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PRIMAVERA

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PRocess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment

Deliverable D*8.5*

Policy briefings for governments, detailing the significance of PRIMAVERA results

Deliverable Title	Policy briefings for governments, detailing the significance of PRIMAVERA results	
Brief Description	Examples of the achievements and meaning of specific investigations in PRIMAVERA that have consequences for decision-making in Europe. This deliverable is distilled from all the work in PRIMAVERA.	
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		CO - Confidential, only for members of the consortium, including the Commission services

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1. Executive Summary

This document exemplifies case studies that have been presented to decision-makers across Europe during the lifetime of the project. These cases studies revolve around storms and deal with risks, as well as opportunities, provide by better simulation of storms, using global models at high resolution. Implications for analysis of the vast data sets produced in PRIMAVERA, again with a view to the high-density information provided by PRIMAVERA models, also reflects on HPC and analysis capabilities, which need to be developed and fostered in concert.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Part B Section 1.1) WP numbers are in brackets:

No.	Objective	Yes	No
A	To develop a new generation of global high-resolution climate models. *(3, 4, 6)*		X
B	To develop new strategies and tools for evaluating global high-resolution climate models at a process level, and for quantifying the uncertainties in the predictions of regional climate. *(1, 2, 5, 9, 10)*		X
C	To provide new high-resolution protocols and flagship simulations for the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP6) project, to inform the Intergovernmental Panel on Climate Change (IPCC) assessments and in support of emerging Climate Services. *(4, 6, 9)*		X
D	To explore the scientific and technological frontiers of capability in global climate modelling to provide guidance for the development of future generations of prediction systems, global climate and Earth System models (informing post-CMIP6 and beyond). *(3, 4)*		X
E	To advance understanding of past and future, natural and anthropogenic, drivers of variability and changes in European climate, including high impact events, by exploiting new capabilities in high-resolution global climate modelling. *(1, 2, 5)*	X	
F	To produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in process understanding. *(2, 3, 5, 6, 10)*		X
G	To engage with targeted end-user groups in key European economic sectors to strengthen their competitiveness, growth, resilience and ability by exploiting new scientific progress. *(10, 11)*	X	
H	To establish cooperation between science and policy actions at European and international level, to support the development of effective climate change policies, optimize public decision making and increase capability to manage climate risks. *(5, 8, 10)*	X	

3. Detailed Report

3.1 Introduction

PRIMAVERA Global Climate Models are designed to produce more trustworthy information about risks to European Society and business interests. The key to being trustworthy is process fidelity, that is, how realistic the simulated phenomena are when compared to the real, observed ones. The philosophy behind the complementary value of simulation and observations is similar to the new EC Destination Earth's concept of Digital Twins.

Constructing more trustworthy weather and climate models can follow several routes: improved physical parametrisation (a semi-empirical version of reality that mimics the explicit properties of physical phenomena at a low computational cost), increased resolution (high-definition, similar to the concept of mega-pixels in digital cameras), large ensembles (collections) of simulations, with the notion that a larger volume of simulation data will better constrain our approximate view of reality, as well as reveal potential surprises, the so called "black swan events", which are very important for robust and reliable risk assessment.

The resolution route is the most expensive of the three: every time we double the resolution (halve the "pixel" size), we require a factor of 10 in computational resources, which means using supercomputers that only larger nations possess, as well as waiting 6-12 months for each simulation to complete, and equally long for data analysis to reveal the phenomena and their impacts.

The information produced by PRIMAVERA combines the efforts of 19 research groups, who ran a collection of 7 independent Global Climate Models on various supercomputers across Europe, to provide robustness in their findings. The size of the PRIMAVERA data set is circa 1.7PB (1'700 times more than a very advanced laptop can hold, 1TB=1'000GB). The data have been deposited at a large facility in Oxfordshire, called CEDA-JASMIN, and is available to the scientific community worldwide for analysis, via the Earth System Grid Federation (ESGF), using web interfaces, making it also usable by any end users.

What has been learned? We provide four examples in the following pages.

3.2 Bomb cyclones impacting Europe

What did we investigate?

A special class of the mid-latitude storms (extratropical cyclones) impacting Europe with high winds and precipitation year-round are bomb cyclones. Bomb cyclones are explosively intensifying extratropical cyclones that can cause severe damage to life and property; their evolution in time and space severely challenges the capabilities of operational prediction models. In terms of the assessment of climate risk for Europe, the poor ability of coarse-resolution climate models used in typical climate assessment, to simulate bomb cyclones, including underestimation of their frequency, remains a challenge.

What did we find?

In this PRIMAVERA-enabled study, the dependence of bomb cyclone characteristics on horizontal resolution from 135 to 18 km revealed a robust resolution dependence of bomb cyclone characteristics, identified for both the models and re-analyses (a model-observations optimal fusion). Finer horizontal resolution significantly and realistically increases the frequency of bomb cyclones and reduces their average horizontal size to more realistic values. The combined used of multiple PRIMAVERA global climate models (GCMs) provided a robust result, as we are dealing with relatively rare events.

A regression analysis indicates that bomb cyclone frequency is roughly doubled from 140 km to 25 km resolution. The overall increase in bomb cyclone number is associated with a large increase in small bomb cyclones and a moderate decrease in large ones. A correct simulation of the size is crucially important for end-user applications, e.g. to estimate the risk to a coastal city when landfall occurs.

Bomb cyclones in higher-resolution models are also accompanied by a higher maximum wind speed and more extreme wind events, which is probably related to the increased pressure gradients, due to the smaller size of the bomb cyclones.

What does it mean for European society?

These results imply that high-resolution models should be used for evaluating the impacts of bomb cyclones: since they have remote origins (across the Atlantic for Europe), a global approach is recommended. Given the nature of the rapid intensification, which occurs over the oceans, an approach that includes simulation of the underlying oceans, and the air-sea interactions, is also recommended. Investments in high resolution capabilities across Europe, as well as coordination of specific operational prediction between individual centres, would make it possible to quantify, and possibly to reduce, our risks related to bomb cyclones. In this context, the process-based diagnostic tools developed in PRIMAVERA can be used to increase the effectiveness of detection and the issuing of alerts.

3.3 Hurricanes and European financial and physical exposure

What did we investigate?

Europe is exposed to hurricanes, severe tropical storms (also called Tropical Cyclones) of unparalleled intensity, because of the global interconnectedness of business interests: for instance, most European insurers and re-insurers are exposed via coverage of global assets belonging to national and international clients. The financial losses incurred are in the tens of billions each year, so that even a small improvement in predictive capability would be of immense benefit to European businesses and society.

What did we find?

Similar to the Bomb Cyclone above, a realistic simulation of Tropical Cyclones is very sensitive to the use of resolution: the typical global climate model used for risk assessment severely underestimates the number and the intensity of such phenomena worldwide, particularly in the North Atlantic, while the PRIMAVERA high-resolution GCMs started to demonstrate real skill at representing these phenomena, at least in terms of annual number and geographical distribution, including year-to-year changes in each ocean basin. Hurricane intensity remains an open problem, and we believe that resolutions of about 1km will be required for fully realistic simulations of intensity (so at least a decade away).

Even more worrying, Europe is also physically threatened by hurricanes. Both the NE coast of the USA and Canada, as well as European coasts are exposed to a special class of storms called “Post-Tropical Cyclones”, that is, Tropical Cyclones that have continued to progress and to develop outside the Tropics, merging with the prevailing Westerly flow and, on everage 3-5 times a year, striking Europe. A single pre-PRIMAVERA study had alerted us to the possibility that these phenomena may become more frequent and even more dangerous in the future, as they make landfall on European coastlines. PRIMAVERA scientists have made use of 7 re-analyses and the full set of PRIMAVERA global climate models to re-assess our risk, which is already substantial at this time, and indeed projected to become worse in the future.

What does it mean for European society?

What this means for Europe is that we must continue to monitor the storms that come across the Atlantic in the period May to November, and to analyse their structures in high detail, to identify those that bear the signatures of their tropical origins. For this, we European operational centres must support the development of both high-resolution global climate models, capable of capturing the genesis, as well as the development of hurricanes in remote regions of the Atlantic, but also to develop analysis capabilities suitable for tracking them from start to end.

Traditionally the expertise around these storms exists in the USA (more recently also in Canada, a high-latitude country that has invested in a hurricane centre), but expertise in Europe is centred around a handful of poorly coordinated individual groups. It would be wise to create a Europe-wide task force, both on observations and modelling, which should include large ensemble of short-range forecasts, in order to issue PTC-specific alerts, and to enable detailed, dedicated impacts modelling to follow up on alerts, particularly in the case of storm surge modelling.

3.4 Renewable energy production

Many of the scientific highlights in PRIMAVERA revolved around cyclonic storms, which impact Europe in terms of wind and precipitation, but also govern the availability of important resources, such as wind energy and water. One of the industries partnered in PRIMAVERA was the wind energy industry. The question was whether better simulation of the number and spatial distribution of Atlantic storms would be sufficient to enable a better estimate of the energy availability across Europe, and inform planning.

What did we investigate?

We wanted to establish whether PRIMAVERA has added value for the energy sector. With increases in the penetration of renewable energy sources, the climate sensitivity of the energy systems has also increased significantly. In this context, understanding the impacts of weather and climate variability on the European energy sector, and projecting likely future changes, is very relevant and timely.

What did we find?

The enhanced resolution of the PRIMAVERA models has been shown to lead to a better representation of different aspects of European weather and climate and they are therefore well suited to impact studies. Research focused on future projections of three dynamical processes that play a fundamental role in conditioning wind speeds – and therefore wind power – over Europe were performed.

Firstly, an analysis of the likely changes in the North Atlantic jet and its impacts on near-surface winter mean wind speeds over Europe revealed a large level of uncertainty in the future changes in these variables, arising both from model spread but also from dramatic changes between horizontal resolutions of the same model. Secondly, on seasonal-to-interannual timescales, a study exploring the role of the North Atlantic Oscillation (NAO) on the future vulnerability of renewable energy sources demonstrated that even though climate change is projected to impact future renewable energy resources over Europe, these impacts are projected to be smaller than the variability induced by the change in NAO, especially in the case of wind power (see Figure 1). Thirdly, atmospheric blocking, a much shorter-lived weather-scale phenomenon, is known to have a large impact on European energy systems, by promoting very cold events that further enhance winter peak demand.

What does it mean for European society?

This investigation shows that, due to its impact on low wind events, blocking can lead to a double challenge in some countries with significant wind power penetrations. Low temperature, low wind and a combination of the two are all more likely to be observed during winter blocking conditions over a large area of central and norther Europe. Initial projections suggest that winter blocking could become less frequent over Europe, but preliminary results also suggest that these compound low-wind low-temperature events will remain more likely during blocking conditions (as opposed to under “non-blocked” conditions).

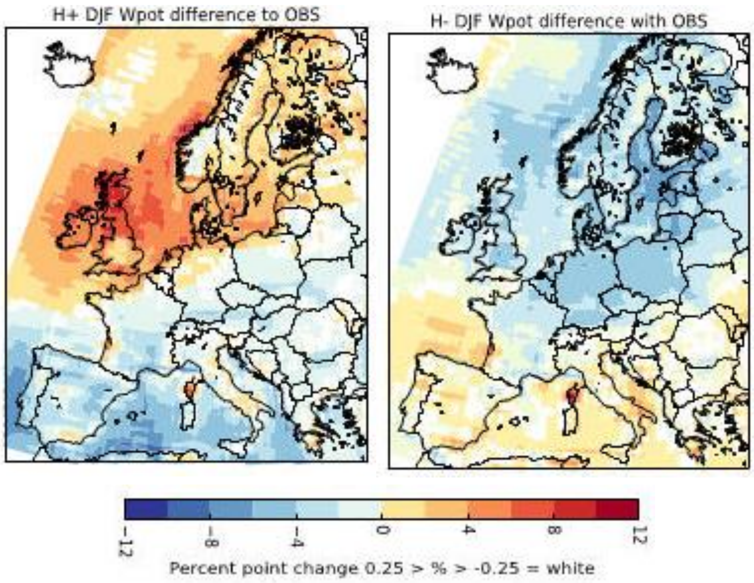

Figure 1: Future projected changes in winter wind power potential over Europe associated with "high" levels of global warming, but under two different plausible atmospheric circulation scenarios ("positive" and "negative" NAO respectively).

3.5 Peta-scale computing and Peta-scale analysis for climate science

Peta-scale (super-)computing means the ability to perform 10^{15} floating point operations (e.g. multiplying two real numbers) computations per second. In comparison, a standard desktop computer reaches a computing performance in the GigaFLOPS range (one GigaFLOPS is 10^9 operations per second), so about a million times slower. Peta-scale became available to climate scientists in Europe about ten years ago, and some of the larger countries were able to afford their own petascale supercomputer. Moreover, via PRACE, European scientists were able to access peta-scale facilities. We currently have access to tens of PetaFLOPS nationally, and we are preparing for hundreds of PetaFLOPS, e.g. via EuroHPC.

What did we investigate?

In PRIMAVERA we wanted to find out whether we could improve the ability of our climate models to make use of such advanced supercomputing resources. Since doubling the model resolution, increasing our capabilities towards high-fidelity (making the pixels of the simulation denser, as in a digital camera) means a ten-fold increased in computing requirements, high-resolution is well-posed to exploit Peta-scale supercomputing.

What did we find?

We found that European global climate models are quite good at exploiting Peta-scale supercomputers, albeit more from the point of view of running multiple instances of the same simulation at the same time (ensemble simulation) rather than performing a single simulation at a faster rate. In more technical words, the models we ran in PRIMAVERA still do not “scale” well beyond about 10’000 computer cores (the computational units on a supercomputer). That is, as we increase the resources available to a single simulation, the model speed-up fails to improve beyond a plateau of about 10’000 cores.

However, as the type of simulations performed for PRIMAVERA have also output a very sizeable amount of data (1.7PB = 1’700TB, about 1’700 times what an advanced desktop computer can hold), the transfer of these data sets to the central storage and analysis facility, the CEDA-JASMIN centre in Oxfordshire, would not have coped with significantly faster production rates, as data transfer speeds are capped and the data need to be re-formatted and documented in order to be usable by a wider community.

In fact, a major success of PRIMAVERA was the ability to centralise all data, arriving from multiple European countries at the same time, and to transform it quickly enough for joint analysis (nearly 80 papers produced by PRIMAVERA so far, a sizeable portion of which used data from all models). PRIMAVERA scientists were thus able to perform data analysis using a class of supercomputer suitable for this task, the LOTUS multi-processor cluster, offering tens of thousands of computer cores, also provided by CEDA-JASMIN.

What does it mean for European society?

If we were to push European high-resolution global climate models further in terms of resolution, aiming for sub-10km resolution, we would need a significant portion of the allocation on the supercomputers in the range of 100PetaFLOPS, but more crucially we would need data storage and analysis facilities of comparable power. The electrical power requirements are similar, but, while a climate simulation may reside on a supercomputer for 6-12 months, data at a facility such as CEDA-JASMIN needs to reside for 5-10 years in order to be fully exploited scientifically.

Significant investment should be made in programmes such as PRACE, which are happening via EuroHPC, but programmatic access needs to be strengthened, to support projects such as PRIMAVERA, which run for multiple years. More importantly, the underlying capability programmes, such as IS-ENES, IS-ENES2, and the ESIWACE centre of excellence have enable many of the long-term developments that PRIMAVERA was able to capitalize on. These investments in technical and scientific capability need to be retained.

Further, a comparable size investment needs to be made in order to create more centres such as CEDA-JASMIN across Europe, providing multiple points of access for the data (under one format and one interface) and supercomputing capabilities offering O(10’000-100’000) cores dedicated to advanced process-based analysis.

More progress, in the range of 1km climate simulation, will require strong investments in an entirely new class of diagnostic software, so as to enable most diagnostics to be computed while the models are running, rather than relying on post-processing, which will take too long for end users, and result in too much expense.

4 Lessons learnt

To analyse high resolution, multi-model ensembles of simulations and look for extreme events (such as the bomb cyclones, tropical cyclones and similar events described above) took a large amount of model output to be transferred to CEDA-JASMIN and processed using many 100's TB of data. Even though we were familiar with CEDA-JASMIN capabilities, and our own software, this was a large undertaking, and likely one that would be difficult to repeat. In future it would make more sense to do such processing as the model is running, and hence share less data but of a more focussed type.

The amount of model simulation and data, coupled to the post-processing requirements, has also meant that time has been short to really discuss and use the insight we have gained with end-users and for government advice. This emphasises that the sooner that useful information can be extracted from the models, the sooner that useful discussions can start about that the implications and opportunities are.

5 Links built

As can be seen in this document, the work required close collaboration between all the different parts of the project, from model diagnostics and software, through analysis and understanding, to applications for end-users and advice. Each strand of these links now has a better understanding of the requirements and opportunities both of the upstream and downstream parts of this workflow.