The Danish Meteorological Institute

DMI Report 21-33 Strengthening DMI's contribution to CMIP6 and climate change assessment

Final scientific report of the 2020 National Centre for Climate Research Work Package 4.1.1, Global modelling for strengthening DMI's contribution to IPCC

DMI Report
22 January 2021

By Shuting Yang, Marianne S. Madsen, Martin Stendel, Christian Rodehacke

Colophon

Serial title	DMI Report
Title	DMI Report 21-33 Strengthening DMI's contribution to CMIP6 and climate change assessment
Subtitle	Final scientific report of the 2020 National Centre for Climate Research Work Package 4.1.1, Global modelling for strengthening DMI's contribution to IPCC
Author(s)	Shuting Yang, Marianne S. Madsen, Martin Stendel, Christian Rodehacke
Other contributors	
Responsible institution	Danish Meteorological Institute
Language	English
Keywords	CMIP6, EC-Earth3, EC-Earth3-Veg, climate change assessment, climate impact of COVID-19, ESGF
URL	https://www.dmi.dk/publikationer/
Digital ISBN	878-87-7478-707-5
ISSN	2445-9127
Version	22 January 2021
Website	www.dmi.dk
Copyright	DMI

The Danish Meteorological Institute

Content

1 Abstract

Assessment of the projected future climate change relies on experiments using complex climate models (i.e., Earth System Models) that can realistically represent the Earth climate system. In this work package we made great efforts to enhance our capability in climate modelling using the family of the EC-Earth3 Earth System Model, and to increase our contribution to the international Coupled Model Intercomparison Project phase 6 (CMIP6). The contributions include performing another set of climate change simulations for the historical period (1850-2014) followed by four future scenarios (i.e., SSP5-8.5, SSP3-7.0, SSP2-4.5, SSp1-2.6, respectively) using the Earth System Model EC-Earth3-Veg; Extending the climate change simulation under the high-end emission scenario SSP5-8.5 to year 2300; and performing the new CMIP6-endorsed CovidMIP aiming at assessing the climate impact of the emission reduction due to COVID19 pandemic.

Archiving the CMIP6 experiment data following the CMIP6 standards and compliance on the Earth System Federation Grid (ESGF) data nodes is important to ensure the contribution to CMIP6 is available for scientists worldwide to access the data for a variety of applications from assessment and understanding of climate change, to studies of climate impacts and mitigation. We have worked a great deal to prepare the above mentioned and other CMIP6 simulation data for publishing on the DMI's ESGF data node. The processes involve in reformatting the simulation data into the CMIP standard and quality control the reformatted data to ensure their correctness.

With our efforts and contributions to CMIP6, we have joined several multi-model multi-member ensemble analyses using the CMIP6 experiment ensembles. We have quantified the future climate changes under variety of future scenarios, and analyzed climate response to the COVID19 related emission reduction. We have also participated in the documentation of the EC-Earth3 model development and performance. These studies have led to a number of scientific papers. We foresee our contributed simulation ensembles, as subsets in the CMIP6 experiment ensembles, have contributed and will continue to contribute to many climate change assessments and studies for many years ahead.

2 Resumé

Vurdering af den projekterede fremtidige klimaforandring afhænger af eksperimenter med komplekse klimamodeller som kan repræsentere Jordens klima realistisk. I denne arbejdspakke har vi anstrengt os for at forbedre vores evne til klimamodellering ved brug af en familie af EC-Earth3 Earth System modeller, og for at øge vores bidrag til det internationale Coupled Model Intercomparison Projects phase 6 (CMIP6). Disse bidrag inkluderer fuldendelsen af endnu et sæt klimaændrings simulationer for den historiske periode (1850-2014), fuldendelsen af fire fremtids-scenarier (SSP5-8.5, SSP3-7.0, SSP2-4.5, SSp1-2.6) med Earth System Model EC-Earth3-Veg, forlængelse af klimaændrings simulationen med high-end udslips-scenariet SSP5-8.5 til år 2300, og involvering i den nye CMIP6-støttede CovidMIP hvis mål er at vurdere klima-påvirkningen af de reducerede udslip relateret til COVID19 pandemien.

For at sikre at bidragene til CMIP6 er tilgængelige for videnskabsfolk i hele verden er det vigtigt at arkivere model data på Earth System Federation Grids (ESGF) data-knudepunkter og at følge CMIP6 standarder. Vi har lagt meget arbejde i at forberede de ovenfor nævnte data (samt andre) til at blive publiceret på DMIs ESGF data-punkt. Denne proces involverer reformattering af model data til CMIP standarder samt kvalitetskontrol af de reformatterede data.

På baggrund af vores indsats og bidrag til CMIP6 er vi blevet involverede i flere analyser af ensembler af klimamodel eksperimenter. Vi har kvantificeret de fremtidige klimaændringer under forskellige scenarier, og analyseret virkningen på klimaet af udslips reduceringer relaterede til COVID19. Vi har også bidraget til dokumentationen af udviklingen og kvaliteten af EC-Earth3 modellerne. Disse studier har ført til et antal videnskabelige artikler. Vi forventer, at vores bidrag til CMIP6 model ensembler vil fortsætte med at indgå i mange vurderinger og studier af klimaet i de kommende år.

3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under 4 general themes:

1. Arctic and Antarctic Research
2. Climate change in the near future
3. Use of climate data
4. Support for the IPCC

Work Package 4.1.1 is to enhance DMI's capability in global climate modelling, and to increase DMI's contribution to the ongoing Coupled Model Intercomparison Project phase 6 (CMIP6) by bringing more CMIP6 climate change simulations using the climate models EC-Earth3 and EC-Earth3-Veg, and making the simulation data publically available. These activities can promote DMI's visibility in the EC-Earth consortium and in the international climate research community.

Climate models are commonly used for assessing the future climate changes as it is the only dynamic-and-physics based means to obtain future climate information that are physically consistent with the assumed forcings. Climate models simulate the physics, chemistry and biology of the atmosphere, land and oceans and their interactions in great detail to obtain information about how the climate has changed in the past and may change in the future. In the past several decades, scientists and climate modelling groups around the world have made continuous efforts to incorporate higher spatial resolution, new physical processes and Earth system components such as biogeochemical cycles and ice sheets in the climate models, leading to tremendous progress in state-of-the-art climate model systems to realistically represent the Earth climate system.

However, there are still large uncertainties in model projected future climate change (Deser et al 2012a). These uncertainties arise from three sources: internal (natural) variability of the climate system that occurs in the absence of any radiative forcing; climate model uncertainty in responses to the same radiative forcings, and scenario uncertainty in future emissions (such as greenhouse gases and aerosols) and other climate forcings (Hawkins and Sutton, 2009). Scenario uncertainty is mainly determined by political decisions and technological development that takes into account different possible socio-economic developments (van Vuuren *et al* 2011, O'Neill *et al* 2014). Model uncertainty arises from the limitation of our understanding of the climate system and the unavoidable discrepancy due to its numerical representation. Internal variability arises from the chaotic behavior of the weather and cannot be reduced when investigating a given region and time period of interest (Hawkins and Sutton 2009, Deser *et al* 2012b). To quantify these uncertainties in climate simulations and projections a technique of multi-model, multi-member ensembles of climate simulations is required (Tebaldi and Knutti, 2007; Deser *et al* 2012b). The technique increases the statistical sample to account for natural variability and structural uncertainties in the model design, and has prompted a variety of approaches to quantify uncertainty in future climate in a probabilistic way. Studies have shown that the combined information of several ensembles is superior to a single-model performance, and ensembles can generally reduce biases, increase the skill and reliability of model forecasts (Tebaldi and Knutti, 2007; Christiansen, 2918; 2019).

The Coupled Model Intercomparison Project (CMIP), led by the World Climate Research Program (WCRP) Working Group on Coupled Modelling (WGCM), is an international effort to coordinate climate model development and model experiments for scientific understanding of the Earth climate system. The CMIP defines protocol and forcing data sets for model experiments, and coordinates the climate modelling community to run experiments that simulate climate change in the past, present and the future following the same standard. This allows results to be directly comparable across different models. The current CMIP phase 6 (CMIP6) consists of a number of common experiments for Diagnostic, Evaluation and Characterization of Klima (DECK), the CMIP historical simulations, and an ensemble of CMIP-Endorsed Model Intercomparison Projects (MIPs) that build on the DECK and CMIP historical simulations (Eyring *et al* 2016). The experiments designed in CMIP6 and CMIP6-endorsed MIPs are to address three broad questions: How does the Earth system respond to forcing? What are the origins and consequences of systematic model biases? How can we assess future climate changes given internal climate variability, predictability, and uncertainties in scenarios?

The past CMIP coordinated multi-model, multi-member ensembles of climate model experiments have formed the science base and essential contributions to the past IPCC Assessment Reports. The last IPCC assessment report (AR5) featured climate models from the last phase of CMIP, i.e., CMIP5 (Taylor *et al* 2012). The current ongoing CMIP6 (Eyring *et al* 2016) has attracted 49 different modelling groups worldwide bringing in simulations from around 100 different state-of-the-art climate models. The new CMIP6 multi-model ensembles will constitute the most important contribution to the upcoming 2021 IPCC Sixth Assessment Report (AR6).

Another important element of CMIP6 is to define common standards, coordination, infrastructure, and documentation that facilitate the distribution of model outputs and the characterization of the model ensemble. Under the coordination of the WGCM, all model outputs of CMIP6 experiments are documented, and the data are archived using comment standards on the Earth System Federation Grid (ESGF, Petrie et al, 2020). The ESGF infrastructure enables users worldwide – irrespective of who and from where they are – to freely download any wanted climate information for applications of climate change assessments, process studies, or climate impact investigations.

The EC-Earth consortium (http://www.ec-earth.org) is one of the modelling groups contributing to the CMIP6. The EC-Earth contributions are collective efforts in the sense that the EC-Earth model is jointly developed, and the CMIP6 simulations are carried out by several consortium members. This has several advantages, from allowing different groups to work with the same tool in parallel, to leveraging the burden of ensemble climate simulations. In this collective way, the consortium is able to deliver large ensembles of CMIP6 and CMIP6-endorsed MIPs experiments using eight different model configurations of the newest generation of the EC-Earth Earth System Model (ESM), the EC-Earth3 family, each with ensembles of multiple members of the CMIP6 simulations.

DMI is one of the active members in the EC-Earth consortium. We have joined the development of the EC-Earth3 model and have performed two members of CMIP6 historical and future scenarios using the atmosphere-ocean-sea ice coupled model configuration, EC-Earth3. In this Work Package, we have enhanced our global modeling capability by exploring the EC-Earth3-Veg, which is a light ESM configuration with a dynamical vegetation component, and a new area to DMI. We used the EC-Earth3-Veg to perform an additional member of the set of CMIP6 climate change experiments so to expend the contribution to CMIP6. We have also made great effort to deal with a number of difficulties toward publishing our CMIP6 results on DMI's ESGF data node.

4 Strengthening DMI's contribution to CMIP6 and climate change assessment

4.1 CMIP6 climate change simulations using EC-Earth3-Veg

DMI has a long experience in developing and running global climate models that are configured as atmosphere, ocean and sea ice coupled model. In the recent decade, DMI has worked together with the EC-Earth partners in development of the EC-Earth models of the past version, EC-Earth2, and the core of the current version, EC-Earth3, both consisting of atmosphere, ocean and sea ice components (Hazeleger et al, 2010; Döscher et al, 2021). DMI has also used these two model versions to perform the CMIP5 and CMIP6 climate change experiment for the historical period and a number of CMIP5/CMIP6 future scenarios. Even though we have also worked on incorporating a dynamical ice sheet model for Greenland ice sheet into EC-Earth2 and, currently EC-Earth3, we have no experience in working with other Earth system components.

To enhance our capability of understanding and simulating climate feedbacks between different components in the Earth climate system, we have started in this Work package a new area of running a climate model with a component model for dynamical vegetation. The model used, EC-Earth3-Veg, is one of the configuration in the EC-Earth3 family of Earth System Models. It simulates the climate with vegetation feedback, so that it can better capture the climate response to anthropogenic forcings. The vegetation feedback is potentially important in a warming climate. The changes of temperature and precipitation due to climate change may lead to changes of vegetation types and coverage. This modifies the surface conditions such as albedo and evapotranspiration, which will in turn influence the climate.

We successfully implemented the EC-Earth3-Veg on the DMI's HPC, and used the model to perform a number of CMIP6 climate change simulations for the historical period and four future scenarios. The four scenarios have been selected by the CMIP6 Scenario Model Intercomparison Project (ScenarioMIP) to drive climate models for CMIP6 experiments of future change (O'Neill et al, 2016). They represent alternative scenarios of future emissions and land use produced with integrated assessment models driven by different socioeconomic assumptions named Shared Socioeconomic Pathways (SSPs). The ScenarioMIP selected SSPs span a wide range of societal development from a strong mitigation low emission (SSP1-2.6), a moderate (SSP2-4.5), a medium to high end (SSP3-7.0), to an optimistic development high end (SSP5-8.5) future forcing pathway. Fig. 1 illustrated the CO2 concentrations and the corresponding anthropogenic radiative forcing of these SSPs scenarios. Following the CMIP6 protocol, the historical simulation covers the time period from 1850 to 2014, while the scenario simulations start from the end of the historical period (2015) and continue to the end of the century (2100). We have also extended the simulation of the high end scenario (SSP5-8.5) to year 2300 for investigations of even longer term climate response. Together with the simulations performed before using the atmosphere-ocean-sea ice coupled configuration of the EC-Earth3 model, we have contributed three members of the CMIP6 climate change experiments.

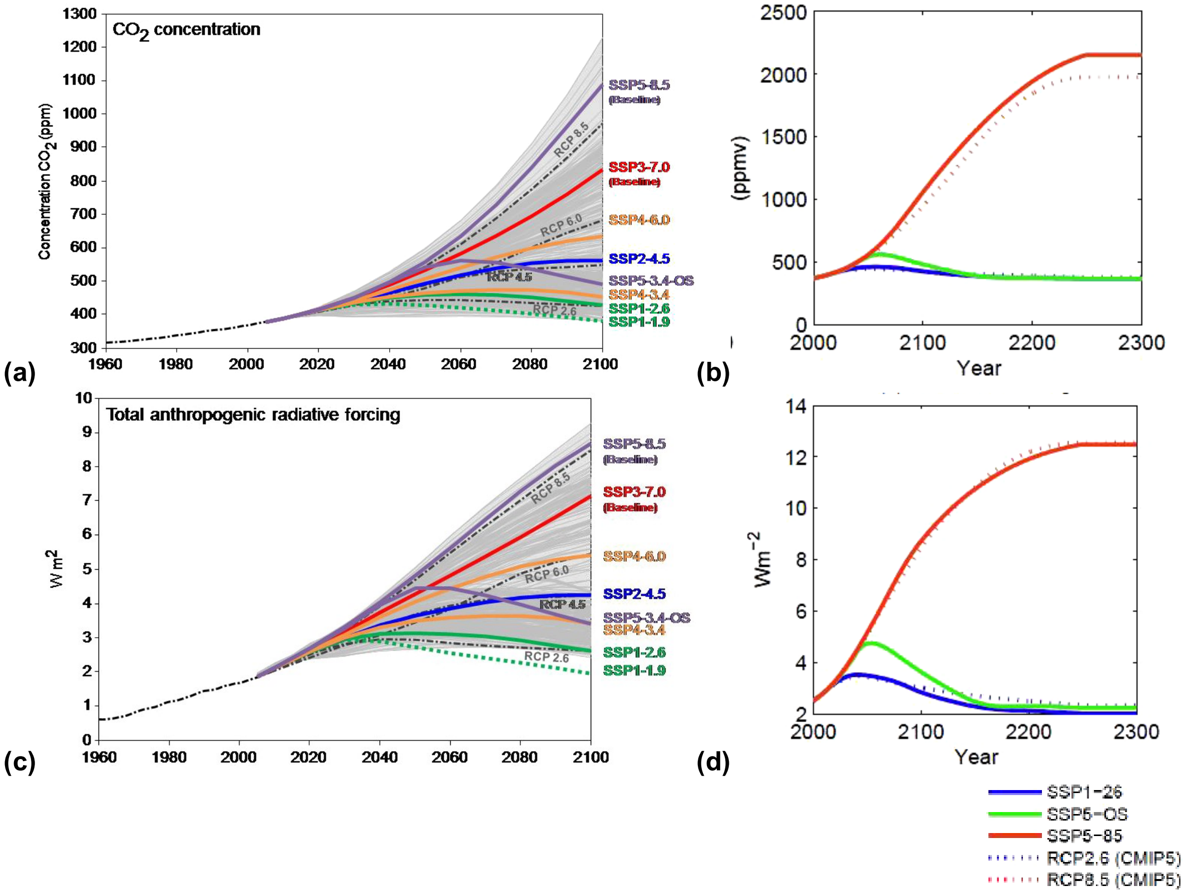

Figure 1. CO2 concentrations (upper panels) and the corresponding anthropogenic radiative forcing (lower panels) for the 21st century scenarios (left) and the three long-term extensions of in the CMIP6 ScenarioMIP design. (Figures from O'Neill et al, 2016).

4.2 The EC-Earth ensembles of the CMIP6 climate change experiments and the DMI contribution

As said above, there are eight model configurations of the EC-Earth3 model family, which are used by the EC-Earth consortium to perform a variety of experiments of CMIP6 and CMIP6-endorsed MIPs, each with multiple members of the simulations. About 16 institutes in the consortium have committed to perform these experiments. As such we are able to contribute to CMIP6 with large ensembles for several configurations, which ensure a good estimate of the uncertainty in the model simulations and projections. In particular, the ensembles of CMIP6 historical and future scenarios consist of 25 members for the core model system, EC-Earth3, and 14 members for the ESM light version, EC-Earth3-Veg. DMI now has completed two members of the experiments using EC-Earth3 and one member using the EC-Earth3-Veg.

Fig. 2 compares the global mean annual surface air temperature (TAS) as simulated by the EC-Earth3 and the EC-Earth3-Veg in the historical and 5 future scenario experiments. The future scenarios include the four SSPs specified in section 4.1 (i.e., SSP5-8.5, SSP3-7.0, SSP2-4.5, and SSP1-2.6), and a low end emission scenario, SSP1-1.9, which envisions a societal development limiting global warming below 1.5°C relative to pre-industrial levels to in 2100. The data for the individual members are downloaded from the ESGF (https://esg-dn1.nsc.liu.se/search/cmip6-liu/). The number of the ensembles, shown in the figure legend, is different from the individual experiments. These are the members of EC-Earth3/EC-Earth3-Veg simulations we were able to access at the ESGF site in January 2021). As can be seen in Fig. 2, the overall feature of the TAS evolutions as simulated by the two model configurations can hardly be distinguished, suggesting that the vegetation feedback does not result in changes in the climate sensitivity. The interactive vegetation in the model system only induces regional and local changes in the circulation.

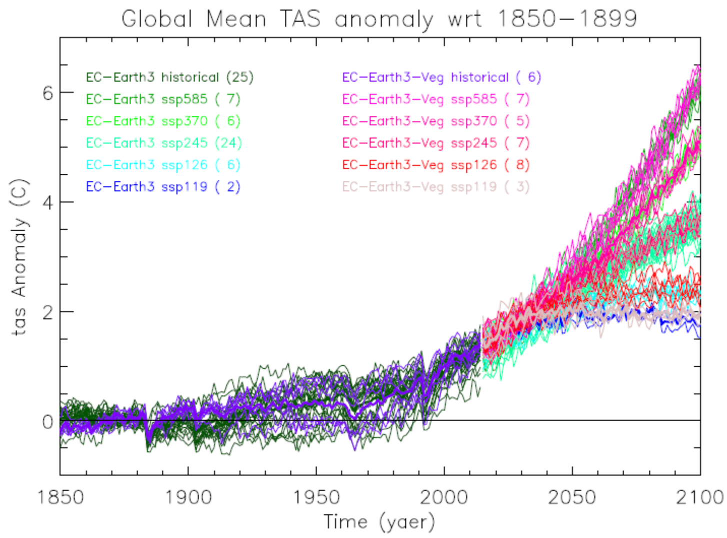

Figure 2. Time evolution of the global mean annual surface air temperature (TAS) changes simulated in the ensembles of the CMIP6 historical and future scenario simulations using the climate model EC-Earth3 and EC-Earth3-Veg respectively. The changes are with respect to the average over 1850-1899. The thin curves represent the individual members, while the thick curves are the ensemble means of the historical or individual SSPs with the respective model as show in the figure legend. The ensemble size for each experiment is given by the number in parentheses, respectively. Unit: °C.

Fig. 3 shows the time evolution of the individual members from DMI's simulations (thin curves) using EC-Earth3 (two members) and EC-Earth3-Veg (one member) in comparison with the full EC-Earth ensembles (color shadings) for the model simulated TAS changes and the total sea ice areas in Northern Hemisphere (NH) in March and September. As seen in the plots, the model spread for the climate simulated by the EC-Earth models is large. For example, the range of simulated temperature anomalies in the historical period span more than half a degree around the ensemble means after 1900 with the standard deviation across all members as large as 0.38. The difference of the NH sea ice area in an individual member with the ensemble mean may be as large as 20% of the ensemble mean for present day (1980-2014). Thus, there exists large uncertainty in the climate estimated using a single model simulation.

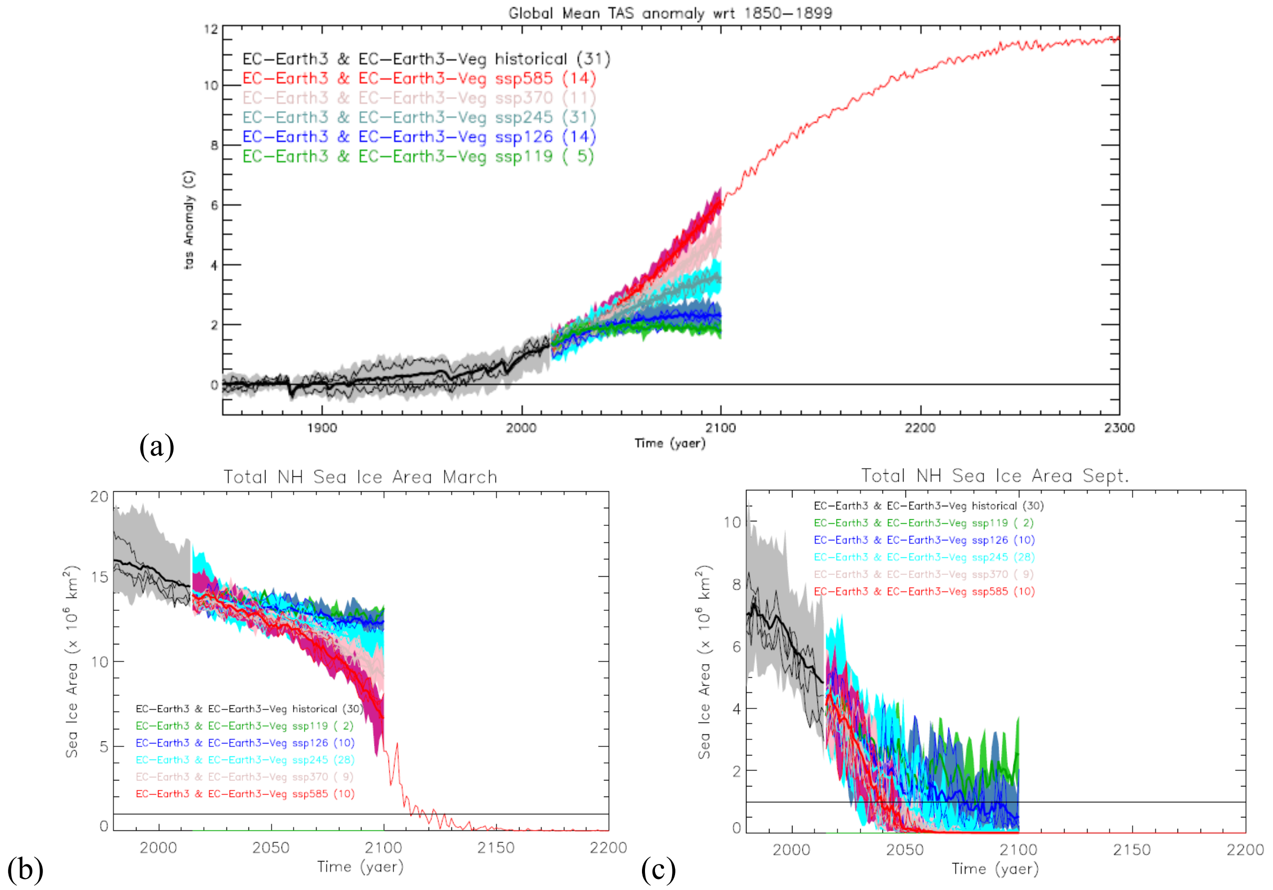

Figure 3. Time evolution of the ensembles of the global mean TAS anomalies with respect to the pre-industrial period over 1850-1899 (a), the Northern Hemisphere total sea ice area in March (b) and September (c) as simulated in the CMIP6 historical (black) and future scenarios SSP5-8.5 (red), SSP3-7.0 (pink) SSP2-4.5 (cyan) SSP1-2.6 (blue) and SSP1-1.9 (green) using the EC-Earth3 and EC-Earth3-Veg, respectively. The shading are the ensemble spread of all members of respective ensemble, the thick curves are the ensemble means, while the thin curves are the individual members carried out by DMI. The historical simulations starts from 1850, but the figures for the sea ice only plots from 1980. All future simulations stop at 2100, except one of the members carried out at DMI which continues until 2300 following the extended SSP5-8.5 scenario. The thin horizontal line in (b) and (c) indicates the 1.0 x 10^6 km^2 threshold which often used as indication of an ice free Arctic. Unit: °C for (a) and 1.0 x 10^6 km^2 for (b) and (c).

The EC-Earth models simulate that the global TAS has arose about 1.0±0.2°C by the end of the historical period (1995-2014) since the pre-industrial period (averaged over 1850-1899). Here the uncertainty level is expressed by the standard deviation cross all members. The models project the global mean surface air temperature continuing to increase throughout the 21st century driven by increases in anthropogenic greenhouse gas concentrations. The projected average warming by the end of this century (averaged over 2081-2100) is likely to be 5.4±0.2°C for the SSP5-8.5 scenario, 4.5±0.2°C for SSP3-7.0, 3.4±0.2°C for SSP2-4.5 and 2.3±0.2°C for SSP1-2.6 scenarios relative to the preindustrial period. Even for the low-end scenario the warming will surpass the 1.5°C target and reach 1.9±0.1°C by the end of the 21st century, which exceeds the natural variability that is seen in the 20th century as simulated in the historical period. The simulated geographical distribution is well known (IPCC, 2007; 2013): the warming is the greatest over land, with a maximum over the high northern latitudes, and least over the Southern Ocean (Fig. 4). An outstanding feature in the distribution of the warming shown in Fig. 4 is the strong Arctic amplification: warming in the Arctic region is about 2–3 times the global average warming. If the warming continues following the high-end scenario, the global temperature will rise about 11.5° by the end of 2300 with respect to preindustrial period, or 10.4°C with respect to present day (1995-2014), as simulated by the DMI's run using EC-Earth3-Veg.

Accompany with the simulated temperature rise in the recent past, the sea ice cover in NH simulated by the EC-Earth models undergoes a rapid retreat (Fig. 3b, c). The declining rate of September sea ice area during 1979-2014 is about -0.70 x 10^6 km^2 per decade, which is comparable to the observed NH sea ice declining rate of -0.66 x 10^6 km^2 per decade as estimated using the HadISST sea ice data set (Rayner et al, 2003). The projected decline of NH sea ice is dramatic. The occurrence of a summer ice free Arctic Ocean may happen as early as around 2040 for the high emission scenario SSP5-8.5, and 2042 for SSP3-7.0. The summer sea ice in the Arctic may survive until around 2050 for the moderate emission scenario SSP2-4.5, but even for the low emission scenario SSP1-2.6 the Arctic summer will be ice free after around 2080. Only for the low-end scenario SSP1-1.9 the Arctic Ocean may remain partly ice covered in summer until the end of the 21st century. The Arctic will remain sea ice in winter for all scenarios. However, the decline of the winter sea ice in the Arctic accelerates in the last two decades for the SSP5-8.5, leading to an abrupt disappearing of the winter sea ice only about one or two decades into the 22nd century according to our extended SSP5-8.5 scenario simulation.

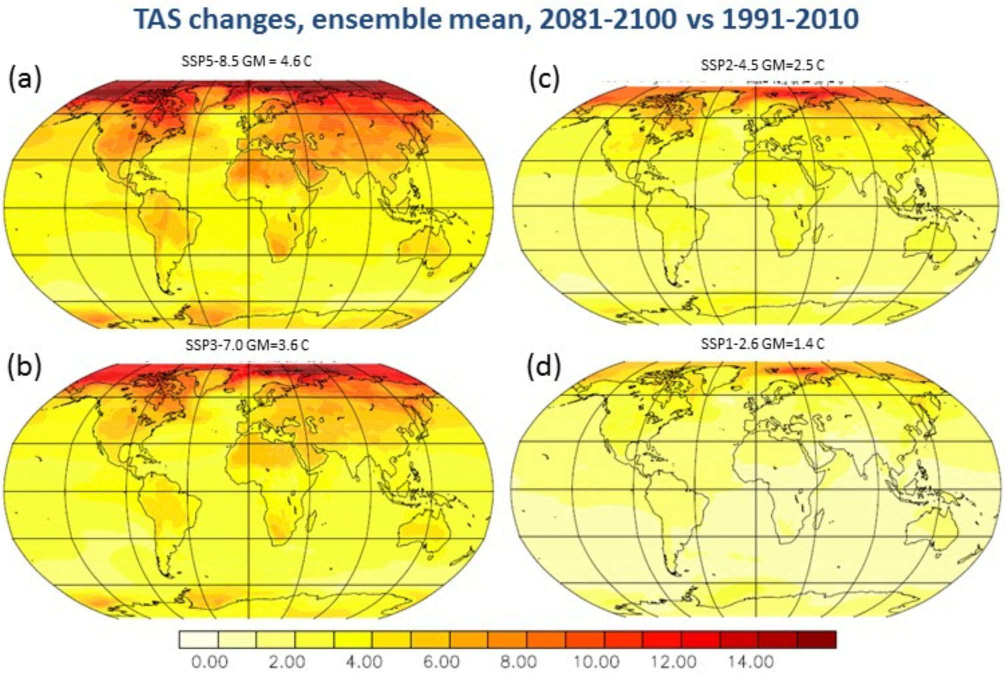

Figure 4. The projected future changes averaged over 2081-2100 with respect to present day (1991-2010) as simulated by the ensembles of the EC-Earth3 and EC-Earth3-Veg together. The numbers shown on each plot represent the global mean changes of the specific SSPs. Unit: °C. (Figures adapted from Yang et al, 2020, Figure 8.4.)

4.3 Toward open access to climate model simulation data

One of the important steps for making our CMIP6 contributions visible internationally is to publish the output of our CMIP6 simulations on the WCRP organized infrastructure ESGF data nodes. The ESGF is an infrastructure that facilitates access to and analysis of the CMIP model output, and makes the CMIP6 data accessible for scientists worldwide – besides those who run the models.

It is a pre-condition for data publishing on the CMIP6 ESGF nodes that the data are written in a common structure and format complying the specifications and standards defined by the WGCM Infrastructure panel (WIP) for CMIP6. One challenge for CMIP6 data publication is therefore to convert the raw output of EC-Earth3 models into the CMIP agreed standard and quality assurance of the data in the new format. The workflow for the date conversion includes three steps:

1. **CMORization** of the EC-Earth3/EC-Earth3-Veg outputs for the CMIP6 requested variables. CMORization is the process that reformats raw model output into the CMIP agreed standard using the WIP developed standard library Climate Model Output Rewriter version 3

(CMOR3). In particular, the CMOR3 generates output data with attributes that comply with the project and CMIP experiment specifications, so that the CMORized output is "self-describing";

2. **Quality assurance** of the CMORized EC-Earth CMIP6 data. It is important to quality control the data to ensure the correctness. The EC-Earth consortium has agreed that two tools for quality control, namely ***nctime*** and ***QA-DKRZ,*** should be applied to the EC-Earth CMIP6 data before they are published on the ESGF data nodes;
3. **Final quality check** applying the tool ***PrePARE*** (Pre-Publication Attribute Reviewer) after the CMORized data have been transferred to the ESGF data node. The ***PrePARE*** is developed by the WIP to ensure that the metadata of the data file comply with CMIP6 specifications. It is a mandatory requirement by the WIP/CMIP6 panel for data publication.

For CMORizing the EC-Earth3 models output, the EC-Earth consortium has developed a tool, ***ece2cmor3*** for applying the CMOR3 library on the EC-Earth3 models grid and data format to CMORize the EC-Earth3 models raw data. We have applied ***ece2cmor3*** to all of our CMIP6 simulation data, which generated about 250 TB of CMORized data. However, as the consortium working with the CMORizing the CMIP6 data, a number of bugs in the CMORized data have been identified, and the ***ece2cmor3*** were updated several times with bug fixes. We have also updated the ***ece2cmor3*** accordingly and re-run the CMORization or the necessary bug-fix to correct the problematic data sets.

nctime is a tool to diagnose the time definition in a data set to ensure a proper analysis. It analyzes the time continuity of datasets split across files and the time axis correctness in the files. This tool is widely used in the climate modelling community and is easy to install and apply.

QA-DKRZ is a Quality Assurance tool developed at DKRZ (The German Climate Computing Centre). It checks conformance of meta-data of climate simulations with conventions and rules of projects (CORDEX, CMIP5, and CMIP6, etc.) and performs additional checks on technical state based on MIP tables. There has been a number of ongoing developments for the tool. Meanwhile the supporting software has also been updated. These inconsistences in the running system for processing the CMIP6 data, the version of ***QA-DKRZ*** and required supporting software has led to numerous technical challenges in installing and running the ***QA-DKRZ*** on our computer system despite a good support from the IT experts. With the help of the IT department, we have overcome a great deal of technical issues and now can finally run the ***QA-DKRZ*** on a dedicated computer node, even though it seems not to run very efficiently. With the 250 TB CMORized data in total, it will take some time to complete the quality control of all the data.

We have also been working on installation of the DMI ESGF data node. In collaboration with the Swedish National Supercomputer Center (NSC), we have set up the data node and are on the process of testing publication. We expect our simulation data will start to be publically available on the ESGF in early 2021.

4.4 Multi-model assessment of future climate change

Even though we have not yet been able to publish our data on the ESGF data node, we have shared our simulation data with EC-Earth consortium partners as well as researchers worldwide, and actively joined common analyses with other modeling groups internationally. For example, in an assessment of the future climate change led by Tebaldi et al (2020), we analyzed CMIP6 climate Scenario simulations using 43 different models/model configurations from 25 modelling groups worldwide and compared them with result from the previous CMIP5 simulations. We find that, for the five scenarios mentioned above, the range of future temperature changes by the end of the century spans between 0.8°C and 4.03°C above the historical baseline (1995-2014), or 1.64°C – 4.87°C above the preindustrial period (1850-1900), with individual models reach significantly larger warming levels under the highest scenario, reaching beyond 5.6°C (above 6.4°C from 1850-1900), as can be seen in the figure below. We confirmed the well-established behavior of the warming pattern similar to what can be seen in Fig. 4: warming is stronger over land than over oceans; the north to south gradient over the globe persists, with strong polar amplification signals resulting in projected warming as twice of the global average in the Arctic region. The cooling North Atlantic upwelling region emerges clearly.

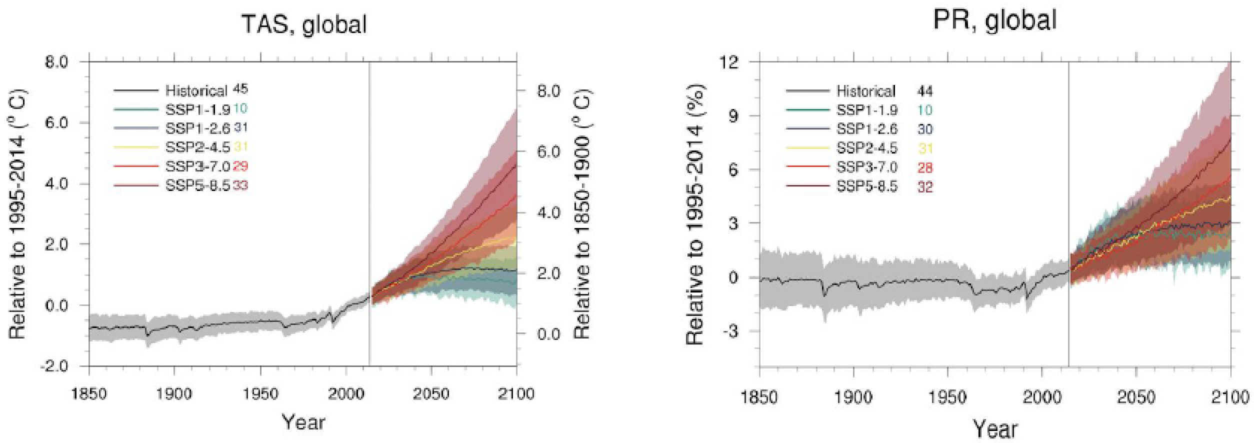

Figure 5. Time series of changes of global average temperature (left) and precipitation (right) from current baseline (1995-2014, left axis) and pre-industrial baseline (1850-1900, right axis, obtained by adding a 0.95 °C offset) for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Thick lines are ensemble means (number of models shown in the legends). The shading represents the ±1.64*sigma interval, where sigma is the standard deviation of the annual means (From Tebaldi, et al, 2020, figure 1).

Global precipitation change follows the pace and magnitude of warming. Precipitation change appears with the known patterns of dry areas becoming drier and wet areas becoming wetter. The high latitudes and the equatorial Pacific see precipitation increases, and the semi-arid regions of the Mediterranean, Australia and South Africa expecting further drying.

We also estimate the times at which various warming levels are reached. According the assessment, the 1.5°C target (above 1850-1900) will be reached on average (across all models analyzed and all scenarios) in the second half of the current decade. The next level of 2.0°C target takes only another 13 more years to reach for the high end scenario (SSP5-8.5) after the 1.5°C has reached, or more than 30 years for the low end scenario (SSP1-2.6).

Comparing these multi-model ensemble results to the EC-Earth3 models ensembles shown in Section 4.2, it is clear that EC-Earth3 models are among the models with middle-to-high temperature changes in response to anthropogenic forcing. Indeed, the equilibrium climate sensitivity (ECS) of the EC-

Earth3 and EC-Earth3-Veg is about 4.1 K and 4.3 K, which is among the models with high ECS. The ECS in EC-Earth3 CMIP6 models are about 1 K higher than that of the EC-Earth model in CMIP5. This increase can be attributed to the more advanced treatment of aerosols, with the largest contribution coming from the effect of aerosols on cloud microphysics, i.e., cloud lifetime or second indirect effect (Wyser et al, 2020).

4.5 Climate impact of emission reduction due to COVID19 lockdown

The covid-19 pandemic resulted in restricting travel and other activities in many nations during 2020. This caused a temporary reduction in emissions of CO2 and other pollutants. DMI joined the decision with the international climate modeling community on meeting the society need for quantifying the impact on climate of these emission reductions. Under this decision a new Model Intercomparison Project, CovidMIP, is quickly formed under the CMIP6 endorsed Detection and Attribution Model Intercomparison Project (DAMIP), to design an experiment protocol for addressing the climate response to the emission reduction due to COVID19 lockdown. The CovidMIP protocol specifies four new experiments, each branching from the SSP2-4.5 scenario simulation on January 1, 2020, and following the new forcing in line with emissions reductions (Forster et al. 2020). The SSP2-4.5 scenario simulation is served as the baseline for the emission reduction experiments. The four CovidMIP experiments are defined below (see Jones et al, 2020 for details):

1. **ssp245-covid**: The experiment aims to investigate the immediate term impact (from 2020-2024) of the “two year blip” scenario under which emissions revert to the baseline levels by the end of 2022;
2. **ssp245-cov-strgrn:** A scenario envisions a possible future economic recovery strategy as a reduction in anthropogenic CO2 emissions post-2020 consistent with enhanced investment in environmentally friendly technologies that are strong “green stimulus”;
3. **ssp245-cov-moderate:** A scenario similar to ssp245-cov-strgrn but with moderate measures on environmentally friendly technologies;
4. **ssp245-cov-fossil**: A scenario envisions an increase in anthropogenic CO2 emissions relative to ssp245 after 2020 consistent with an investment in more traditional fossil-fuel based energy production (or “fossil-fuelled recovery”).

Following the protocol, the experiments 2-4 should cover the period 2020-2050, while the experiment 1 only covers the five years of 2020-2024.

Seven EC-Earth institutes committed to carry out the CovidMIP experiments. The implementation of these experiments on the EC-Earth3 was made as a common effort quickly after the protocol was defined and the forcing data were available. Ensembles of each of experiments were performed. In total EC-Earth contributes 30 members for the ssp245-covid experiment, and 24 members of the other 3 longer experiments, of which two of the members are contributed by DMI.

Because any climate signal due to COVID-19-induced emissions reductions was considered likely to be small, it is advantageous to carry out multi-model and large multi-member ensembles for detection of any response. By the end of 2020, CovidMIP has gathered contributions from 12 Earth System Models (including EC-Earth) with over 280 simulations using multiple initial-conditions

We have joined the multi-model analysis led by Jones at the MetOffice (Jones et al, 2020), with focus on the immediate term climate impact using the SSP245-covid experiments. In this analysis, results from the multi-model multi-member ensemble simulations are compared with the baseline experiment (i.e., SSP2-4.5) to see if the emission reductions have affected climate in the coming years. We find a consensus that aerosol amounts are reduced, especially over East Asia, during 2020-2024. This leads to increases in solar radiation reaching the surface in this region. However, we cannot detect any associated impact on temperature or rainfall (Jones et al, 2020). More analyses to investigate the response on regional scales and extreme weather have been planned and will be carried out in 2021.

4.6 Summary

In this Work Package, we have extended our capability in working with and running the EC-Earth3 Earth System Model. In particular we have started the practice of applying the EC-Earth3-Veg, a configuration of the EC-Earth3 climate model with a dynamical vegetation component, to better represent the climate response with consideration of the vegetation feedback. A set of CMIP6 climate change experiments consisting of the historical and four future scenarios has been performed using the EC-Earth3-Veg. Together with the experiments previously performed, DMI has contributed 3 members of CMIP6 experiment sets to the EC-Earth multi-member ensembles for CMIP6 using two different configurations of the model (i.e., EC-Earth3 and EC-Earth3-Veg), out of 44 members in total made by the EC-Earth consortium (25 for EC-Earth3 and 14 for EC-Earth3-Veg, respectively).

The EC-Earth3 model ensembles project a future climate warming spanning from 5.42±0.22°C for the high emission scenario SSP5-8.5, 4.50±0.24°C for SSP3-7.0, 3.42±0.22°C for SSP2-4.5, 2.29±0.20°C for SSP1-2.6, and 1.87±0.12°C for the low-end emission scenario SSP1-1.9 by the end of the 21st century with respect to the preindustrial period (i.e., 1850-1899), all surpassing the 1.5°C target in the Paris agreement. The EC-Earth3 models also project that the Arctic sea ice will continue to decline rapidly. The Arctic Ocean may become seasonally ice free as soon as in about two decades (i.e., ~2040) for the higher emission scenarios SSP5-8.5 and SSP3-7.0, or about 3 decades (i.e., ~2050) for the moderate scenario SSP2-4.5. Even for the low emission scenario, the Arctic Ocean will be ice free in summer around 2080. Arctic sea ice can survive in summer only for the low-end scenario SSP1-1.9. The winter sea ice in the Arctic will also retreat in the future, especially toward the last decades in 21st century for the high-end scenario SSP5-8.5, for which the Arctic may become ice free all year round around 2120.

Our contributions to CMIP6 experiments and experience in climate modelling using EC-Earth3 have led us to participations of several common analyses of multi-model, multi-member ensembles, including a study to assess the projected future climate changes using the CMIP6 multi-model ensembles. In addition, we have also taken part in the new initiative, CovidMIP, to investigate the climate impact of the emission reduction due the COVID19 pandemic. The analysis of the multi-model multi-member ensembles of CovidMIP indicates that there are no detectable responses on temperature or rainfall that are associated with the COVID19 emission reduction in the immediate term climate.

We have also made great efforts to built knowledge and skills for preparation of both the model simulation data and the infrastructure (i.e., the ESGF data node) for making the CMIP6 simulation data publically accessible following the CMIP6 standard and compliance. These efforts including the CMORization of the CMIP6 experiment output and quality assurance of the data to be publish. A great amount of data are been processing in preparation for publish on DMI's ESGF data node. These activities will promote the DMI's visibility in the EC-Earth consortium as well as in the international climate research community.

5 References

Christiansen, B., 2018: Ensemble averaging and the curse of dimensionality. *J. Climate*, 31, 1587–1596, https://doi.org/10.1175/JCLI-D-17-0197.1.

Christiansen, B., 2019: Analysis of ensemble mean forecasts: The blessings of high dimensionality. *Mon. Wea. Rev.*, 147, 1699–1712, https://doi.org/10.1175/MWR-D-18-0211.1.

Deser C, Knutti R, Solomon S and Phillips A S, 2012a: Communication of the role of natural variability in future North American climate *Nat. Clim. Change* **2** 775–9.

Deser C, Phillips A S, Bourdette V and Teng H, 2012b: Uncertainty in climate change projections: the role of internal variability *Clim. Dyn.* **38** 527–46.

Döscher, Ralf, et al, 2021: The EC-Earth3 Earth System Model for the Climate Model Intercomparison Project 6. Submitted to *Geoscientific Model Development* (GMD).

Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., & Rummukainen, M. (2013). Evaluation of climate models. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, UK/New York: Cambridge University Press.

Hawkins, E., and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions, *Bull. Am. Meteorol. Soc.*, 90, 1095– 1107, doi:10.1175/2009BAMS2607.1.

Hazeleger, W., X. Wang, C. Severijns, S. Ştefănescu, R. Bintanja, A. Sterl, K. Wyser, T. Semmler, **S. Yang**, B. van den Hurk, T. van Noije, E. van der Linden, K. van der Wiel, 2012: EC-Earth V2.2: description and validation of a new seamless Earth system prediction model. *Clim Dyn.*, **39**, 2611–2629, doi:10.1007/s00382-011-1228-5.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge: Cambridge University Press, 996 pp.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jones, et al, 2020: The Climate Response to Emissions Reductions due to COVID-19. Submitted to *Geophysical Research Letters.*

O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M., 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016.

Petrie, R., Denvil, S., Ames, S., Levavasseur, G., Fiore, S., Allen, C., Antonio, F., Berger, K., Bretonnière, P.-A., Cinquini, L., Dart, E., Dwarakanath, P., Druken, K., Evans, B., Franchistéguy, L., Gardoll, S., Gerbier, E., Greenslade, M., Hassell, D., Iwi, A., Juckes, M., Kindermann, S., Lacinski, L., Mirto, M., Nasser, A. B., Nassisi, P., Nienhouse, E., Nikonov, S., Nuzzo, A., Richards, C., Ridzwan, S., Rixen, M., Serradell, K., Snow, K., Stephens, A., Stockhause, M., Vahlenkamp, H., and Wagner, R.: Coordinating an operational data distribution network for CMIP6 data, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2020-153, in review, 2020.

Rayner, N. *et al.* Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research-Atmospheres* **108**, doi:10.1029/2002JD002670 (2003).

Taylor, K E, Stouffer R J and Meehl G A, 2012: An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98.

Tebaldi, C., and R. Knutti, 2007: The use of the multi-model ensemble in probabilistic climate projections. Philos. Trans. R. Soc. London A, **365** 2053–2075.

Tebaldi, et al, 2020: Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Accepted by *Earth System Dynamics*, https://doi.org/10.5194/esd-2020-68

van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31

Wyser, Klaus, Twan van Noije, Shuting Yang, Jost von Hardenberg, Declan O'Donnell, and Ralf Döscher, 2020: On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6. *Geosci. Model Dev.*, 13, 3465–3474, 2020. https://doi.org/10.5194/gmd-13-3465-2020

Yang S., Gao Y., Koenigk K., Keenlyside N., Counillon F. (2021) The Climate Model: An ARCPATH Tool to Understand and Predict Climate Change. In: Nord D.C. (eds) *Nordic Perspectives on the Responsible Development of the Arctic: Pathways to Action*. Springer Polar Sciences. Springer, Cham. https://doi.org/10.1007/978-3-030-52324-4_8

Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., aldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. Geophysical Research Letters, 47, e2019GL085782. https://doi.org/10.1029/2019GL085782

6 Previous reports

Previous reports from the Danish Meteorological Institute can be found on:
https://www.dmi.dk/publikationer/