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Deliverable D*8.3*

Final summary and synthesis of results

Deliverable Title	*Final summary and synthesis of results*	
Brief Description	*Final Summary Report: This report will synthesise the results, and will quantify and assess the robustness of climate variability and change over Europe to the representation of small scales. This will combine the approaches used in WP2, 3, 4, 5, the metrics from WP1 and model integrations from WP4 and 6, to assess the consequent climate risks to sectors represented in WP10, 11*	
WP number	8	
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1. Executive Summary

This deliverable gives a summary overview of what the project has achieved, the key results, insights and applications, how well we have delivered on our project stated objectives, and what the promise is for the future.

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 What we achieved

Highlight achievements of PRIMAVERA include:

- Produced new CMIP6 HighResMIP protocol, delivered multi-model experiments, uploaded data to ESGF (about 12,000 years of simulation, 1.7 PB, in storage terms equivalent to the whole of the CMIP5 archive)
- Produced new metrics and incorporated 14 new functions into community package ESMValTool, so benefiting the community for years to come
- Coordinated multi-model analysis on common JASMIN platform, including sharing of data, code and derived diagnostics
- Developed new model components suited to higher resolution that will become standard in next generation of climate models (aerosol-microphysics, ocean mixing, sea ice melt ponds, land surface physics).
- Developed a new generation of models (e.g. the frontier simulations using the eddy-rich ocean, and sub-10km atmosphere), giving insight into new and future opportunities and challenges in modelling, many of which will be used to support future EU projects.
- Included coupled model with novel unstructured mesh ocean-sea-ice model (FESOM) within CMIP multi-model comparison
- Tested new stochastic physics schemes in all model components, with generally positive and computationally-efficient results.
- Published 91+ peer-reviewed articles (30 in 2020 so far, 29 in 2019, 20 in 2018, 8 in 2017, 4 in 2016), with 54+ submitted or in prep. Of these, 11 were published in “high-impact”, wider readership journals (e.g. Nature family, BAMS, GRL). https://www.primavera-h2020.eu/output/scientific-papers/
- Delivered CMIP6 DCPP-C multi-model experiments, uploaded data to JASMIN for coordinated analysis and to ESGF
- Provided usable climate information to end users using coproduction methods
- New insights into climate risk and extremes from high resolution models and (limited) ensembles

3.2 What are the key results, insights and applications?

The key results and insights include:

- Effective model resolution is not the same as grid spacing, more like 2.5-4.8x grid spacing (Klaver et al., 2020). We must not confuse the two measures, and the community should be made more aware of this;
- We found some robust changes with model resolution across multi-model ensemble for processes including: sea surface temperature (SST; Bock et al.,

2020), deep ocean biases (Rackow et al., 2019; M. J. Roberts et al., 2019), precipitation and hydrological cycle (Vannière et al., 2019) and associated river discharge (Müller O. V., 2020), tropical cyclones (M. J. Roberts et al., 2020; Vannière et al., 2020; Vidale & coauthors, 2020; Yamada et al., 2020; Zhang et al., 2020), Atlantic northward heat transport and AMOC (Docquier et al., 2019; Grist et al., 2018; Jackson et al., 2020; M.J. Roberts et al., 2020); air-sea coupling (Bellucci & coauthors, 2020; Moreton & coauthors, 2020; Tsartsali & co-authors, 2020); post-tropical cyclone storms (Baker et al., 2020a), and explosively deepening storms (Gao et al., 2020);

- We found several chains of mechanisms better (or more strongly) represented at higher resolution, including: improved SST gradients (e.g. Gulf Stream) influencing jet stream, blocking and storm track (Athanasiadis et al., 2020; De Vries et al., 2020; de Vries et al., 2018); ENSO influence on tropical Atlantic SST, via reduced mixed layer depth biases (García-Serrano et al., 2017; Lopez-Parages & Terray, 2020); higher resolution models with stronger deep water formation, Atlantic Ocean overturning circulation and heat transports, have larger decline in future (Jackson et al., 2020; Koenigk et al., 2020; M.J. Roberts et al., 2020) with implications for Euro-Atlantic regional climate, potentially enhanced drought in summer (Haarsma et al. 2015; Van der Wiel et al. 2020);
- Gained some key insights into climate sensitivity and compensating biases from work on aerosol-cloud-radiation-microphysics interactions (McCoy et al., 2020; McCoy et al., 2020; McCoy et al., 2018);
- Eddy rich simulations have given new insights into climate processes and future risk. Reducing bias in the North Atlantic Gulf Stream (M. J. Roberts et al., 2019) can lead to enhanced future rainfall and storminess over Europe (Grist et al., 2020; Moreno-Chamarro et al. 2020), and vertical heat pumping by ocean eddies can lead to increased upper ocean warming globally (Chang & coauthors, 2020), with consequences for future global surface temperature;

- More broadly, this suggests that non-eddy resolving simulations like those uniformly used in CMIP6 are missing key processes, which may have a significant impact on climate projections and derived risk assessments. No amount of dynamical downscaling of such models, regardless of the resolution, can fix this (indeed all dynamical downscaling using such models inherit these weaknesses and hence cannot encompass the full risk);

- We are now able to compare models directly to observations for some processes that were previously parameterised (e.g. ocean eddies and their air-sea interactions; Moreton et al. 2020, Moreton et al. 2020), and hence strengthen links between modelling and observations;

- There are some improvements in predictability (C. D. Roberts et al. 2020) and some hints that an improvement in the signal-to-noise may be within reach (Scaife et al., 2019; Vidale & coauthors, 2020) for the frontier resolutions;

- Over Europe for precipitation, scientific performance of 25km global models is competitive (or slightly better) than regional CORDEX simulations at similar resolution (Demory et al., 2020); similarly for Southeast Asia rainy season (Hariadi et al., 2020).

- Gained insight into what end-users often require in terms of climate information (Bojovic et al., 2020), which can be challenging for models – high space and time resolution, larger ensemble sizes, longer simulations in order to look at risk.

End-user applications:

- Case studies co-developed with champion users from energy and insurance sector (Gonzalez et al., 2019; Soares et al., 2019)
- PRIMAVERA Data Viewer for showcasing project results to broader stakeholder community
- Webinars and meetings for exchanging knowledge and building a community of PRIMAVERA users

3.3 What were our objectives (taken from the PRIMAVERA proposal) and how have we delivered on them?

1. To develop a new generation of global high-resolution climate models.

The project timeline called for the models to be ready to produce simulations somewhat before the modelling centres' CMIP6 models were finalised, made more complicated because the higher resolutions model versions were only to be used for PRIMAVERA. Colleagues in WP6 worked closely with their respective model developers to produce the required model versions. These then had to be adapted specifically for the CMIP6 HighResMIP experiments by: incorporating the MACv2-SP aerosol scheme into the models; to optimise the high resolution models sufficiently such that they could fit into the project timescales; to incorporate the required model diagnostics; to set up all the external forcings for the model from CMIP6 inputs (both standard and HighResMIP forcings), including sea surface temperature, sea ice, ozone, aerosol; to develop the software to convert model output in the standard CMIP6 CMOR format to make it shareable.

All these developments produced six models capable of performing the HighResMIP atmosphere-only simulations, and seven models able to complete the coupled model simulations, with the high resolution models having atmosphere resolution of around 25km and using "eddy-present" ocean resolutions of around 25km. These were completed as part of deliverables D6.2-D6.7 and form the backbone of the CMIP6 HighResMIP datasets in ESGF (https://www.primavera-h2020.eu/modelling/) (Cherchi et al., 2019; Gutjahr et al., 2019; Haarsma et al, 2020; C. D. Roberts et al., 2018; M. J. Roberts et al., 2019; Sidorenko et al., 2019; Voldoire et al., 2019).

In the meantime, WP3 were developing and testing possible enhancements to the "standard" model versions produced above, for potential use in production simulations or as sensitivity studies and future model implementation. Aspects of the models that were examined included sea-ice processes (D Docquier et al., 2017; Koldunov et al., 2019; F Massonnet et al., 2019; Moreno-Chamarro et al., 2019; Scholz et al., 2019; Sterlin J., 2020), ocean mixing (Grant & Nurser., 2020; Gutjahr et al., 2020), river routing schemes and land-atmosphere coupling (Müller et al., 2020). In addition, aerosol-radiation-cloud interactions were studied; this helped to understand the role of the simplified aerosol scheme (MACv2-SP; Stevens et al., 2017) used in HighResMIP compared to the fully prognostic aerosol schemes in the standard CMIP6 model configurations, but also gives an important insight into processes associated with clouds and climate sensitivity (Ekman et al., 2020; McCoy et al., et al., 2020; McCoy et al., 2018).

In addition WP4 developed frontier resolution model simulations, that is one level beyond the models used in WP6. This included coupled models reaching to "eddy-rich" ocean resolutions of 1/10-1/12 degree, with either a uniform grid (Putrasahan & coauthors, 2020; M. J. Roberts et al., 2019) or an unstructured mesh (Sidorenko et al., 2019), as well as atmosphere-only simulations of up to 5-10km resolution (Judt & coauthors, 2020; Muetzelfeldt et al., 2020). Very few international groups have explored these resolution regimes previously, none in such a coordinated way, and there remains much to learn (Hewitt & coauthors, 2020).

2. 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.

Given the demands of higher resolution models in terms of data volumes, as well as more interest in higher frequency aspects of the simulations (e.g. weather), analysis packages written for analysing "standard resolution" models have often proven inadequate. It has also been the case that previously developed metrics and code is often lost once a project or specific researcher moves on. We planned to rectify both these issues in PRIMAVERA, by working with other projects and communities.

In WP1 we determined to develop new metrics and tools targeted at our higher resolutions, as well as building them into an existing and widely used package (ESMValTool) where they would be available for the community to use. An initial contribution to ESMValTool2.0 development was some effort to replace the "backend" processing software from NCL to python-iris language, and to greatly revise and improve pre-processing capability, to give improved performance for higher resolution models, which have specific memory and computing requirements (Righi et al., 2020). This version is publicly available (https://doi.org/10.5281/zenodo.3401363), was installed on JASMIN and available for use across the project, and has already produced figures for articles and the IPCC AR6 report in several chapters (e.g. Bock et al. 2020).

Over the project we have included 14 new functions within ESMValTool for model metrics as documented in D1.3, including: ocean heat content, tropical cyclones (Kreussler & coauthors, 2020), blocking, jet latitude (Athanasiadis et al., 2020), energy budget and hydrological cycle (Vannière et al., 2018), clustering, precipitation extremes and land-atmosphere interactions (Eyring et al., 2019). This is, along with the datasets generated, a unique legacy of the project that will benefit the community for many years to come.

Our strategy for evaluating the model simulations in a joined-up way was to use a single platform (CEDA-JASMIN) on which all the model and observational data and analysis tools would be available (Seddon et al., 2020). This is in contrast to most projects, where data would be downloaded to individual's desktops, and was chosen deliberately to enhance coordination and collaboration, and make data access easier. The Data Management Tool (DMT) was developed within WP9 to manage the model data on tape and disc (there was a maximum of 200 TB of disk space available for analysis, but upwards of 1.7 PB of model data), as well as being a search tool to find required data for analysis. The DMT software has been released as open source software for future projects to use (https://github.com/PRIMAVERA-H2020/primavera-dmt).

While not a new method, it became clear when discussing the second round of model simulations (Stream 2) that in order to examine uncertainties from predictions of regional climate, additional model ensemble members would be needed to be able to quantify variability. Four of the modelling groups managed to find sufficient person and supercomputing resources to increase the model ensemble size (up to 9 in some cases) to enable such analysis (https://www.primavera-h2020.eu/modelling/ensemble-members/).

3. 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.

The development of a new experimental protocol for CMIP6, HighResMIP (Haarsma et al., 2016), was led by PRIMAVERA partners, in collaboration with other international groups. There were several components involved: the required details of model simulations, start and end dates, high and low resolution configurations, minimal model tuning between the resolutions; providing initial conditions, forcing fields specific to HighResMIP, recommendations on science configurations (such as the simplified aerosol scheme, and future SST and sea-ice forcing datasets) that made the model more comparable; the required model outputs to enable coordinated analysis - this took considerable discussion with many international groups, given the volumes of data at high resolution, but also the opportunities afforded for novel analysis using high frequency, high resolution outputs; ensuring that model outputs would be made available in standardised formats, both for submission to the ESGF network and for project analysis.

Project members were also heavily involved in developing the CMIP6-DCPP decadal prediction experimental protocol and diagnostics lists, and a slightly modified DCPP-C experiment was used for PRIMAVERA in WP5 in order to include the higher resolution models. Five groups (CNRM-CM6-1, EC-Earth3P, ECMWF-IFS, MetUM-GOML2 and MPI-ESM1.2) completed these simulations. Further simulations at high resolution are planned by BSC to deliver to H2020 EUCP, and groups including EC-Earth, Met Office and CNRM-CERFACS will deliver DCPP simulations to ESGF.

Seven PRIMAVERA modelling groups were able to complete the CMIP6 HighResMIP experiments including both atmosphere-only and coupled global simulations. At present, 10 other international groups have contributed simulations to at least one experiment of CMIP6 HighResMIP, including two each from China and Japan and three from the US.

All the HighResMIP model output was converted to standard CMOR format by each modelling group and published onto the ESGF system via (for most data) CEDA-JASMIN, making it available to the community. This process was complicated by various issues, including revisions to the CMIP6 data request, passing stringent metadata standards, and disk space required on ESGF to publish the data - about 1.7 PB of PRIMAVERA data will eventually be published (a similar size to the whole of the CMIP5 archive). This was a considerable challenge, both from the file size and data volume aspect, and also because the format of the “Data Request” - the formal data specification for CMIP6 experiments - continued to change during the project since our timescales were ahead of CMIP6. This required considerable modification of file metadata so that it could be published.

In the IPCC AR6 Second Order Draft, there were numerous mentions of HighResMIP in many places, including Chapters 3,8,9,10,11, and currently in Figs. 3.2, 9.10, 10.6, 10.7. DCPP experiments are mentioned in Chapter 4 and Chapter 10 and in Technical Annex VI on Modes of Variability. Figure 4.10 in Chapter 4 shows DCPP results from 3 model groups (EC-Earth, Met-Office and MPI).

4. 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).

We approached the scientific frontiers of global climate simulation in several different ways. Starting from the high resolution model configurations used for production runs in WP6, we developed and tested enhancements targeted at high resolution in WP3. The representation of interactions between clouds, aerosols, microphysics and radiation were studied, both when parameterised and when explicitly represented at km-scale. A new microphysics scheme (CASIM) was developed and tested for one model at 10km as part of the frontiers work (McCoy et al., 2018), and will be implemented in the standard model over the next few years. New methods for the representation of river routing in models, the process of taking water from hydrological catchments over land to the ocean, were explored, and led to new model configuration files for future applications. New sea-ice dynamics and thermodynamics schemes (Flocco et al., 2010; Holland et al., 2012; Massonnet et al., 2019; Moreno-Chamarro et al., 2019; Sterlin J., 2020) were implemented and tested across several models, to assess whether these may play a part in the widespread in projected sea-ice changes. Upper ocean mixing processes are known to be important in aspects of climate variability and air-sea interaction, and two new schemes were developed and tested. One was implemented into the PRIMAVERA production runs (IDEMIX; Eden et al. 2014; Gutjahr et al., 2020), while the other (OSMOSIS; Belcher et al., 2012, Grant and Nurser., 2020) has been incorporated as a standard option in the NEMO ocean model code.

A second approach was to test the impact of stochastic physics schemes in different model components. Such schemes introduce a random component to parameterisation and physics components in an attempt to better represent the sub-gridscale. Schemes were tested in the atmosphere (two models) and the ocean and sea-ice (one model), with generally very positive scientific results and a very small computational overhead (Davini, et al., 2017; Meccia et al., 2020; Strommen et al., 2019; Vidale & coauthors, 2020; Watson et al., 2017; Yang et al., 2019). Such schemes either are already a standard model component or will become so in the near future.

A third approach was to enhance resolution even further than done in WP6, to enable new processes to act. One target was the ocean mesoscale at about 10km, where key ocean processes such as boundary currents and ocean eddies become resolved. Three models were able to run with a uniform enhancement in ocean resolution (Putrasahan et al. 2020; Roberts et al. 2019), while the novel FESOM ocean-sea-ice model uses an unstructured mesh in order to enhance resolution in targeted regions (Sein et al., 2018, 2017; Sidorenko et al., 2019). Some important insights have been gained from assessing these simulations, for example the improved representation of the Gulf Stream near the US coast in the historic simulations allows for a new aspect of future change, with potentially important consequences for European climate risk (Grist et al., 2020; Moreno-Chamarro et al., 2020).

Enhanced resolutions in the atmosphere model were also investigated, going from multi-year 10km resolutions in one model to shorter simulations at 4-5km resolution in two models. Such resolutions enable testing of the convective parameterisation (switching off can improve the diurnal cycle of precipitation but generally brings other errors, Muetzelfeldt et al., 2020) and adding extra capability (including graupel enabled some investigation of lightning production, Field et al. 2018). It also enabled participation in the DYAMOND project, where a group of 8 modelling centres produced 40-day simulations at sub-5km resolutions, which are currently being analysed (Judt et al., 2020; Stevens et al., 2019).

In parallel to these science areas, we needed to push some of our software and hardware capabilities. The enhanced model resolutions required optimisation work to have them run efficiently (Haarsma et al. 2020; Vidale et al., 2020), while their large data outputs also tasked our post-processing capability. In particular for the 10km and below atmosphere models, some of these were made to run 2x faster, due to optimisation, better workflows, better IO and experiments with different solvers (such as semi-Lagrangian advection at the poles and multi-grid). The resources available at both local compute and on JASMIN were stretched in order to complete CMORisation and data sharing of these simulations.

5. 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.

The drivers of variability of particular importance for Europe, and their sensitivity to resolution and forcing, were primarily assessed in WP2,5 with new metrics developed in WP1. Although most models managed to represent the teleconnections between the natural modes of variability (e.g. Atlantic Multidecadal Variability AMV, El Nino-Southern Oscillation ENSO, Pacific Decadal Oscillation PDO, Atlantic Meridional Overturning Circulation AMOC) and European climate, the amplitude of the response varied quite widely across models (Ayarzagüena et al., 2018; Hodson & coauthors, 2020; Molteni et al., 2020; Qasmi & coauthors, 2020; Ruggieri & coauthors, 2020; Ruprich-Robert & coauthors, 2020). For example, the AMV influence on the wintertime Euro-Atlantic Weather Regimes and the ENSO impact on tropical North Atlantic SSTs (Lopez-Parages & Terray, 2020) were both captured but with lower amplitude than observed. In contrast the AMV impact on European temperatures was not consistently represented. The impact of resolution on these teleconnections was generally small, with exceptions including the ENSO-tropical Atlantic, ENSO-AMV and AMOC and northern hemisphere temperatures links. The ENSO-tropical Atlantic SST link seems to be robustly stronger at higher resolution, possibly linked to reduced mixed layer depth biases off the coast of Africa. Several modes of variability, ENSO and NAO, and their cloud radiative impact were also evaluated (Thomas et al., 2019) – this suggested that resolution may give slight improvements regionally, but model physics may be dominant in the biases..

The decadal experiments used in WP5 looked at the AMV and also the Arctic sea-ice as drivers of variability (Garcia-Serraon & coauthors, 2020; Santolaria-Otín, J., M., & Bech, 2020). Responses to changes in sea-ice were not very consistent across the models/resolutions (Delhaye et al., 2020), however the higher resolution models consistently have a stronger weakening of the polar vortex than the lower resolution models (Chripko et al., 2020). The AMV plays a small role in future surface temperature and precipitation changes over Europe, with some differences across resolution on the spatial patterns (Qasmi & coauthors, 2020).

Various climate processes important for European variability and change have been studied, including: Euro-Atlantic blocking (Davini et al., 2017; P. & D'Andrea, 2020; Schiemann et al., 2020) and associated mid-latitude jet (Athanasiadis et al., 2020; Ruggieri & coauthors, 2020) and weather regimes (Fabiano et al., 2020; Strommen et al., 2019)(Fabiano & co-authors, 2020), air-sea coupling along the Gulf Stream (Bellucci & coauthors, 2020; Haarsma et al., 2019; Scher et al., 2017; H. de Vries et al., 2018), Arctic and sea-ice processes (Delhaye et al., 2020; D Docquier et al., 2017; Docquier et al., 2020; Docquier et al., 2019; Massonnet et al., 2019; Massonnet et al., 2018; Ponsoni et al., 2020; Tandon et al., 2018; Wang et al., 2019). We found some evidence that blocking frequency (but not persistence) slightly improves with model resolution (and also has improved between CMIP5 and CMIP6 standard resolution models), coupled with some improvement in the frequency at which the jet exists in a more northern state. Some of these improvements may be linked to better representation of the Gulf Stream path and gradients.

The AMOC is an important regional driver of Atlantic and European climate. Via both its mean state and variations it has an important influence on the northward heat transport, surface fluxes and heat content in the Atlantic (Docquier et al., 2019; Grist et al., 2018; Wu et al., 2019). The higher resolution (primarily ocean) models have an enhanced strength of AMOC compared to lower resolutions, which agrees better with observations at 26.5°N (Hirschi et al., 2020; Jackson et al., 2020; M.J. Roberts, Jackson, et al., 2020). In future projections, the higher resolution models have stronger AMOC decline, which has consequences for Atlantic surface temperatures and, at eddy-rich resolutions, implications for the storm track and storminess and rainfall over Europe (J P Grist et al., 2020; Moreno-Chamarro et al., 2020).

High impact events over Europe such as the extra-tropical transition of tropical cyclones (post-TC storms), wind storms and explosively developing extra-tropical storms (bomb cyclones) have all been investigated. Observational and reanalysis datasets are rather short in length to produce fully robust results, but there is some indication that post-TC storms are more frequent when SSTs show an AMO-like pattern (A J Baker & coauthors, 2020b, 2020a). Wind storms become stronger at higher resolution, and a catalogue was produced for use with the reinsurance industry (Lockwood et al. 2020), while bomb cyclones are also more frequent at higher resolution and better agree with recent ERA5 reanalyses (Gao et al., 2020).

This new generation of models have a greatly improved capability to assess such extreme events against reanalyses.

6. 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.

The modelling groups produced simulations from 1950-2050, in atmosphere-only and coupled mode, with some groups managing additional ensemble members (typically 3 or more) to try and help with distinguishing a signal (from climate change, model resolution etc) compared to internal variability in the models.

The improvement in the climate mean state and aspects of variability at higher resolution over the Atlantic and Europe, and the associated process representation, are the starting point for trustworthy understanding and future projections. The multi-model, heterogeneous ensemble, using our tightly coordinated protocol, allows us to look at robustness. Much of the project has been working on assessing the changes due to resolution, whether these are robust across models, and whether they are due to improved processes and chains of processes. This is no guarantee that any future projections at higher resolution will be more "correct" than those of standard resolutions, but when they are different (for example when using the eddy-rich ocean model, which includes processes completely absent from CMIP6, see below) then we need to understand why and revise our climate risk assessments.

Over the Atlantic Ocean there are a variety of improvements in the models as we increase resolution. The SST cold biases are considerably reduced as the ocean better represents the Gulf Stream and mesoscale, with consequently improved air-sea interactions along the Gulf Stream particularly when the atmosphere resolution is also enhanced (Bellucci & coauthors, 2020; Bock et al., 2020). Precipitation and the hydrological cycle are improved (Vannière et al., 2018), together with river discharge (Müller, 2020), with the tropical Atlantic also having improved SSTs (Bock et al., 2020; de la Vara et al., 2020). The storm track and mid-latitude jet position also improve (likely linked to the above SST improvements), and some aspects of blocking and weather regimes also agree better with observations (Davini et al., 2017; Fabiano et al., 2020; Schiemann et al., 2020; Strommen et al., 2019). The ocean circulation is enhanced (e.g. boundary currents, AMOC), with increased northward heat transports (Grist et al., 2018; M.J. Roberts, Jackson, et al., 2020), which is a factor in the Arctic climate where sea-ice extents and other sea-ice processes are better represented (Docquier et al., 2020, 2019; Wang et al., 2019). Storms such as tropical and extra-tropical cyclones (Baker et al., 2019; Kreussler & coauthors, 2020; M. J. Roberts et al., 2020) are better represented, both in terms of spatial distribution and intensity, and for tropical storms also in terms of interannual variability (Roberts et al., 2020). Extra-tropical storms of tropical origin pose a threat to Europe of wind and rain damage, and biases in such storms are also reduced at higher resolution (Baker & coauthors, 2020a, 2020b).

Over European land there are also indications that resolution is important, although the influence of variability can make definitive multi-model statements challenging. A comparison of precipitation with regional CMIP6 CORDEX simulations shows that global PRIMAVERA models are at least competitive, if not slightly better, over most of Europe (Demory et al., 2020). In addition to resolution, the type of dynamical core plays a role in the precipitation change near orography. Soil moisture biases are reduced in central-western Europe due to the improved rainfall (van der Linden, Haarsma, & van der Schrier, 2019). Some tropical teleconnections to Europe also show some indication of improvement at higher resolution. Temperature and precipitation extremes tend to increase with resolution (Bador et al., 2020; Squintu et al., 2020), but in most regions this agrees worse with observations - equally historic warming trends are not better represented at higher resolution (Boe, 2020).

This is a strong baseline on which to assess how robust the future projections are to model resolution (i.e. do climate risks change when we use a higher model resolution?). In many ways where the large-scale global warming forcing dominates, then the difference between low and high resolution is small. However there are some significant aspects where resolution does change the magnitude of future response. The soil moisture, being somewhat drier in present day, becomes drier still in future at high resolution, and this has implications for surface fluxes such as sensible heat, and hence temperature (van der Linden et al., 2019). In the eddy-rich simulations (of which there are none in the standard CMIP5/6), the reduction in AMOC leads to a strong warming on the US east coast, which in turn affects the storm track and increases storminess and winter rainfall over Europe (Grist et al., 2020; Moreno-Chamarro et al., 2020). The stronger AMOC decline at higher resolution also cools the North Atlantic, and this can induce a circulation causing Europe to become warmer and drier in summer, with the potential for stronger droughts (Haarsma et al., 2015; Van der Wiel et al., 2020).

7. 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.

The sectors targeted by the project included reinsurance, renewable energy, water and transport. For reinsurance, we produced a catalogue of wind storms over Europe from the models (Lockwood & coauthors, 2020), and engaged with end-users on how such information could be used instead of the standard methods (which often resample the historic record but do not take account of changes in the mean-state climate). Renewable energy grids have complex requirements in terms of information, as they have to balance both a varying supply and a varying demand,

and need to do this on short timescales over large scales. Stream 2 simulations produced much more high frequency outputs to better engage with these end-users. Case studies for the water sector used storylines to show how a chain of physical mechanisms (higher resolution causing stronger AMOC decline, which influences European summer circulation) could lead to increased drought risk. Historic comparable events were chosen to highlight the potential impacts of such enhanced risks.

Engagement took a range of forms, from the User Interface Platform on the project web site, which illustrates model outputs, together with factsheets and sector studies, to face-to-face interviews and in-depth discussions to elucidate what types of climate information are useful for each user. Coproduction was used to develop better understanding of what each side needed (Bojovic et al., 2020) and could provide in terms of information and to provide new shared knowledge. All of this engagement, and its metrics, and summarised in D11.7.

As a project, we chose to focus on a relatively narrow set of sectors, users and use cases, in order that the engagement with them could be more in-depth and meaningful. Given the limited number of use cases of PRIMAVERA data beyond academia, it is difficult to speak about PRIMAVERA’s role in strengthening the competitiveness and growth of companies. However we have illustrated to these users the potential of new climate data, and the possibilities compared to their current methods, so there are future possibilities in this area.

8. 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.

The priority outcome from the project in terms of policy was to have a strong visibility in the IPCC AR6 report, since we are the first international coordinated group to look at the impact of resolutions higher than 1-2° in atmosphere and/or ocean. Although still in draft form, the IPCC report has considerable mention of PRIMAVERA and HighResMIP, featuring in many of the Chapters (3,8,9,10,11) and with associated figures in several of them. This was helped by our joint GA4 annual meeting being in conjunction with the CMIP6 analysis workshop in 2019. International collaborations were also initiated within various CLIVAR groups.

Project members attended various relevant EC meetings to ensure that higher resolution modelling was being considered in various contexts (e.g. EU-Japan Workshop in 2020; Workshop on the Convergent Use of EU HPC, Cloud, Data & AI Resources for Earth System Modelling in 2019; Joint H2020 project meeting 2017; Ciência 2018 Science and Technology Summit, Portugal; Climate Prediction

Workshop, Bergen 2019). We also discussed with the Program Manager at the Department of Energy, USA, about opportunities for exploiting the HighResMIP simulation database, which has led to collaborations with several US groups. PRIMAVERA data is widely used for the coming KNMI national climate reports: Signaal’21 and KNMI’23, and was used to give insight into some of the UKCP 2018 climate projections. PRIMAVERA has also had active collaborations with other European projects (in particular Blue-Action, APPLICATE, CRECP), sharing data and results, as well as with JPI-Climate.

We have contributed to the capability to inform climate risks with work in WP10, our link between scientific analysis and end-user interactions. The multi-model ensemble has been used to produce storyline approaches to illustrate risk assessment and potential impacts of future climate change. We have also engaged directly in looking at some climate impacts such as marine heatwaves (Darmaraki et al., 2019), wind storms (Lockwood & coauthors, 2020) and storm surge (Bloemendaal et al., 2019).

3.4 How to build on this work in the future

As a community, we need to continue to exploit the datasets we have produced as part of HighResMIP, further refining our knowledge of where and how higher resolution impacts climate fidelity. International groups are also still contributing to the HighResMIP data archive on ESGF.

There is great scope for further work with regional modelling groups, e.g. CORDEX, to combine knowledge of large-scale simulations and drivers of climate change, with enhanced regional downscaling. Driving future CORDEX simulations with global 25km and above models is an obvious target, currently made difficult by the large amount of boundary data that needs to be stored. We may also extract CORDEX regions from our global models and submit to the CORDEX archive to enhance collaboration.

PRIMAVERA groups are continuing to develop and exploit the frontier models, especially with the eddy-rich ocean, as well as adding to the ensemble sizes. One proposal for CMIP7 would be to continue with the same HighResMIP experimental design, increasing the ensemble size further for more robust statistics, and continuing the simulations to 2100 to enhance the climate change signal compared to variability.

The models that we have developed and tested during PRIMAVERA will continue to be used. As part of EUCP, BSC plan further simulations using the DCPP-C decadal protocol with their EC-Earth3P-HR model, which would not have been possible without the experience gained. Similarly several groups (including Met Office) plan further simulations with eddy-rich coupled models, with the PRIMAVERA simulations as a baseline for model science performance, particularly given the evidence that projected climate risk over Europe in such models may lie outside CMIP range due to improved mean state. In addition, the continuing development of new processes and parameterisations arising from WP3 will provide a long-lasting legacy for the improvement for future coupled climate models.

4. Lessons Learnt

We are still rather inexperienced as a community in using higher resolution models for climate. In theory there may be further untapped improvements at these resolutions if we can learn how to better tune or configure them as the lower resolution models have been over the last decades.

It was unfortunate to be so dependent on the CMIP6 forcing datasets for our simulations, since it led to significant delays at the start of the project. In future one would need to carefully weigh up the advantages of using an old forcing set (it would have been very difficult for us to use CMIP5 forcings and would have meant our models were not classed as CMIP6) against the timing uncertainties. The consequent shifting of the analysis until later in the project is probably why there are so many papers submitted or in prep. in 2020 (54) and published (30) compared to previous years (e.g. 29 in 2019, 20 in 2018)

Although we used models from seven different European groups, they were not as diverse as would be ideal. There were only five groups who used a different ocean resolution in LR and HR (low resolution and high resolution), and of these four used the same NEMO ocean model (though with slightly differing configurations), one of which could not perform the future simulations. Given the European nature of the project, the common use of NEMO is not surprising, but perhaps with hindsight we could have compared the NEMO configurations further (to understand resolution vs parameter settings).

The number of ensemble members that were produced for each model were less than ideal for examining model variability and comparing the signal of anthropogenic climate change against natural variability. Simulations only run to 2050 contributed to this problem. Given the lack of person time and HPC resource, the project did its best to produce as many simulations as possible across the range of resolutions and experiments, and our project did target the next few decades (rather than longer term change).

The volume of data required to be produced by the models was extremely large. This was unavoidable given that we configured the model outputs for the full CMIP6 HighResMIP data request, and hence we had some obligation to produce it for the community (though perhaps we could be more selective as to what is considered priority 1 or lower for each variable - ongoing analysis of data usage can inform this). For any new project, we need to do more work in both choosing which diagnostics and what time/space resolution is required for given applications. Much more automation is also required, for example automated feature tracking, regridding as the model is running, both to reduce storage and data movement.

The deep engagement with the end-users was later into the project than anticipated, partly due to the initial model delays. This made it more difficult for full coproduction and ownership of the second set of simulations, where the data outputs were more configured for the users. Data requirements for some users are very challenging - high spatial and temporal resolution (albeit mainly just for surface variables), sufficient model years and ensemble size to evaluate climate change against internal variability. This will continue to be challenging in the future. However, the new partnerships established with a few champion users built trust among the user community and project scientists. It provided new knowledge and capacities for both users and scientists. The project scientists received valuable feedback from the champion users about the usability of the project's results, improving our understanding of the added value of the high-resolution climate data produced in PRIMAVERA.

5. Links Built

Since this is a project summary, it encompasses work from across the whole project, as well as the collaborations we have formed outside the project.

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