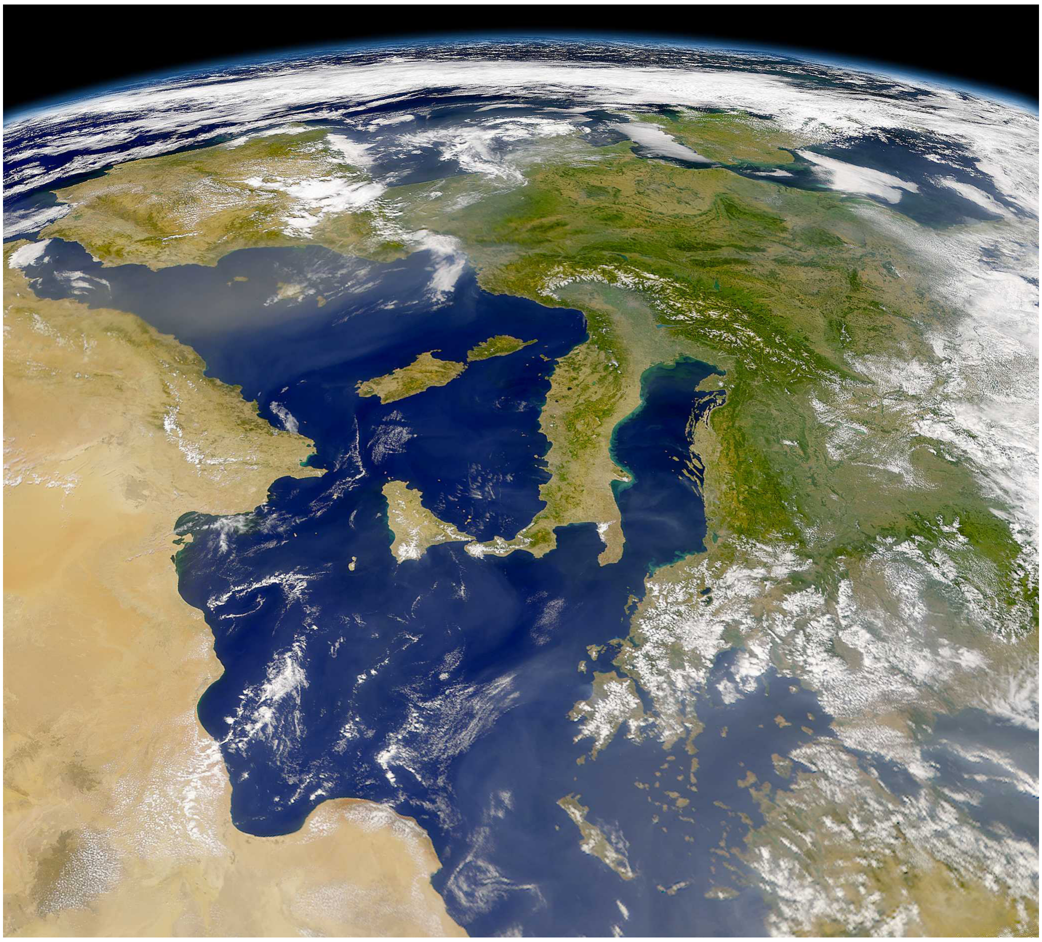
The implications of this vision for infrastructure are set out. The most demanding goal is to ensure by the end of the decade convective scales are resolved in European climate models of the Earth system with the objective to obtain regional climate predictions for next few decades which are more reliable. This in turn will require intensive and adapted access to exascale computing (10^{18} operations per second), co-located to an unusually large data archive, which needs to be connected to national archives by networks transferring data at rates faster than Tera bits/second. European models will benefit from being more modern in terms of flexibility and usability, and having a designed diversity, with the number of model «families» possibly reduced and commensurate with the resources available for their development and use.They should scale very well on high performance computers, but also allow usage across the whole computing pyramid. This will mandate a better connected and organized European community, agreeing and working together on common goals.

The requirements to ensure the availability of appropriately skilled experts is outlined, and possible funding and governance are discussed.

ENES recommends the following action items for the climate modelling research infrastructure:

1. Provide a blend of high-performance computing facilities ranging from national machines to a world-class computing facility suitable for climate applications, which, given the workload anticipated, may well have to be dedicated to climate simulations.
2. Accelerate the preparation for exascale computing, e.g. by establishing closer links to PRACE and by developing new algorithms for massively parallel many-core computing.
3. Ensure data from climate simulations are easily available and well documented, especially for the climate impacts community.
4. Build a physical network connecting national archives with transfer capacities exceeding Tbits/sec.
5. Strengthen the European expertise in climate science and computing to enable the long term vision to be realized.

Strengthening the European climate modelling infrastructure will provide Europe with the necessary evidence and expertise for its mitigation and adaptation policies.



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1. Introduction

The science of global climate change continues to advance, and with that advance comes the necessity for an infrastructure to support that progress. This document sets out a strategy for the next decade, and beyond, to provide the large-scale infrastructure components necessary for the European community working on climate models to deliver on the foreseeable scientific and societal requirements.

The strategy is set in the context of both the scientific needs developed at the international level within the World Climate Research Program (WCRP) and the International Geosphere-Biosphere Program (IGBP), and those identified at a number of workshops organised under the auspices of the European Network for Earth System modelling (ENES).

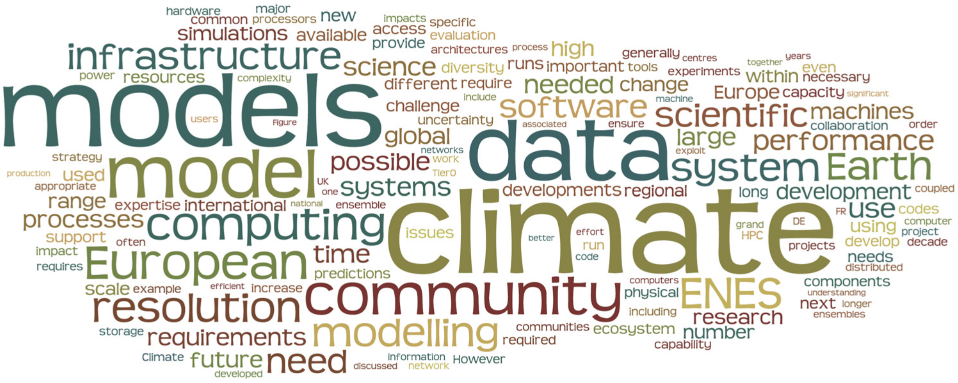
ENES gathers the European community developing and applying climate models of the Earth system. This community aims to better understand present and past observed climates and predict future changes under given boundary conditions of anthropogenic and natural forcing. The ENES community has made significant contributions to the Intergovernmental Panel on Climate Change (IPCC) assessment reports, and has long been working within several European Framework Programs via projects devoted to improve the European knowledge of climate change and related issues. The ENES network was established in 2001 following a first foresight exercise performed by the community in 1998 within the EU Euroclivar concerted action (http://www.knmi.nl/euroclivar/frsum.html) which recommended "*a better integration of the European modelling effort with respect to human potential, hardware and software*" and "*to develop collaboration, to establish a European climate computing facility, and to enhance the exchange of software and model results*".

This exercise, more than ten years later, is to provide foresight through to 2022 and beyond via an analysis of requirements and establishment of a strategic plan. It is an activity of the FP7 IS-ENES project "Infrastructure for ENES" (http://is.enes.org), addressing the future needs for infrastructure for climate modelling. It focuses on the global climate models at the base of climate change projections but encompasses regional climate models and the interface with the climate impact community.

It will strengthen the European community to face the scientific challenges of climate change research. The strategy will address support for the climate community itself, as well as, for the impact community relying on climate model results and policy makers concerned with climate change policy. It focuses on future collaboration and synergy, with particular attention to developing areas of collaboration which would not happen anyway. The general approach is to maintain scientific diversity, a European strength, whilst avoiding "dispersion" of technical approaches.

This strategy aims to «strengthen the European community to face the scientific challenges of climate change research.»

The rest of this document is organized as follows: In the next section, we provide the context of this exercise. We discuss the drivers of climate research. They include the scientific "push" of new opportunities which become possible through emerging scientific advances, and the "pull" to meet requirements from policy and business. The drivers impose certain requirements which the necessary modelling infrastructure needs to meet, and these are discussed in section 3. This includes organisation of science, software, hardware and people. In section 4, the implications of these requirements are discussed in the last section, the plan is drawn together, and some wider issues are discussed.



2. Context

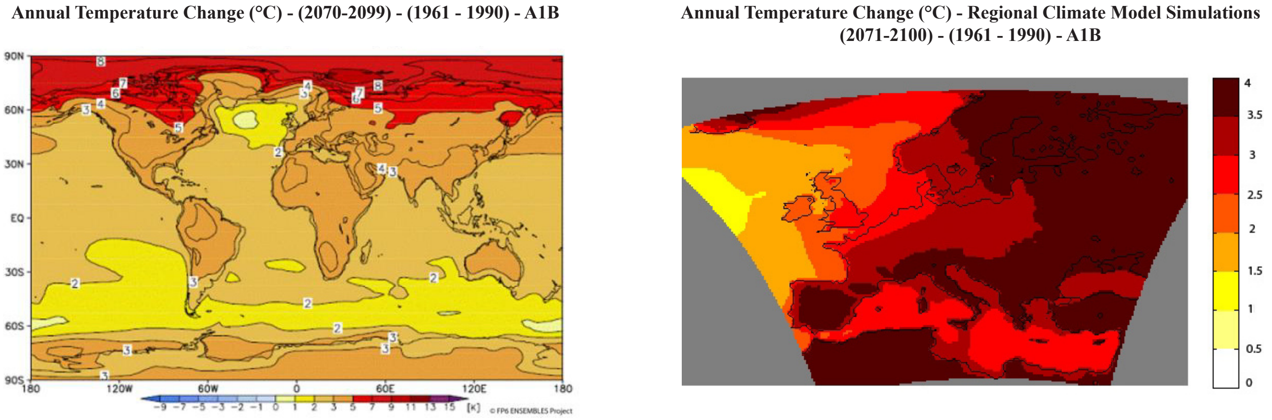
In the decade since the original Euroclivar foresight exercise, our understanding of climate change has increased, as has the societal need for pull through to advice and policy. The latter has resulted in pressure to do science which can be applied in the short term, in addition to (and sometimes instead of) research which might result in much improved utility in the longer term, particularly in relevance to guiding climate related policies. Where it occurs, this tension between research and applications can be appropriate, but has risks which need to be managed to maintain a sensible balance. One of the purposes here is to ensure that there is a healthy and sustainable balance between application "pull" and research "push".

2.1 Policy pull: Societal requirements

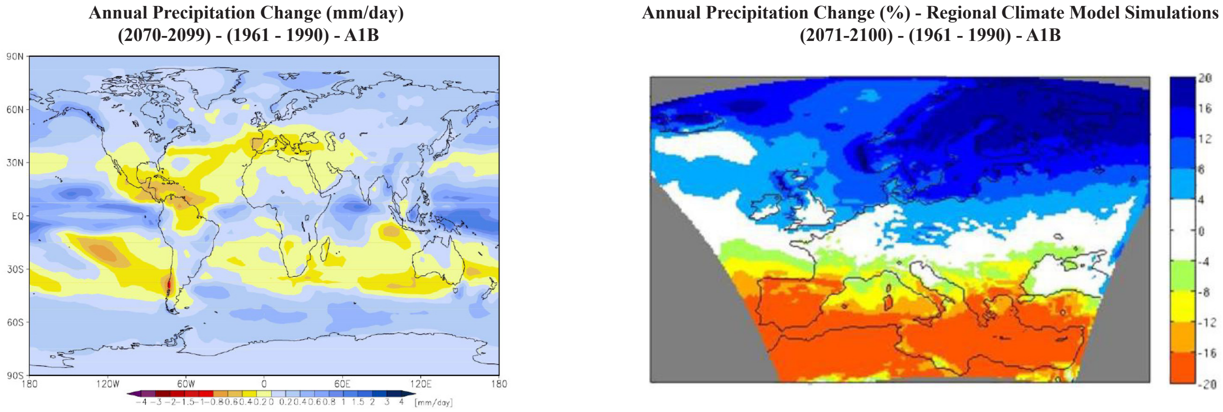
Climate models have been extensively used to detect the occurrence of climate changes and attribute their causes as well as investigate possible future climate changes under different economic scenarios. In the last few years, the emphasis on "policy relevance" has moved beyond the issues of the existence of a human effect on climate and how to mitigate future change. As it becomes more likely that a certain level of climate change will be inevitable, interest has extended to how climate will change in the next few decades, and evaluating the most effective ways to adapt to it.

Hence, from a policy point of view, there are two important timescales that have to be understood: the next few decades where vulnerabilities can be assessed and adaptation responses planned, and the centennial scale on which we can understand how global strategies to mitigate climate change could work. Of course, from a scientific point of view, these timescales are not unconnected - particularly where mitigation strategies may take decades to have impact.

The need for climate information from seasons to decades to guide adaptation to climate change has led to the World Meteorological Organisation setting up a Global Framework for Climate Services to help make sure that research on climate change is translated into advice and predictions which are useful to those who are vulnerable to climate change and variability.


Annual Temperature Change (°C) - (2070-2099) - (1961 - 1990) - A1B

Annual Temperature Change (°C) - Regional Climate Model Simulations (2071-2100) - (1961 - 1990) - A1B


Annual Precipitation Change (mm/day) (2070-2099) - (1961 - 1990) - A1B

Annual Precipitation Change (%) - Regional Climate Model Simulations (2071-2100) - (1961 - 1990) - A1B

Figure 1: *Simulations of an ensemble of European climate models from the ENSEMBLES FP6 project showing temperature changes (top)and precipitation changes (bottom) for the end of the century under the scenario A1B from an ensemble of European global climate models (left) and regional models using results from global models as boundary forcing (right). Note that for precipitation changes, global model results are shown in mm/day and for regional models in % change.*

To provide this kind of guidance high spatial and temporal resolution information is essential, higher than can be achieved with the current generation of global models. Thus, there is a role, at least for the next decade, to complement global climate models by downscaling approaches to provide information at the regional scale using very high resolution regional models and statistical methods (Figure 1).

Recent research also begins to investigate the possibility to develop decadal prediction systems, which, through more realistic initial conditions, aim at improving the realism of future simulations. Climate services will also need to infer impacts of climate change on different sectors such as water, ecosystem, health and the need to understand societal behaviour. This will require the strengthening of the interface and interactions between the climate modelling community and the large community of model data users, leading to a complementary strong need for communication and training on the meaning of climate information, and its associated uncertainties.

Centennial scale projections are the basis of current (e.g. Conference of the Parties of the United Nations Framework Convention on Climate Change) and future international mitigation negotiations. Of particular importance will be to quantify and reduce uncertainties which impact upon the usability of the projections – both for mitigation and adaptation.

Climate models will also be important to investigate possible nonlinear behaviour of the Earth system (such as those that may arise from permafrost melting) and will be useful to investigate geo-engineering proposals for mitigation, since they are the only tools we have to assess the limitations, uncertainties, and risks of such activities.

This interest in mitigation, adaptation and vulnerability both relies heavily upon, and drives improvements in climate models of the Earth system. The ENES strategy presented here takes this shift in emphasis into account. It will ensure that the infrastructure will deliver research to support climate services - although the scope of ENES does not extend to providing those services. This will require a continuous dialogue from the outset with stakeholders to ensure that the right problems are targeted and that the proposed solutions are likely to be fit for purpose.

2.2 Science Drivers

The overall aim of ENES is to understand and predict global and regional climate change and climate variability using numerical models. There is a wide range of underlying scientific issues which have been raised by the international community, for example within the WCRP strategy COPES “Coordinated Observation and Prediction of the Earth System” 2005-2015 (http://wcrp.ipsl.jussieu.fr/).The major issues, taking into account the interests and strengths of the European climate science community and the aim to answer societal needs, include:

- How predictable is climate on a range of timescales and what are the limiting factors? Can the range of uncertainty be fully represented with the models we have available, and without exaggerating the range of possible futures ?

- What is the sensitivity of climate and how much can we reduce the current uncertainty in the major feedbacks, including those due to clouds, atmospheric chemistry and the carbon cycle ?

- What is needed to provide reliable predictions of regional changes in weather and climate ?

- Can we model and understand glacial – interglacial cycles, including changes in carbon cycle and major ice sheets? Can we use observational evidence from past climates to calibrate the sensitivity of complex climate models and respective adjustable model parameters ?

- To what extent can we attribute signals in the period of the instrumental record to understand Earth system processes – from weather scales to those typical of anthropogenic climate change ?

2.3 Landscape of European climate modelling

Global climate models of the Earth system are fundamental to climate understanding and prediction. Numerical models are constructed by joining together 3-dimensional models of the physical components - atmosphere, oceans and land-surface -, each of which is itself composed of further physical (e.g. clouds and radiation) or biogeochemical subsystems (e.g. aerosols, atmospheric chemistry, vegetation dynamics...) (Figure 2). The physical part of the system is based on coupled atmosphere-ocean general circulation models (AOGCMs) which, when they include the modelling of the biogeochemical processes of the system are called Earth system models (ESMs).

All these subsystems are calculated on a spatial grid which is characterised by its average spatial resolution. The degree of complexity and the resolution of climate models have evolved through time depending on available computing power and the advancement of knowledge on climate processes. A typical Earth system model represents about 500 to 1000 man years of code development and has a strong legacy history.

Seven major global climate models are available in Europe and are participating to the international Coupled Model Intercomparison Project 5 (CMIP5) set up to prepare the 5th Assessment Report of IPCC (see table 1). Their documentation can be accessed through the ENES portal (http://enes.org).

Most of these models are run and analysed by several user groups either nationally or within several countries. Even if the models have been developed by different modelling groups, several of them share some common components or tools, such as the OASIS coupler or the NEMO ocean platform, developed through European collaboration (Table 1).

The landscape of regional climate models (RCMs) is more diverse in Europe and world-wide. RCMs are essentially 3-dimensional atmospheric models run over a limited area domain and forced on their lateral boundaries by conditions obtained from observations or from global climate models. Some groups are beginning to develop coupled versions of RCMs encompassing several components of the Earth system. As example, more than 10 RCMs were used in the ENES FP6 ENSEMBLES project. The new international WCRP COordinated Regional climate Downscaling Experiment (CORDEX), coordinated by European scientists, follows CMIP5 strategy, and will certainly modify and structure the landscape of RCMs. It also offers an opportunity to improve the interactions between global and regional climate modelling communities.

2.4 Implications of science drivers

As the resolution and number of subsystems increase, so too does the complexity of the software architecture and the computer time required, and there are more issues with data management. The same issues arise from long duration runs, and from the multiple predictions which result from ensembles with one or several models. Hence, from an infrastructure strategic point of view, it is helpful to additionally ask questions about the science drivers in terms of the following characteristics:

Resolution

What resolution is required to give credible and useful results? What degree of detail is required for assessing the impacts of climate change, and, more fundamentally, do predictions of climate change converge as one increases resolution, and for what timescales can models follow the observed trajectory of climate and its extremes?

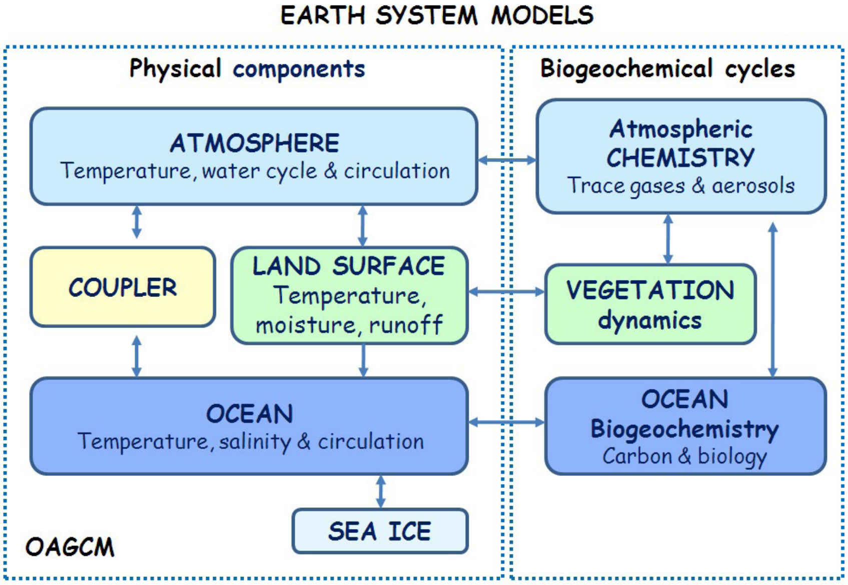


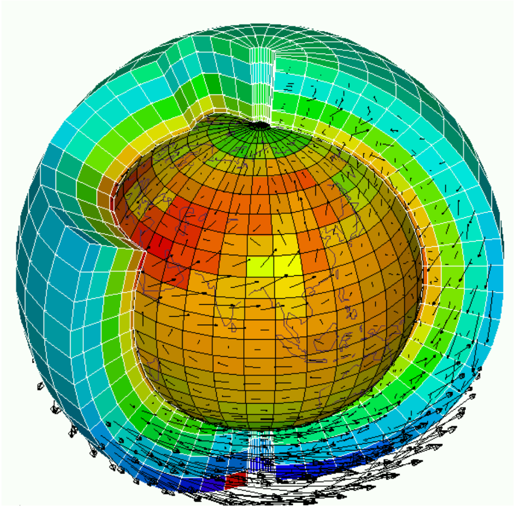
Figure 2: schematic description of global climate models and their interactions. Coupled atmosphere-ocean general circulation models (AOGCMs) represent the physical components of the Earth's climate system. Earth system models (ESMs) are based on AOGCM coupled to biogeochemical cycles.

Complexity

What is the sensitivity of predictions to unresolved physical and non-physical processes including those governing cloud feedbacks, and the representation of biology and chemistry processes including, for example, those involving the land surface and aerosols?

Ensembles and Duration

Theoretical limits on predictability, together with uncertain initial state and future forcing, lead to the use of a range of ensemble techniques to add statistical estimates of uncertainty to climate predictions and projections made with climate models. This information is of critical value in order to develop appropriate policies for tackling situations of high uncertainty and high risk. The number of realisations needed (and even the ensemble strategy) is problem dependent, but the robustness of such uncertainty estimates is generally constrained by the number of simulations that can be produced, rather than the number desired. Optimal model run length is similarly problem dependent, and generally constrained by resources.



Basic equations are numerically solved on grids (copyright CNRS).

Data

What data is needed to initialise and evaluate these models and their predictions or to drive nested regional models? What data products are needed, and how best can these be stored, shared and utilised by the target user communities? Are the appropriate user communities aware of what is possible and how to use the data available? Is there a continuous dialogue between data producers and the potential users of such data? Is the data accompanied by uncertainty estimates and appropriate documentation?

Group	Country	Name of model (CMIP5)	Atmosphere	Ocean	Sea Ice	Coupler	Land Surface *Vegetation	Atmosphere Chemistry	Ocean Bio-geochemistry
EC-EARTH	Consortium	**EC-EARTH**	IFS	NEMO	LIM	OASIS	HTESSEL	TM5	
IPSL	France	**IPSLCM5**	LMDz	NEMO	LIM	OASIS	ORCHIDEE	INCA	PISCES
CNRM-Cerfacrs	France	**CNRM-Cerfacs**	ARPEGE	NEMO	GELATO	OASIS	SURFEX		
MPI Hamburg & Finland	Germany	**COSMOS**	ECHAM5	MPIOM	MPIOM	OASIS	JSBACH*	HAM	HAMOCC
CMCC	Itlay	**C-ESM**	ECHAM5	NEMO	LIM	OASIS	SILVA		PELAGOS
MetOffice-Hadley Center	UK	**HadGEM2**	UM	UM	CICE	OASIS	TRIFFID*	UKCA	diat-HADOCC
Norclim	Norway	**NorESM**	NCAR	MICOM	CICE	CPL7	CLM	Chemistry	HAMOCC

EC-Earth Consortium Netherlands, Sweden, Ireland, Denmark, Spain, Portugal, Italy, Belgium

Table 1:The seven European ESMs which are participating to CMIP5.The description of the model components outlines the components shared between the models (same colors). Description of the different components and their acronyms can be found on http://enes.org and is not displayed for simplicity.

3. Infrastucture

The previous section has outlined the scientific and policy drivers for reliable Earth system simulations, and some of the constraints on doing so. It has highlighted the importance of communication between those carrying out simulations, and the users of the simulations, and the importance of the propagation of data and information between communities. All of this requires both physical and software infrastructures as well as human capital. Our ability to improve the reliability and capability of our simulations is directly constrained by the existing infrastructure and the available workforce. In this section, we discuss these constraints in terms of the computing environment, models, data, (computing) networks, and workforce. We begin by outlining how the scientific requirements lead to specific requirements on model composition and diversity, and then discuss the current and expected physical and software infrastructural environment. The section concludes with the implications for the workforce required and how it needs to be organised on a European scale.

3.1 Scientific infrastructure requirements

One of the main assumptions driving the form of infrastructure required is that Europe will continue for the time being to support a number of independent Earth system models – although not necessarily as many as now. Although much progress has been made on improving climate models in the last couple of decades, there are still processes for which there is no commonly agreed mathematical basis (e.g. cloud feedbacks) leading to a wide range of predictions of climate change associated with a given emissions scenario. It is therefore prudent at present not to work towards a single European climate model, but to retain a small number of independent models to reflect this uncertainty whilst better understanding the sources of diversity and working towards more interchangeable modelling structure in the longer term.

This reflects developments at an international level – the IPCC WGI AR4 assessment relied heavily on multi-model ensembles to obtain a measure of the uncertainty in climate projections – while reflecting a desire to exploit our resources more effectively. We now consider in more detail five separate aspects of scientific infrastructure requirements, which are those associated with model diversity, process understanding, evaluation, initialisation, and long duration runs.

It will be seen that all five aspects of the scientific infrastructure requirements have associated model and data requirements all of which will become more significant over the next decade, leading to significant model and data infrastructure requirements.

Model diversity

The need for model diversity impacts on nearly all the other components of Earth system modelling infrastructure, since it leads to different algorithmic descriptions of real world processes. This is reflected by the existence of several major global and regional climate models within Europe. It leads to tensions between community efficiency (minimising the number of such models and their individual human, software and physical infrastructures) and the scientific need for diversity (which would tend towards maximising the number of some classes of models to improve estimates of the contribution of model uncertainty to overall uncertainty budgets).
This tension underpins discussion in all the following sections, as it has major implications for both the way the climate science community organises itself and interacts internally, as well as the concomitant software and hardware infrastructures. Some diversity is unambiguously necessary (including that associated with the difference between models used for decadal prediction, and those used for paleoclimate simulations). Whatever diversity is needed, maintaining traceability and/or distinguishability between versions requires sustained effort.

Physical & biogeochemical processes

As well as the models themselves, it is clear that there should be an emphasis on improving our understanding of climate processes within them, majorly in order to reduce uncertainties, biases and omissions. There is a wide range of work on model development within Europe which needs to be brought together in a co-ordinated way. This is addressed to some extent in ENES EU projects such as the FP7 projects COMBINE, EUCLIPSE and EMBRACE. However, one of the roles of ENES is to ensure that such work is consistent with an agreed European strategy. Improving the representation of crucial processes in climate models is a task that is much broader than the work at the institutions developing the models. This is even more so with Earth system models that include a larger range of components of the climate system. Detailed process investigations, both theoretically-numerically and observationally-experimentally, are usually required.

the expertise and technical infrastructure required to perform these investigations often outstrip what is available at the climate modelling centres. A close cooperation with a much wider research community is often needed to integrate into the models the knowledge gained elsewhere. This integration also requires an effective software infrastructure so that improved process modules can be integrated or updated quickly, particularly where the improved process representation needs to be tested in more than a single modelling environment (or family).

Box 1: Typical Earth system modelling workflows

(a) Within a work group:

An Earth system model is usually driven via a complex infrastructure of scripts which acquire initialisation and boundary data from storage, extract or perhaps compile some specific code, and then bind that code to the data and specific parameters (usually via "namelists") before executing it. The final model configuration will normally be specifically targeted at one type of parallelisation (for example, using a specific decomposition of the model grid onto a specific number of processors) for a specific piece of hardware, and thus cannot be easily reused. Typically the software infrastructure to do this is tightly coupled to the model software itself ("custom designed"), with the tools for parallelisation embedded within the scientific code. Often different scientific sub-models have approached the parallelisation and input/output methodologies differently, and a special software component, called a coupler, is used to feed data between those components, which may be running on their own sub-grid of processors. The resulting systems are heavily optimised for a particular computing environment and are very efficient since such models generally have long run-times, and are thus both expensive of resources and time. The output data is usually written to storage, and post-processing scripts and codes are used to produce diagnostic variables, interpretation and visualisation. Such post-processing often occurs after data has been downloaded to other computing systems, and will involve inter-comparison with other model data as well as with individual real-world observations such as those from Earth Observation satellites.

(b) International:

Model Inter-comparison Projects (or MIPs) provide three key tools for improving and exploiting Earth system models: methods of evaluating model skill (in comparative terms), methods of improving complex process understanding, and finally, of providing projections for the future (which are themselves evaluated by using hindcasts, that is, projections of the past which can be compared with observations). Results from MIPs are a key input to climate policy, such as Coupled Model Intercomparison Projects (CMIP) intensively used in IPCC Assessment reports.

These projects are based upon numerical experiments (simulations) with different climate - coupled or component - models in comparable configurations (initial values and boundary conditions, resolution, processes) run on different computers in different places. These experiments use substantial parts of (generally) Tier1 computing systems and bind substantial fractions of the workforce in the participating institutes. They generate vast amounts of data, e.g. CMIP5, is expected to generate tens of petabytes of data, several petabytes of which will be globally replicated to aid access and exploitation. These MIPs may be inter-related, with interdependencies: for example, regional model intercomparison projects may be dependent on large amounts of data from global model intercomparison projects.

In order to compare these runs they need to be finished at about the same time. Scientists then start to collect information about the models, the configurations and the experiments, and also start to aggregate data about the different processes and properties of the experiments which they are scientifically interested in. Peer reviewed publishing finalises this process. Generally these projects are hampered by the diversity of formats in which data and information is initially stored, the insufficient availability of compute time and storage space for the analysis process and the difficulty to transfer large amounts of data between different centres.

Initialising models

The increasing emphasis on shorter timescales will require new work on initialising climate models and reducing known biases. There is a lot of experience from weather prediction centres on assimilating atmospheric observations into models, where an underlying theoretical framework exists. However, much of that framework may not be directly applicable for assimilating data over the longer time scales needed to initialise climate models, and much less is known on how to assimilate data into coupled models (those with multiple major subsystems). Data may not be available for all the variables important to climate model initialisation, and even where it is, significant experience is needed to work out how to assimilate it. All these remain ongoing challenges.

Model evaluation and understanding

An even broader interaction across the research community is required to ensure appropriate model evaluation (including the evaluation of the representation of small-scale processes in models). Model evaluation requires easy access to observational information including an efficient infrastructure (both hardware and software) for quantitative comparison. An important international effort is devoted to model evaluation through intercomparison projects (see box 1). The efficient evaluation of climate models will also require tapping into the research community that is knowledgeable of observational errors and limitations. Again, sustainably supporting the necessary interactions represents a challenge in scientific infrastructure. While Earth observation data help with some aspects of model evaluation and paleoclimate data with others, there is no opportunity to validate longer (centennial) predictions detailed model output against observed outcomes as is done for weather forecasts, so understanding the model response is the major route to building confidence in model predictions. This will require the model infrastructure to be flexible enough to be run in a hierarchy of configurations (more or less idealized, with more or less complexity).

Long simulations

Running longer simulations (as needed to address the glacial and inter-glacial cycles) will require scientifically defensible models, which include the essential processes for such long time scales, and which, nevertheless, allow a high forecast performance rate (in simulated years per working day). Such models typically include more processes than models used for shorter time scales, so that the processes and feedbacks acting over long timescales are captured. Consequently high forecast performance rates can only be achieved by reducing the resolution. Such models cause different stresses on the physical infrastructure. Typically the scalability of such models is limited compared to higher resolved models, so that the speed depends more strongly on the single CPU performance than on the number of available CPUs.

3.2 Physical Infrastructure requirements

Before describing the infrastructure requirements in detail, it is helpful to consider typical Earth system model workflows (box 1). It can be seen that simulations with climate models require large computers, produce large amounts of data, and that this data needs to be used in a variety of locations, leading to significant requirements for network performance. All three aspects, computing, data, and networks, are discussed here. The following section addresses software infrastructure.

3.2.1 Computing

Earth system modelling has traditionally required access to the largest possible computing resources. What we can simulate has always been limited by computing resources as the science requires more computing than is technically possible and/or affordable. In the last decade those limits have been pushed in the direction of exploiting both the biggest possible supercomputers (for example, the Japanese Earth Simulator) and the largest possible number of computers (for example, the climateprediction.net project). However, as well as populating the limits of computing, Earth system modelling exploits the full range in between, and is likely to do so for the foreseeable future, as discussed below.

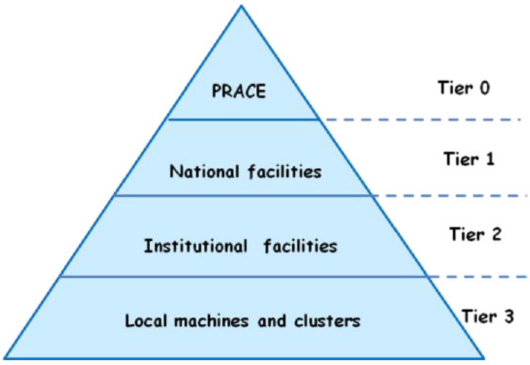


Figure 3: Categorisation of computing types: Tier0 are the largest systems available in Europe, Tier 1 are the large national facilities. Tier2 consists of large institutional facilities as well as clouds and grids of remote resources. Local resources appear at Tier3 and include multi-processor machines as well as clusters and local pools providing access to such resources.

The computing ecosystem

The range of computing can be conveniently categorised with the tier model, see figure 3. Tier0 is defined as the biggest and fastest possible computers available in Europe, Tier1 as the large national facilities, Tier2 as institutional facilities in universities or research labs, whereas Tier3 includes departmental servers, smaller clusters or pools of workstations. A strategy for Earth system modelling has to address how to exploit all of these systems, defined as the "computing ecosystem" – in the near future, while the architectures are familiar, and beyond, where the expected computer architectures may introduce new challenges for exploitation.

Computing can also be categorised in terms of capability and capacity. "Capability" machines are generally those which have the greatest ability to run "big" jobs, and/or are the first of a new generation of hardware. "Capacity" machines are generally those which are used for the bulk of "production" runs, generally after codes have been developed in capability mode. The largest machines (generally Tier1 and above) can be used in both modes: if a large part of the machine is dedicated to capacity jobs for some of the time, and is used for production runs at other times.

An ecosystem of models

The interaction of capability and capacity can, in part, be seen in Figure 4, which depicts a possible set of futures showing the relationship between global climate model development, a capability activity, which spawns off capacity activities at intervals. Indeed, global climate model ensembles (and/or model intercomparison projects) themselves spin off regional climate model ensembles (and/or model intercomparison projects), the data from which is used for specific impact models. Although the figure is schematic (for example, impacts models will use data from global models etc), the key concept is that of an ecosystem of models, data transfer, and data interpretation which is what an European infrastructure must support.

Computing power requirements

The impact of the scientific requirements outlined earlier on the requirements for computing power are well known (e.g., see the HPC scientific case prepared for PRACE in 2006, http://www.hpcineuropetaskforce.eu/ to which ENES contributed). In practice the community has an effectively insatiable demand for computing power (Figure 5).

The scientific implications outlined in section 2.4 request increases in computing power:

- Resolution: Each increase by a factor 2 of the horizontal resolution requires about a six to eightfold increase in computing power.

- Complexity: For example, including representation of biogeochemical cycles using different biochemical tracers and aerosols typically increase time by a factor of 5 to 10.

- Data assimilation: Complex initialisation strategies (data assimilation) significantly impact runtimes.

- Ensembles: Computing requirements scale directly with the number of ensemble members which are required to better represent uncertainties associated to both internal variability and model parameterisations, but the number of members required to keep the same signal-to-noise ratio in climate forecasts also increases as the spatial resolution increases!

- Duration. The need for longer historical runs, both current-era hindcasts and paleoclimates, or for long runs to investigate possible future nonlinear changes is evident, and the computing needs to scale accordingly. Equilibration of slow pools in climate models is likely to be necessary for initialisation and validation, requiring very long spin-ups.

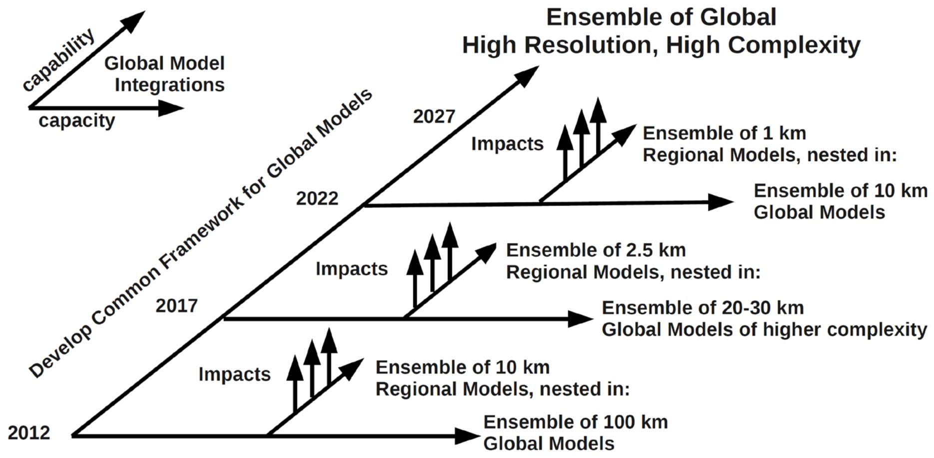


Figure 4: Schematic of a possible future of an ecosystem of Earth system model development and exploitation.

From an infrastructure point of view, the need of keeping a particular numerical experiment running has implications (both for storage needed for checkpointing and for uptime and/or length of sustained access to the machine). Meeting the scientific challenges described in 2.2 will need an increase of the model performance by several orders of magnitude. Nevertheless, each increase of computing performance allows improving one of the above axes (resolution, complexity, data assimilation, ensembles, duration).

Dealing with limitations in computing power

Computing power is a strong constraint to the type of problem that can be addressed. For a given computing power and time frame, within which the experiment must be completed, global climate models are run at a resolution that allows performing the experiment with the required complexity, duration and ensemble size. Current global climate models have typical resolutions of the order of 100-200 km today, whereas regional models, using data from global models as boundary conditions, are run at higher resolution (e.g. about 10-20 km) and used for impact studies. In principle, as more computing power becomes available, it can be deployed along any or all of the axes described above (resolution, complexity, ensemble size, duration). However, in practice, the science, software, and nature of the computing itself all impact on the choice of how to use the resource.

Need for both capability and capacity

ENES supports the view that, both capability and capacity computing are important for Earth system modelling; both are necessary for pushing the envelope of our research. Capability is needed given the long time scales every coupled model configuration needs to spin up to a stable state; furthermore paleoclimate-studies need capability as long as there is no parallelisation in time. Higher resolution simulations also strongly benefit from capability. But, carry out control and transient ensemble runs dealing with modern climate is a typical capacity problem. Producing the set of experiments for IPCC AR5, such as organised through CMIP5, requires the running of a high number of experiments (typically cumulated 10 000 simulated years for each modelling centre) at the best spatial resolution possible, and is a typical combination of capability and capacity needs. All of these runs need to be considered as being part of the same experiment. So systems specially suited for ESM high-performance computing (HPC) applications need to provide both capability and capacity. In any case, capacity demanding ensemble type runs with high resolution models are generally done most efficiently on central HPC systems, and not in a distributed manner, although there are applications where distributed systems provide good performance.

However, those cases generally depend on models with high portability and on relatively low input/output volumes. Many high-end Earth system modelling applications do not fulfil those criteria.

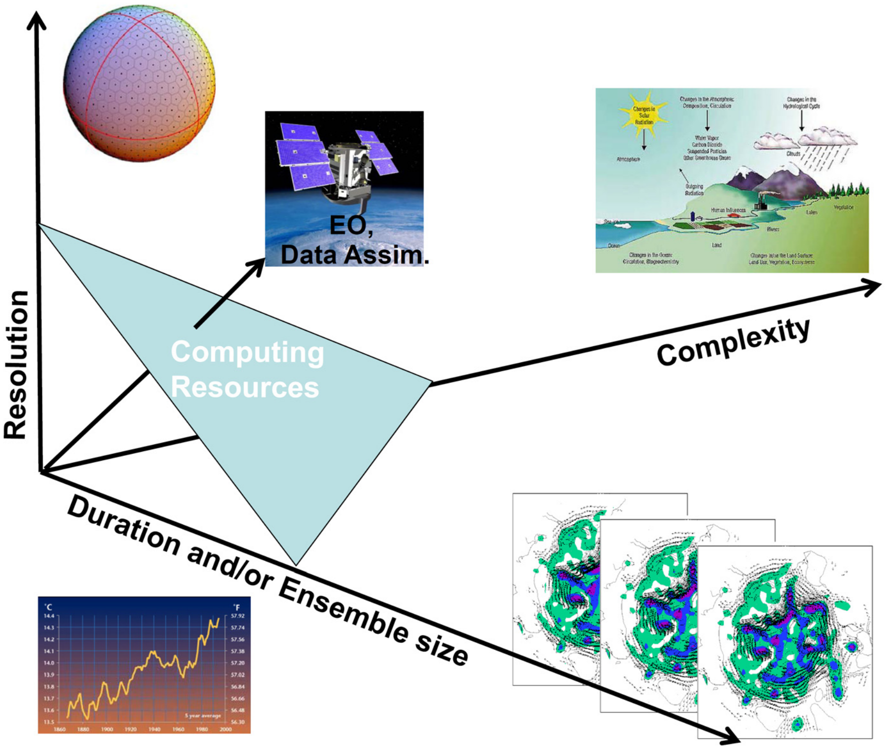


Figure 5: Computing resources for climate modelling are highly dependent on resolution, complexity, duration, ensemble runs and data assimilation (from Jim Kinter, The world Modelling Summit, 2008)

In general, there is the need for a good balance between computer power and storage system size and performance (read/write efficiency).

Need to prepare for future computer architectures

This insatiable demand for computing is occurring even as the computer world is facing an accelerating trend away from distributed memory systems (with relatively few processors, each with significant memory and at most a few cores per processor) towards systems with millions of processors (each with hundreds of cores and relatively low amounts of memory, memory-bandwidth and network-bandwidth per core). Even the processors themselves are likely to be more heterogeneous as both per-processor power demand and instruction set size (the internal core capabilities) fall. The transition associated with this trend is expected to be even more disruptive to the scientific programming community than the transition from vector computing to distributed memory systems more than a decade ago.

Even now the climate modelling community is struggling to exploit the current generation of systems efficiently as most codes have not been designed to scale to use hundreds of processors (or more). Already efficiencies are well below 10% of peak performance for most codes, and limited improved scalability is being hard won by major bespoke efforts for each individual code. The situation is likely to get worse over the next decade as the memory per core falls and thus inter-processor communication overheads increase even further. It seems clear that to contend with the challenges posed by current and expected architectures, many of the algorithms, numerics and systems currently in use need redesigning, but this will be difficult for most centres, not only will it be expensive in time (even if the staff are available), but also not directly scientifically rewarding.

The situation is further exacerbated by the distinct differences between the types of systems seen at each Tier of the computing pyramid. These differences go beyond those listed above, and include significant differences in software libraries and compilers, and in queue systems. Very different data systems are attached. Such differences have major influences on not only the codes themselves, but also the accompanying software infrastructure and workflows (see box 1 on typical workflows).

Dealing with the European HPC ecosystem

Tier0 machines are available within the PRACE EU infrastructure. The European climate community is just starting to use Tier0 machines but faces difficulties associated with the multi-purpose and massively parallel characteristics of these machines. Most climate models are executed (e.g. for IPCC scenarios) on Tier1 national, sometimes purpose built systems or Tier2 dedicated national machines, both much more tailored towards climate applications. Thus climate science could appear to be one to two generations behind state-of-the-art supercomputing; on the other hand climate modelling has special demands as specialised scientific computing with high performance requirements with difficulties to find machines tailored for its requirements.

Multipurpose machines are hard to exploit for climate purposes – because consistent access, long runs, appropriate queue structures, access to high volume data archiving, and very high inter-processor and I/O bandwidths are all needed. Ideally, supercomputer architectures targeted for climate are needed.

Where topic specific machines are available (DKRZ, ECMWF, UK Met Office, CMCC) these have shown significantly more throughput for a range of users – from individuals to large international projects – because their jobs share more predictable characteristics than a general purpose job mix.

Massively parallel machines pose problems of scalability (alluded to above) – they are hard to use efficiently for existing climate codes. Although there are real experiments that can be done now using massively parallel machines (such as high-resolution decadal prediction experiments with multiple initialisation dates and multiple ensemble members per initialisation date), they may not be permitted, being seen as essentially capacity jobs, and the data handling is likely to be challenging given existing archive and networks.

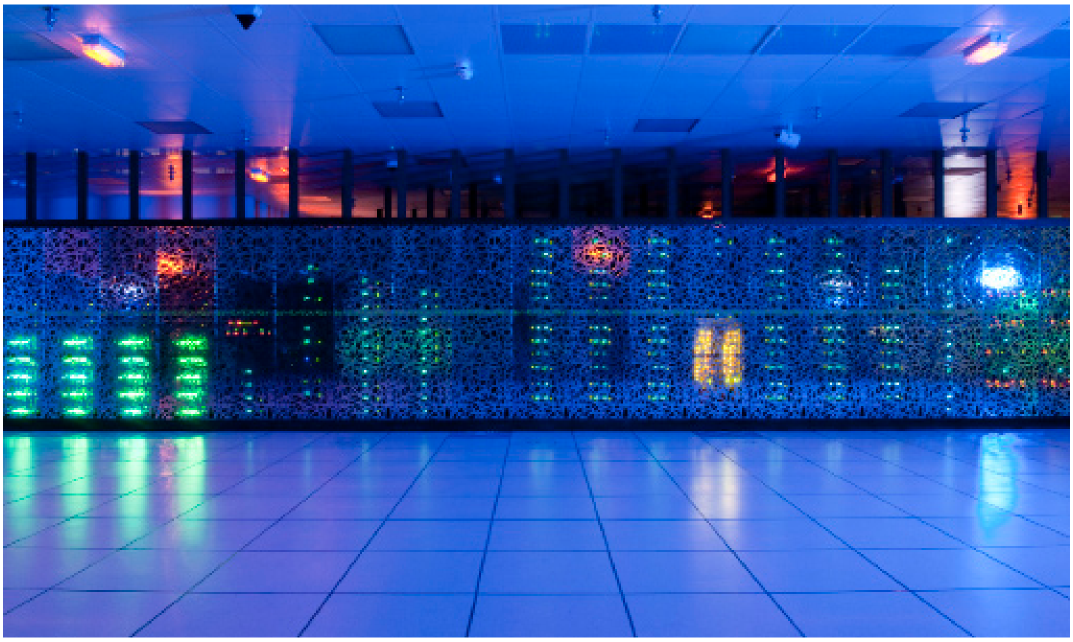
However, clearly the climate community can usefully exploit a Tier0 machine. This requires codes that are capable of exploiting the machine (as discussed above), and consideration of the nature of the workload mix on the machine. ENES believes a climate specific Tier0 machine is necessary to account for specificities described above. Access to a dedicated facility would also allow production of a large number of simulations at the highest possible resolution relevant for society.

In the interim, the community expects to exploit general-purpose Tier0 machines as much as possible and describes below possible ways of splitting activities among the HPC ecosystem. The organizational facts within the community require models to run across most or all of the Tiers in the HPC ecosystem. Furthermore, over time platforms evolve and systems are renewed. Based on experience, we cannot assume that compilers, languages and other tools and methods supplied by the industry will ease these transitions. In the next decade, it will be increasingly difficult to design and implement codes which are sufficiently independent of the systems and which ensure both good portability and sufficient performance. It is even possible that continuing to increase computing performance can only be achieved by co-designing application and systems (see box 2). This would lock modelling codes – and the centres developing them – to single system vendors (or at least, single architectures) for very long phases, with rather disadvantageous consequences for price-performance.

In any case, dealing with different computing architectures and sites can safely be assumed, since we expect the full ecosystem of both models and applications to be geographically distributed, even if the high-end jobs can be aggregated onto a Tier0 machine. This might mean splitting science applications according to machine performance. For example:

- Occasional exploratory global runs could be run at the highest resolution practical possible on Tier0,
- Small ensembles of medium resolution runs using prescribed emission scenarios used for impact studies or for shorter predictions initialised from real data may need Tier1 machines,
- Large ensembles of global runs at lower resolution to explore issues of complexity and span the range of climate sensitivity may be possible on Tier2 machines.

The occasional high resolution experiments accelerate the development of higher resolution models which then become the next generation of "production" models to address the wider scientific issues of climate sensitivity, specific emission scenarios etc.



PRACE Curie machine. Credit : CNRS Phototheque/C. Fressillon

3.2.2 Data storage

The accompanying data management is possibly an even harder problem than the computing. Integrating a climate model in time generates vast amounts of data, which are nowadays on the order of 10s to 100s of TBytes per experiment. These data are required for the analyses of each model simulation by each modelling group. For many of these simulations, data need more and more to be accessed by other modelling groups within international coordinated experiments, such as CMIP5 and CORDEX for the preparation of IPCC AR5, and by a large range of users such as regional modellers and the impact community.

These data need to be saved, which means in most centres that they are written to disk during the experiment, archived on some medium- or long-term storage device (depending on the storage strategy of the project and the centre), and post-processed for time series and other derived quantities, then maintained on disk until post-processing is complete. Key variables may be kept at high spatial and temporal resolution to support use as boundary conditions for higher resolution models integrated at a later date.

Earth system modelling requires a large long-term storage capacity. In many cases, it is possible to devise a post-processing strategy that rarely requires access to the "raw data" stored in the long-term archive, but in almost all circumstances the raw data will need to be accessed again during the lifetime of a project. This mandates fast search and retrieval mechanisms for the long-term archive, including data based search where possible. Where tape is used, strategies for efficient decomposition of datasets across tape are necessary.

Most general purpose computing centres often do not invest enough in a balance between computing and storage capacities suitable for Earth system modelling. Either the amount of data stored there is reduced too much for ESM purposes, resulting in the need to repeat expensive experiments, or the wide-area-network access to storage is not reliable and fast enough to stream the data produced to remote centres for post-processing and archival.

ENES believes it is necessary to identify, address and lower the technical and institutional barriers in order to fund and manage storage capacity at HPC centres in a manor sufficient for the ENES community.

Box 2: Maintaining model performance

The "forecast performance" rate, in years simulated per real time day, is the most important measure for the performance of an Earth system model code on any given machine (and/or processor configuration). This measure depends both on the raw performance of the machine, and the software system employed and the type of experiment being performed.

Which performance is sufficient depends not only on the patience of the researcher, but also upon the project under consideration. For seasonal or decadal simulation forecast performances in the range of 1 years/day might suffice, for centennial or millennium experiments 10s or 100s of yrs/day would be acceptable, whereas for paleoclimate studies it would be completely insufficient. Whatever the application, as resolution and/or complexity increase, forecast performance needs to be maintained or increased (to allow more ensemble members). However, as both resolution and complexity increase, the demands for communication speed and bandwidth between processors also rise. The performance of the single core or thread will become relatively unimportant, whereas the bandwidth between processing element and memory as well as the network performance will become increasingly important. Unfortunately the relevant bandwidths (per processor) are likely to decrease for the next generations of computing systems.

With current model codes it is already difficult to increase resolution and at the same time maintain the rate of forecast performance – even by adding processors in large machines. The situation is expected to be worse in the future. Code refactoring will be needed, and possibly a way to speed up "physics" (vertical or local processes like radiation, cloud parameterisation, vertical processes) by inherent on-chip (data) parallelism. Such parallelism is likely to exploit new generations of heterogeneous processors, leading to portability issues. It's even possible that bespoke processor architectures could be designed to target the new climate code requirements: a process known as "co-design".

3.2.3 Networks

The evaluation and use of Earth system model output requires to move data around in Europe and internationally. However, even with fast national and international networks such as GEANT, limits at or on institutional boundaries (from either financial or technical origins) tend to hinder effective use of networks for large volume data transfer. The result is that existing networks bandwidth into institutions are at best 10 Gbit/s peak, with 1 Gbit/s peak not uncommon. The expertise in using tools which get the best of even this bandwidth, is not well distributed, and as a consequence effective average bandwidths for file transfer between institutions is typically a few 100 Mbit/s at best. Network load leads to further fluctuations downward in performance.

As a consequence, it is still quite commonplace to send tapes or hard disks back and forth between co-operating institutions. This discourages data exchange, consuming valuable time from skilled staff, and turns many model evaluation and inter-comparison projects into tediously slow processes. Many data comparison tasks are simply not undertaken because of the potential effort.

The IS-ENES project is currently establishing a European system of federated data archives, based on technologies developed and deployed in the Earth System Grid Federation (ESGF), under the auspices of the Global Organisation for Earth System Science Portals (GO-ESSP). These federated archives will deploy petascale resources, but to avoid overloading the archive data nodes, managed data replication and dedicated network links will be needed. ENES anticipates that key nodes will be linked by dedicated network links (light paths) within a few years, and in the longer term, that “Quality of Service” and “Bandwidth on Demand” tools (perhaps dynamical light paths) will have been deployed, facilitating data transfer at speeds in the Tbit/s scale. Even with these fast networks, data volumes will still be too large for massively distributed data access, so Europe will still be deploying a network of dedicated archives, supporting specific communities of users.

3.3 Software Infrastructure requirements

The process of simulating the climate system requires an extensive software ecosystem in parallel to the computing ecosystem. This will include a complex workflow to marshal input data, configuration information and specific code elements into a runtime environment, classically tightly coupled to the target computer hardware upon which it will run. Each component in this ecosystem is usually developed locally within a modelling group. Much of it needs to be, if not rewritten, at least heavily modified with each new computing architecture. The science code is often particularly tightly coupled to the computing architecture since efficient use of the computer memory along with vectorisation and/or parallelisation is necessary to have satisfactory execution times. Because of the tight coupling between science, parallelisation, and hardware, those responsible for this task need to blend a range of expertise. Skilled practitioners are rare and in high demand. Their scarcity is often exacerbated by poor career prospects.

Model software

The models themselves are generally developed using a modular framework with major physical subsystems (such as the atmosphere and ocean) handled separately, and within each of those, modules cover each of the basic physical processes (dynamics, transport, parameterized processes). Model “couplers” are used to bind the physical subsystems together so that fluxes of energy, momentum, and mass can be exchanged as appropriate. The decomposition of these sub-models onto processors is generally handled independently, with load balancing handled in a variety of ways to avoid some processors standing idle while others are still computing. It is not obvious that current coupling methodologies will scale to really massively parallel computing systems running very high resolution coupled models.

A number of approaches (worldwide) have been used to formalise this model infrastructure, and at the same time achieve more scalable “coupling” methodologies. Such approaches are generally known as a model “frameworks”. Ideally from a scientific point of view, the framework should hide as much of the coupling and parallelisation from the scientific models and sub-models as is possible. As well as increasing performance and parallelisation, these are generally aimed at minimising the effort of migrating codes to new architectures, so that porting and optimisation should become more an effort of migrating frameworks, rather than migrating the “encapsulated” scientific codes. Such encapsulation, if standardised and reused across the community, would allow reducing the time for porting Earth system models to new architectures, thus increasing the scientific productivity. With a suitable coupler/framework in place, some elements of model diversity could be established by coupling and tuning different sub-models combinations, rather than having to develop entire model software stacks. This could lead to fewer, more flexible models.

Developing such a coupling framework is a significant effort, with major technical and social risks, and there would need to be on-going research to ensure that the resulting software would evolve to handle future computational and model evolution. Nonetheless, the payoff could be even more significant in terms of model performance, portability throughout the HPC ecosystem, and efficient use of effort across the community. While such a separation of concerns between the model frameworks and the science code is desirable, it should be understood that there are scientific limitations. Some algorithm choices are constrained by the efficiency of the implementation of their parallelisation, and there is a limit to how-much the frameworks can be decoupled from the model components and their coupling. Nonetheless, improving the exploitation of model frameworks is one aim of this strategy.

Data software

One of the distinguishing features of the Earth system prediction community in comparison with other users of high performance computing is that major resources are needed to support the use of the data produced as well as its production. Such resources include the development and maintenance of data archives, common data conventions, and common data manipulation and visualization tools. This requires hardware (see above) but also sophisticated database and data management solutions. There is in particular the need to minimise data traffic and maximise data availability to handle the highly distributed databases in a way as transparent as possible to users.

The ESM community will need to invest heavily in federated data infrastructures to get the rewards from investing the software and hardware developed for simulation. The problems due to physical distribution of centres is exacerbated by the need to exploit observational data, including high volume Earth observation data – held by other communities – to help validate model hindcasts. Common metadata for documenting models and their output is a key component of successful model intercomparison projects, as well as an integral part of ensuring satisfactory provenance for the scientific method in general. Both those who execute Earth system model workflows (to run simulations), and those who consume the products, are heavily dependent on metadata structures. Within the workflow of running, compiling and executing models, clear metadata structures to allow automatic coupling and deployment of components are crucial. Prospects for further automation of both simulation production and data consumption are also dependent on further development of metadata systems. Within ENES, international standards have been developed within the EU FP7 METAFOR project, but more work is needed.

The evaluation and exploitation of climate simulations depends on tools, which can manipulate both the simulated data and observations. Such tools include complex visualisation codes. Within Europe there is a raft of successful activities producing such tools, but there are difficulties with maintenance, and some duplication of effort could be rationalised. There is considerable scope for developing grid and cloud enabled analysis systems – although network issues will need to be well understood. Also, visualisation tools are needed for model developers and for trouble shooting, not just presentation.

As data usage grows, so too grows the diversity of user communities. This diversity means that data specification and documentation are important components to enable appropriate data use. Other important components will be the development of appropriate interoperable tools, services, and products for new communities (e.g. GIS interfaces to climate data for the impacts communities who are unlikely to invest in using the formats, tools and services familiar to Earth system modellers).

3.4 People and Organisations

The Earth system modelling community depends on a cadre of individuals with a range of skills, from advanced software engineering and numerical analysis through a deep scientific understanding of the processes and their interactions in the environment. Often these skills have been acquired “on the job”, since there are few (if any) institutions teaching the full range of skills needed. Much progress is often down to one or two key individuals who have skills across the range, but they generally depend on teams to deliver the full gamut of infrastructure described above. Typically, an Earth system model has required about 500 to 1000 man years and has a long life time with gradual evolution through time as science progresses and computer systems evolve.

In Europe, different types of organisations develop the existing ESMs, ranging from academic to Meteorological services. They are all based on collaborations between teams developing and using such models. The scientists that use the models to investigate climate processes and dynamics most often also do model developments.

A recent study has shown that the strong involvement of the modellers themselves in the development ensures a very good quality of codes, similar to open source codes. However, modelling groups often have difficulties ensuring continuous model development at the same time as developing model applications, delivering expertise on climate and interactions, and all with a large range of users of climate simulations.

There are also a number of issues in building teams focussed on the software end of the problem. Software engineers are essential to integrate scientific developments into shared and maintained codes. They bring expertise for new technology and develop efficient code environments and tools. Software engineers (IT) often have less opportunity for career advancement than those on the scientific end of the problem (even though in some cases they might have more security of tenure).

There are more lucrative markets for IT skills elsewhere. IT staff often do not have the same motivation as scientists in a scientific organisation. While the scientific problem itself can be motivating, the skills developed are not transferable outside of the modelling arena, making posts less attractive in the first instance.

It is clear from the issues raised in the hardware and software sections that the requirements for software expertise are only going to grow: it is possible that without positive intervention the community will not have enough individuals available with the awareness of, and skill for programming for, today's and tomorrow's multi- and many-core and/or heterogeneous processors, nor to do the deep refactoring needed to provide software subsystems that can hide such issues from the science code.

4. Roadmap

In the coming decade, the climate modelling community will face an increasing demand for reliable information on climate change at both regional scale and decadal timescales. A grand challenge to develop global models at about 1 km resolution in order to resolve small scale processes, such as convective scale motions, was emphasized at the WCRP World Modelling Summit for Climate Prediction in 2008. This is expected to improve the reliability of climate information at regional scales for decision makers to prepare for adaptation, although adaptation policy will also require further interdisciplinary analyses of vulnerabilities. ENES believes that responding to this challenge will require infrastructure investments that will support the delivery of nearly all the science issues introduced elsewhere in this document.

ENES proposes to strengthen the European infrastructure of climate models in order to improve the European capacity to respond to this challenge. This infrastructure aims at:

- Accelerating model development through shared expertise and easy access to model components and evaluation diagnostics
- Improving model environment and share software developments
- Accelerating the use of high-end computing and prepare for future architectures by sharing common technical developments
- Improving access to model data for the ENES community itself and for the impact community

4.1 A grand challenge: Towards 1 km global resolution

A “grand challenge” for the longer term is to develop global climate models which resolve convective scale motions (nominally around 1km horizontal resolution). Although ostensibly this challenge is only about resolution, ENES believes that addressing this challenge will also support nearly all of the other scientific goals outlined earlier.

One of the aims of the challenge is to determine whether or not convective scale resolution is necessary for credible predictions of regional climate change. This will directly address resolving convective systems, allowing a better representation of orographic effects, atmospheric structure and greater regional detail. This will not be easy; it will represent a scientific grand challenge to improve the representation of the relevant small-scale processes. However, the scientific benefits will accrue not only for high resolution predictions; for example, the high resolution runs will aid the optimisation and evaluation of lower resolution codes necessary for long duration simulations.

It will also be a technical challenge through the resolution of common technical issues, which will enable much greater efficiency in running and analysing climate simulations in Europe. However, it is likely to have only a limited effect on reducing uncertainty from other sources, for example uncertainty in climate sensitivity arising from our incomplete knowledge of cloud physics and biological processes. Thus, it is unlikely on its own to remove the need for continued diversity in models: This will depend on advances in reducing the other sources of uncertainty needed to be investigated in parallel. However, uncertainties in climate sensitivity only become more evident at longer timescales, so initially the grand challenge might focus on seasonal to decadal timescales.

The move to 1km resolution will not be achieved in one step, but through a combination of gradual progression, and planned step changes, as illustrated in Figure 4. Thus a possible development path over the next 5 to 10 years is progression of global models from around 100 km resolution at present through 30 km (current operational forecasting resolution) (Figure 6) to about 10 km, which is probably the highest resolution which avoids the problems of only partially resolving convective systems. This will allow time for the development in parallel of new algorithms to run efficiently on exascale computers, which probably will be used as well in RCMs that already have started to move to resolving convective scales.

This sequence of events includes both capacity runs, using relatively stable models at intervals, and capability development – pushing the envelope of what the science can support, and the models can do. Undoubtedly such capability work will soon include global cloud resolving runs (with scales of 1-4 km), focussing on our ability to simulate extreme events both now, and in a range of possible futures, but we don’t anticipate that scientifically defensible, computationally efficient long production runs at such high resolution will be easily attainable in the next 10 years. As indicated above, the achievement of the grand challenge is unlikely to be the end of the line in climate prediction. However, it does provide a logical approach to assessing the importance of resolving convective scales on model reliability, and the importance of spatial resolution relative to other sources of uncertainty. Indeed, if similar projects are carried out elsewhere, (e.g. the USA, Japan, China) it will enhance the value of this project, and allow a review of the importance of maintaining model diversity in the longer term.

The grand challenge will also accelerate the technical work needed to run models efficiently on the next generation of supercomputers, and the software needed to enable the sharing of data and analysis of simulations across Europe.

Achieving the grand challenge requires a major increase in computing power available, the use of models suitable for the future generation of computer architectures, improved data handling facilities and networks, and improved organisation of the community to best use this European ecosystem.

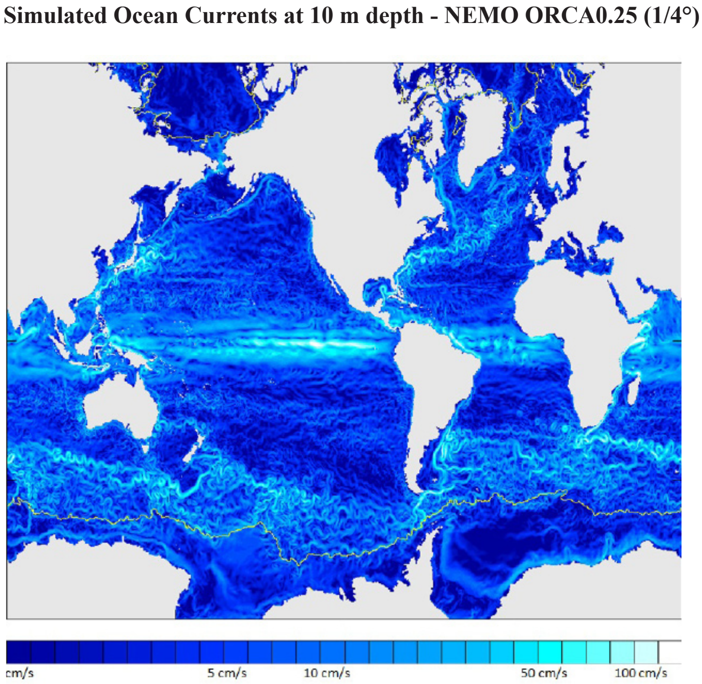


Figure 6a: *Snapshot (i.e. 5 day mean) of ocean current speed at 10 m depth on 30 July 2004 in a simulation carried out with the DRAKKAR 1/4° NEMO-based model configuration. Current meanders and mesoscale eddies are ubiquitous. The yellow line shows the limit of the sea-ice extent. Credit: CNRS/LEGI and CINES.*

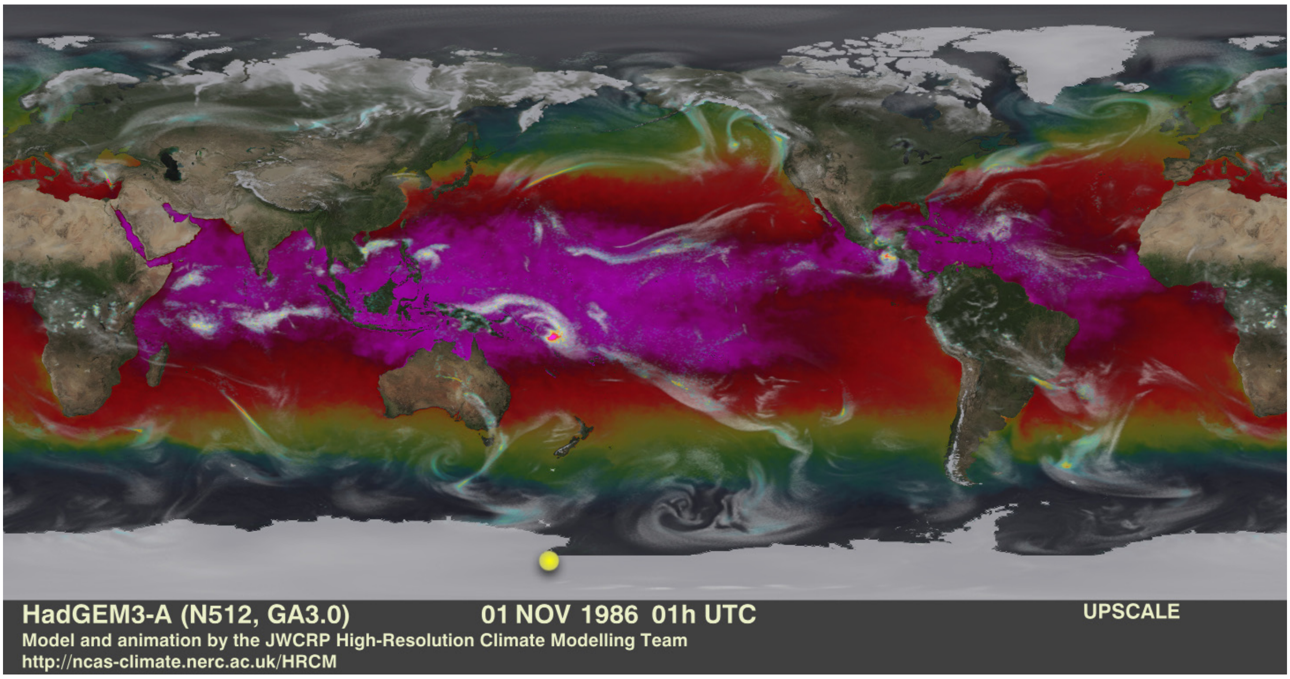


Figure 6b: *Snapshot simulation of the Hadley Centre (HadGEM3) atmospheric model at a resolution of 25km (N512). These simulations, part of the UPSCALE project, were performed on the PRACE HERMIT supercomputer. Ocean temperatures used to force the atmospheric model are shown in the background (in colour going from blue for cold to violet for warm), while simulated clouds (black and white scale) and precipitation (colour) are shown in the foreground. Over land, simulated snow cover is shown in white. Credits: P.L. Vidale and R. Schiemann (NCAS-Climate, Univ. of Reading) and the PRACE-UPSCALE team.*

4.2 Roadmap for the physical Infrastructure

Develop access to world-class computers for climate models

Europe has started to provide access to world-class computers for research within PRACE. We hope this will further develop and allow access to machines that can serve the need of the climate modelling community for HPC.

The ENES community has from the beginning endorsed the PRACE project. In order to cope with the near- to mid-term capability demands, ENES has started collaboration with PRACE. A first step focuses on one coupled ESM configuration to test machines in a realistic configuration with the idea that results will benefit to the other models that all need to access Tier0 machines.

On the mid to long-term, ENES aims at easing the use of Tier0 machines for the community. ENES will also work to ensure that the Tier0 systems can fulfil the needs of the community. PRACE has started with general-purpose machines that serve all research fields. The specific requirements of the climate community, such as appropriate queue structures and access to high volume data archiving (see 3.2.1), would strongly benefit from a dedicated world-class machine for climate in the future. Such a facility would also allow the production of ensembles of very high resolution simulations for future climate relevant for the development of Climate Services.

Develop the interface with the European HPC ecosystem

The computing needs of the European community will not be limited to Tier0. Such machines can best be used for high-end cases such as very high-resolution simulations, or for managing the data initialisation and aggregation from very large and complex ensembles. But capacity demands, such as ensembles at lower resolution to explore issues of complexity and span the range of climate sensitivity require Tier1 or Tier2 machines. Impact models coupled to data from other models may use a large number of Tier3 machines using distributed solutions. Maintaining that balance between the broad categories of experiments, probably using very different machines is also important if progress in increasing confidence in predictions is to be maintained – for example there is little point in using all computing resources at highest resolution possible to reduce the uncertainty in simulating the dynamics of ocean and atmosphere, if the other sources of uncertainty in physical and biological processes are not also addressed. ENES therefore proposes to ease the use of the complete European HPC ecosystem.

A significant component of easing the use of the HPC ecosystem is associated with the software, discussed below. It will be important to maintain and develop models portable relatively easily from capability machines to capacity machines. Better computer networks will also be necessary. Key institutions will need to be linked by very high bandwidths (tens of Gigabit/s in the near term, many Terabits/s in the longer term). With such networks in place, the migration of very large input (including both initialisation and boundary data) and output datasets will allow the efficient use of HPC resources wherever they, and the data archives, are located.

Strengthen collaboration with IT

Climate models would benefit from faster processors than today, from improvement of the ratio of network speed to processor performance, from higher memory bandwidth than today, and from homogeneous cores on a chip for easy programmability. Data storage is also critical and need to be consistent with computing power. Answers to these challenges are in the hands of industry but the ENES community will closely follow and collaborate with industry and computing centres to ensure best fit to our needs.

4.3 Future software developments

Strengthen European collaboration for model development

A massive performance increase is needed not only from the hardware but also from models themselves. This may require new choices of algorithms, numerics, data structures, and partitioning. The grand challenge will also require new parameterization developments for very high spatial resolution.

Strengthening European collaboration will help share the large range of developments required to prepare the future generation of Earth system models able to be run on exascale machines. The collective capabilities of European institutions are highly competitive worldwide.It will also be an opportunity to assess the extent of model diversity that is needed and organise the European model diversity in order to better address uncertainties associated with models.

Prepare for future computer architectures

We need developments that enable systems to deliver for the fully coupled ESMs, including I/O, a much higher efficiency (sustained performance over peak performance) than today given the raw peak performance increase to be expected from future systems at the same price range.

There is a need to revisit the dynamical part of atmosphere and ocean models in terms of the underlying equations and their discretisation and numerical solution – possibly on new types of grids – to make them better suited for a large number of processors. Europe is lagging in such developments compared to the USA and Japan. ENES will foster the exchange of expertise in Europe on new dynamical cores and will ease their use. ENES will foster the sharing of expertise and developments to improve I/O efficiency which is an important bottleneck for climate models use of massively parallel computers.

Developing new models suitable for exascale raises the question of revisiting the coupler approach followed until now and even of investigating the possibility to develop common European modelframework(s). The best way forward is not known, but ENES believes it will be unproductive for many European institutes to solve these problems on their own. ENES will foster common investigations and production of (a) European coupler(s) or framework(s), enabling optimised efficient parallel input/output between components, and to storage, as well as easing share of model sub-components. Alongside an improved coupler/framework, improved workflow tooling should support the construction, submission and management of complex ensembles, and the accompanying input and output data.

Improve model parameterizations

It is clear that the science agenda outlined earlier will require both new and improved parameterisations. While specific scientific communities will do the initial development of parameterisations, the common European infrastructures to support model-data inter-comparison discussed below will, support the on-going evaluation and improvement of such parameterisations, particularly where complex process interactions make interpretation difficult.
To support this, ENES reaffirms the importance of:

- Maintaining the European network of instrumented sites (such as the former CloudNet project) and of supporting activities devoted to the formatting and the distribution of data for processes studies and parameterization test beds.
- Producing very-high resolution simulations (such as Large Eddy Simulations and/or Cloud resolving Models) and making them available to guide parameterization developments.
- Promoting tests of parameterizations on a wide range of resolutions (eventually in a coordinated manner using European infrastructure).

4.4 Data & interoperability

Integrate distributed databases

With increasing size of databases for model results, the community is starting to work with very large distributed databases with massive cache copies distributed in key locations. While it will be important for the ENES community to continue to provide the European contribution to wider international federated infrastructures (as it does now for CMIP5), it will be just as important to extend the federation within Europe. The incipient European infrastructure developed within IS-ENES will need to be strengthened, with more data nodes associated with the smaller modelling groups, and more coordinated service development and deployment. Along with a common generic interface to European data holdings, targeted portals for specific communities will be necessary.

Common data infrastructures on the European and wider international scale will be dependent on common conventions and standards for describing and storing data. An important component of these will be controlled vocabularies which provide reliable and precise descriptions of data, and which are supported by community governance. The construction, governance and maintenance of these vocabularies will depend on both new and existing software tooling. The ENES community will provide both voluntary and funded effort to sustain such usage. ENES will also foster the use of common vocabularies and extended metadata (such as that conforming to the METAFOR Common Information Model) in order to provide a higher level of documentation and quality assurance for users of simulation output.

Develop interoperability with observations

While the collection of observations is outside the scope of ENES, the modelling community is dependent on quality observations: the right variables collected at the right time, and often over long periods. To that end, ENES reaffirms the importance of:

- Quality controlled and homogenized observational datasets, particularly those which can be used to evaluate processes and trends simulated in models,

- International activities aimed at improving the availability, discoverability and interoperability of data (such as the Global Earth Observation System of Systems and the Global Monitoring for Environment and Security programmes),
- Reanalysis datasets, suitable for process studies,
- The migration of observational datasets into formats which are optimised for model-data comparison, and conversely,
- The production of simulation datasets which are optimised for comparison with observations (such as those produced from observing system simulators).

ENES recognises that these last two will require technical support and funding, but believe they are crucial both for exploiting data efficiently, and for addressing the science agenda discussed here.

Develop interface with impact community

There are at least three modes of interaction between the ENES and impacts community: The impacts community uses 1) global and regional climate model data directly, in their own right, 2) data to drive impacts models (effectively offline from the ENES perspective), and 3) their own models embedded in the larger scale models at runtime.

In practice, given the large number of potential impact models, and the relatively asymmetric relationship between the outputs of impacts models (which are generally very small scale, and/or not calculated over the entire larger scale model domain), the latter mode is not encouraged since it doesn’t scale with the modelling resources available. However, the ENES community can do much to facilitate the first two modes of use by providing both data and information portals targeted at impacts community users, and by providing services to help extract the appropriate “driving” data for the impacts community (including that needed to set up very large ensembles of impacts model runs). Such developments will depend on current and futureinteractions between the communities, and appropriate effort to both ensure the right data is available, and that it is discoverable, documented, and delivered using the right interfaces. ENES will foster the interaction with user communities to ease the large use of climate model results to address climate change.

4.5 Workforce for the future

Human resources are a crucial part of the research infrastructure required for climate modelling. ENES proposes to strengthen the collaboration among the modelling groups and develop training to speed-up developments of climate science. It also emphasizes the need for more human resources to cope with the challenges facing the community.

Strengthen the network

Developing collaboration, networking expertise can help share and speed-up developments. The European development of a common coupler OASIS, widely used internationally, is a good example. It illustrates that bottom-up approaches can be more successful than prescriptive top-down approaches. Enhancing the networking of science experts and software engineers is important for enhancing future common developments. Sharing common experiments through the grand challenge will also have an important impact on collaboration.

Develop training

Training will become an important issue. As climate science is getting more complex with the challenge of representing the full Earth system, training will help complement the disciplinary expertise of researchers. Both researchers and engineers will need training to benefit from ongoing technology developments. ENES will favor the development of training in climate science, HPC, computer science, software engineering. It plans to develop a series of training schools for young researchers in climate Earth system modelling with the objective to strengthen the European expertise and integration of the young generation.

Need for human resources

Science experts are needed to develop, evaluate and exploit models. While those that exploit models don’t necessarily need to be co-located with those who develop and evaluate, the developers do need to be alongside some of those who do evaluation. Critical mass is important. Nonetheless, so too is the conduit from research, and application through to development; and much of the research and application is distributed throughout Europe. The demand to evaluate and exploit models often limits the capacity of the community to sustain development of future models. Science experts will also be needed to ensure that the knowledge gained from high-resolution modelling translates into improvements of lower-resolution modelling (e.g., through parameterizations development).

This should not be taken for granted, as it will be a key bottleneck in translating in exploiting our grand challenge to address all the ENES science issues.

The growing complexity of HPC architectures also requires increasingly dedicated expertise. The number of software engineers has grown through time but is still insufficient. Computational scientists are needed to develop the scalable algorithms in order to get the benefit of the next generation of high performance computers.

Moreover, the strong demand for expertise on climate change together with the development of applications and growing interfaces with other communities strongly limits the availability of skilled people for model developments. Clearly Europe needs to grow the community of those with the requisite skills, but it also needs to better link together the existing community, developing "virtual critical mass" by better use of remote working and conferencing technology.

4.6 Bringing these things together: ENES in the next decade

Developing the European infrastructure for climate modelling

The overall strategy emphasizes the willingness of the ENES community to develop and expand its infrastructure to improve climate science and encourage its use by a larger community. The infrastructure should encompass the science, software and hardware needed for research and form a sustained virtual laboratory for climate Earth system modelling. This will speed-up the development of models and the use of high-performance computers, improve the efficiency of the modelling community and improve the dissemination of model results to a large community of users, including climate services. In order for this to happen, there will need to be a large increase in co-ordinated resources at the expense of national resources.

It will require the long-term support of the EU and national research institutions for this to be successful. Such support is critical for the network activities, the common infrastructure developments, and the availability of hardware infrastructure. It also assumes a stronger more active ENES, duly recognised by all stakeholders and institutions. The European Joint Programming Initiative on Climate is a strong opportunity to strengthen the coordination of the different national activities in the field of climate modelling between countries and with EC.

Developing the international collaboration

Both the science drivers and policy pull discussed above require a strong, internationally competitive European climate modelling community. However, strong European activity will be strengthened by collaboration on the international scale, and so ENES recommends that, as well as focussing on European problems and solutions, the community also focuses on opportunities for collaboration on the wider international scale.

This European infrastructure will enhance European competitiveness at the international level. It will further strengthen the role of Europe in international collaborations as already shown through the G8 call to prepare for exascale and collaborations within the international WCRP Coupled Modelling Intercomparison Project in preparation of next IPCC assessment report. This also includes further collaboration with space agencies (ESA, NASA, EUMETSAT) to enhance interoperability with Earth observations. Further developments of international collaboration are one of the objectives of the ENES infrastructure.

ENES hopes that this Infrastructure roadmap will provide Europe with the necessary evidence and expertise for its mitigation and adaptation policies.

Convective Cloud from the Space Shuttle
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ACRONYMS

AOGCM: atmosphere-ocean general circulation models
AR5: IPCC 5th Assessment Report
AWI: Alfred-Wegener-Institut für Polar- und Meeresforschung
BADC: British Atmospheric Data Centre
BCCR: Bjerknes Centre for Climate Research
BSC: , Barcelona Supercomputing Centre
CERFACS: Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
CMCC: Centro Euro-Mediterraneo per i Cambiamenti Climatici
COMBINE: Comprehensive Modelling of the Earth System for Better Climate Predication and Projection
COPES: Coordinated Observation and Prediction of the Earth System
CORDEX: COordinated Regional climate Downscaling Experiment
DKRZ: Deutsche Klimarechenzentrum
DMI: Danish Meteorological Institute
DWD: Deutscher Wetterdienst
EC: European Commission
ECMWF: European Centre for Medium-Range Weather Forecasts
ENES: European Network for Earth System modelling
ESGF: Earth System Grid Federation
ESM : Earth System Model
EUCLIPSE: EU Cloud Intercomparison, Process Susty and Evaluation Project
FMI: Finnish Meteorological Institute
GO-ESSP: Global Organisation for Earth System Science Portals
HPC: High Performance Computing
IC3: Institut Català de Ciències del Clima
IGBP: International Geosphere-Biosphere Program
I/O: Input/Output
IPCC: Intergovernmental Panel on Climate Change
IPSL: Institut Pierre Simon Laplace
KNMI: Koninklijk Nederlands Meteorologisch Instituut
LIU-NSC: Linköping University National Supercomputer Center
METAFOR: Common Metadata for Climate Modelling Digital repositories
MET FU Berlin: Meteorologisches Institut der FU-Berlin
MIP: Model Inter-comparison Project
MPI-Met: Max-Planck-Institut für Meteorologie
NCAS: National Centre for Atmospheric Science- Climate,
NEMO: Nucleus for European Modelling of the Ocean
OASIS: Ocean Atmosphere Sea Ice and Soil coupler
PRACE : Partnership for Advanced Computing in Europe
RCM: regional climate model
SMHI: Sveriges Meteorologiska och Hydrologiska Institut
UCL: Université catholique de Louvain
Uni. Bonn: University of Bonn
UNIMAN: University of Manchester
WCRP:World Climate Research Programme
WU: Wageningen University

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